Harran University
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Reading Texts For Mechanical Engineering

Technical English I & II

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Chapter 1

Introduction

1.1 Preliminary Remarks

Fluid mechanics is the study of fluids either in motion (fluid *dynamics*) or at rest (fluid *statics*) and the subsequent effects of the fluid upon the boundaries, which may be either solid surfaces or interfaces with other fluids. Both gases and liquids are classified as fluids, and the number of fluids engineering applications is enormous: breathing, blood flow, swimming, pumps, fans, turbines, airplanes, ships, rivers, windmills, pipes, missiles, icebergs, engines, filters, jets, and sprinklers, to name a few. When you think about it, almost everything on this planet either is a fluid or moves within or near a fluid.

The essence of the subject of fluid flow is a judicious compromise between theory and experiment. Since fluid flow is a branch of mechanics, it satisfies a set of well-documented basic laws, and thus a great deal of theoretical treatment is available. However, the theory is often frustrating, because it applies mainly to idealized situations which may be invalid in practical problems. The two chief obstacles to a workable theory are geometry and viscosity. The basic equations of fluid motion (Chap. 4) are too difficult to enable the analyst to attack arbitrary geometric configurations. Thus most textbooks concentrate on flat plates, circular pipes, and other easy geometries. It is possible to apply numerical computer techniques to complex geometries, and specialized textbooks are now available to explain the new *computational fluid dynamics* (CFD) approximations and methods [1, 2, 29].[1] This book will present many theoretical results while keeping their limitations in mind.

The second obstacle to a workable theory is the action of viscosity, which can be neglected only in certain idealized flows (Chap. 8). First, viscosity increases the difficulty of the basic equations, although the boundary-layer approximation found by Ludwig Prandtl in 1904 (Chap. 7) has greatly simplified viscous-flow analyses. Second, viscosity has a destabilizing effect on all fluids, giving rise, at frustratingly small velocities, to a disorderly, random phenomenon called *turbulence*. The theory of turbulent flow is crude and heavily backed up by experiment (Chap. 6), yet it can be quite serviceable as an engineering estimate. Textbooks now present digital-computer techniques for turbulent-flow analysis [32], but they are based strictly upon empirical assumptions regarding the time mean of the turbulent stress field.

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[1] Numbered references appear at the end of each chapter.

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Thus there is theory available for fluid-flow problems, but in all cases it should be backed up by experiment. Often the experimental data provide the main source of information about specific flows, such as the drag and lift of immersed bodies (Chap. 7). Fortunately, fluid mechanics is a highly visual subject, with good instrumentation [4, 5, 35], and the use of dimensional analysis and modeling concepts (Chap. 5) is widespread. Thus experimentation provides a natural and easy complement to the theory. You should keep in mind that theory and experiment should go hand in hand in all studies of fluid mechanics.

1.2 The Concept of a Fluid

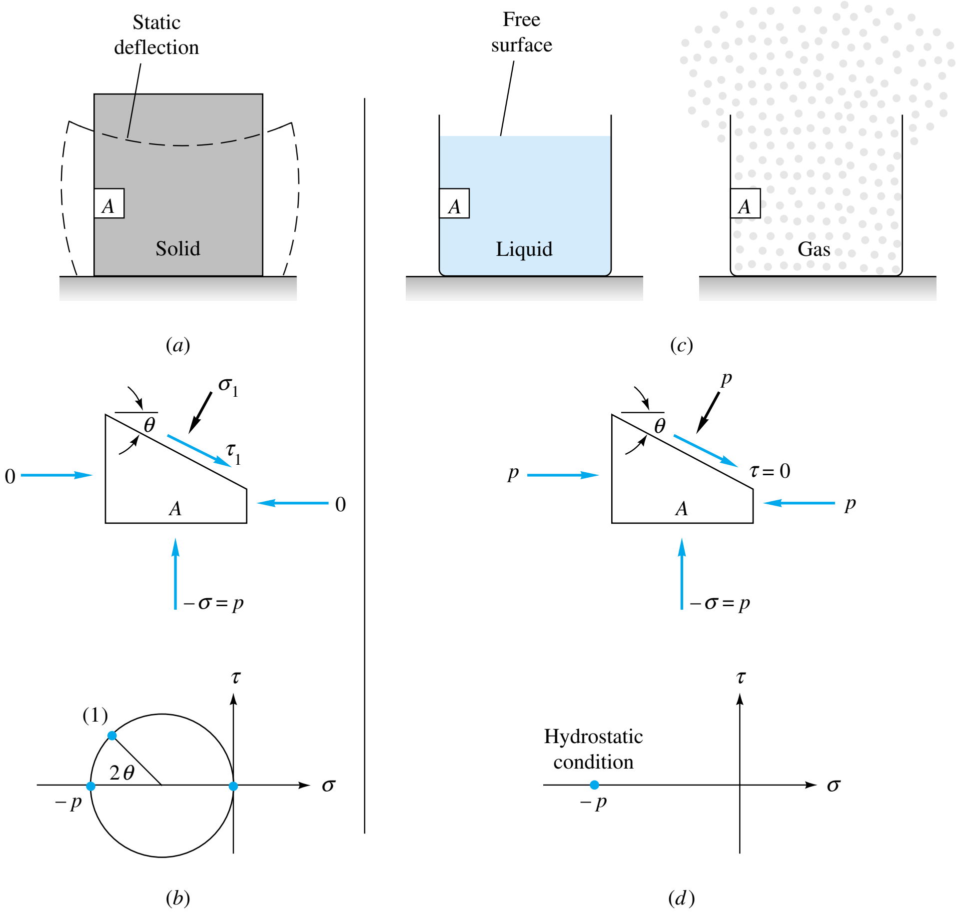
From the point of view of fluid mechanics, all matter consists of only two states, fluid and solid. The difference between the two is perfectly obvious to the layperson, and it is an interesting exercise to ask a layperson to put this difference into words. The technical distinction lies with the reaction of the two to an applied shear or tangential stress. *A solid can resist a shear stress by a static deformation; a fluid cannot*. Any shear stress applied to a fluid, no matter how small, will result in motion of that fluid. The fluid moves and deforms continuously as long as the shear stress is applied. As a corollary, we can say that a fluid at rest must be in a state of zero shear stress, a state often called the hydrostatic stress condition in structural analysis. In this condition, Mohr's circle for stress reduces to a point, and there is no shear stress on any plane cut through the element under stress.

Given the definition of a fluid above, every layperson also knows that there are two classes of fluids, *liquids* and *gases*. Again the distinction is a technical one concerning the effect of cohesive forces. A liquid, being composed of relatively close-packed molecules with strong cohesive forces, tends to retain its volume and will form a free surface in a gravitational field if unconfined from above. Free-surface flows are dominated by gravitational effects and are studied in Chaps. 5 and 10. Since gas molecules are widely spaced with negligible cohesive forces, a gas is free to expand until it encounters confining walls. A gas has no definite volume, and when left to itself without confinement, a gas forms an atmosphere which is essentially hydrostatic. The hydrostatic behavior of liquids and gases is taken up in Chap. 2. Gases cannot form a free surface, and thus gas flows are rarely concerned with gravitational effects other than buoyancy.

Figure 1.1 illustrates a solid block resting on a rigid plane and stressed by its own weight. The solid sags into a static deflection, shown as a highly exaggerated dashed line, resisting shear without flow. A free-body diagram of element A on the side of the block shows that there is shear in the block along a plane cut at an angle θ through A. Since the block sides are unsupported, element A has zero stress on the left and right sides and compression stress $\sigma = -p$ on the top and bottom. Mohr's circle does not reduce to a point, and there is nonzero shear stress in the block.

By contrast, the liquid and gas at rest in Fig. 1.1 require the supporting walls in order to eliminate shear stress. The walls exert a compression stress of $-p$ and reduce Mohr's circle to a point with zero shear everywhere, i.e., the hydrostatic condition. The liquid retains its volume and forms a free surface in the container. If the walls are removed, shear develops in the liquid and a big splash results. If the container is tilted, shear again develops, waves form, and the free surface seeks a horizontal configura-

Fig. 1.1 A solid at rest can resist shear. (*a*) Static deflection of the solid; (*b*) equilibrium and Mohr's circle for solid element *A*. A fluid cannot resist shear. (*c*) Containing walls are needed; (*d*) equilibrium and Mohr's circle for fluid element *A*.



tion, pouring out over the lip if necessary. Meanwhile, the gas is unrestrained and expands out of the container, filling all available space. Element *A* in the gas is also hydrostatic and exerts a compression stress $-p$ on the walls.

In the above discussion, clear decisions could be made about solids, liquids, and gases. Most engineering fluid-mechanics problems deal with these clear cases, i.e., the common liquids, such as water, oil, mercury, gasoline, and alcohol, and the common gases, such as air, helium, hydrogen, and steam, in their common temperature and pressure ranges. There are many borderline cases, however, of which you should be aware. Some apparently "solid" substances such as asphalt and lead resist shear stress for short periods but actually deform slowly and exhibit definite fluid behavior over long periods. Other substances, notably colloid and slurry mixtures, resist small shear stresses but "yield" at large stress and begin to flow as fluids do. Specialized textbooks are devoted to this study of more general deformation and flow, a field called *rheology* [6]. Also, liquids and gases can coexist in two-phase mixtures, such as steam-water mixtures or water with entrapped air bubbles. Specialized textbooks present the analysis above which aggregate variations may be important. The *density* ρ of a fluid is best defined as

$$\rho = \lim_{\delta\mathcal{V}\to\delta\mathcal{V}^*} \frac{\delta m}{\delta\mathcal{V}} \tag{1.1}$$

The limiting volume $\delta\mathcal{V}^*$ is about 10^{-9} mm^3 for all liquids and for gases at atmospheric pressure. For example, 10^{-9} mm^3 of air at standard conditions contains approximately 3×10^7 molecules, which is sufficient to define a nearly constant density according to Eq. (1.1). Most engineering problems are concerned with physical dimensions much larger than this limiting volume, so that density is essentially a point function and fluid properties can be thought of as varying continually in space, as sketched in Fig. 1.2*a*. Such a fluid is called a *continuum,* which simply means that its variation in properties is so smooth that the differential calculus can be used to analyze the substance. We shall assume that continuum calculus is valid for all the analyses in this book. Again there are borderline cases for gases at such low pressures that molecular spacing and mean free path[3] are comparable to, or larger than, the physical size of the system. This requires that the continuum approximation be dropped in favor of a molecular theory of rarefied-gas flow [8]. In principle, all fluid-mechanics problems can be attacked from the molecular viewpoint, but no such attempt will be made here. Note that the use of continuum calculus does not preclude the possibility of discontinuous jumps in fluid properties across a free surface or fluid interface or across a shock wave in a compressible fluid (Chap. 9). Our calculus in Chap. 4 must be flexible enough to handle discontinuous boundary conditions.

1.4 Dimensions and Units

A *dimension* is the measure by which a physical variable is expressed quantitatively. A *unit* is a particular way of attaching a number to the quantitative dimension. Thus length is a dimension associated with such variables as distance, displacement, width, deflection, and height, while centimeters and inches are both numerical units for expressing length. Dimension is a powerful concept about which a splendid tool called *dimensional analysis* has been developed (Chap. 5), while units are the nitty-gritty, the number which the customer wants as the final answer.

Systems of units have always varied widely from country to country, even after international agreements have been reached. Engineers need numbers and therefore unit systems, and the numbers must be accurate because the safety of the public is at stake. You cannot design and build a piping system whose diameter is D and whose length is L. And U.S. engineers have persisted too long in clinging to British systems of units. There is too much margin for error in most British systems, and many an engineering student has flunked a test because of a missing or improper conversion factor of 12 or 144 or 32.2 or 60 or 1.8. Practicing engineers can make the same errors. The writer is aware from personal experience of a serious preliminary error in the design of an aircraft due to a missing factor of 32.2 to convert pounds of mass to slugs.

In 1872 an international meeting in France proposed a treaty called the Metric Convention, which was signed in 1875 by 17 countries including the United States. It was an improvement over British systems because its use of base 10 is the foundation of our number system, learned from childhood by all. Problems still remained because

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[3] The mean distance traveled by molecules between collisions.

even the metric countries differed in their use of kiloponds instead of dynes or newtons, kilograms instead of grams, or calories instead of joules. To standardize the metric system, a General Conference of Weights and Measures attended in 1960 by 40 countries proposed the *International System of Units* (SI). We are now undergoing a painful period of transition to SI, an adjustment which may take many more years to complete. The professional societies have led the way. Since July 1, 1974, SI units have been required by all papers published by the American Society of Mechanical Engineers, which prepared a useful booklet explaining the SI [9]. The present text will use SI units together with British gravitational (BG) units.

Primary Dimensions

In fluid mechanics there are only four *primary dimensions* from which all other dimensions can be derived: mass, length, time, and temperature.[4] These dimensions and their units in both systems are given in Table 1.1. Note that the kelvin unit uses no degree symbol. The braces around a symbol like $\{M\}$ mean "the dimension" of mass. All other variables in fluid mechanics can be expressed in terms of $\{M\}$, $\{L\}$, $\{T\}$, and $\{\Theta\}$. For example, acceleration has the dimensions $\{LT^{-2}\}$. The most crucial of these secondary dimensions is force, which is directly related to mass, length, and time by Newton's second law

$$\mathbf{F} = m\mathbf{a} \tag{1.2}$$

From this we see that, dimensionally, $\{F\} = \{MLT^{-2}\}$. A constant of proportionality is avoided by defining the force unit exactly in terms of the primary units. Thus we define the newton and the pound of force

$$\begin{aligned} 1 \text{ newton of force} &= 1 \text{ N} \equiv 1 \text{ kg} \cdot \text{m/s}^2 \\ 1 \text{ pound of force} &= 1 \text{ lbf} \equiv 1 \text{ slug} \cdot \text{ft/s}^2 = 4.4482 \text{ N} \end{aligned} \tag{1.3}$$

In this book the abbreviation *lbf* is used for pound-force and *lb* for pound-mass. If instead one adopts other force units such as the dyne or the poundal or kilopond or adopts other mass units such as the gram or pound-mass, a constant of proportionality called g_c must be included in Eq. (1.2). We shall not use g_c in this book since it is not necessary in the SI and BG systems.

A list of some important secondary variables in fluid mechanics, with dimensions derived as combinations of the four primary dimensions, is given in Table 1.2. A more complete list of conversion factors is given in App. C.

Table 1.1 Primary Dimensions in SI and BG Systems

Primary dimension	SI unit	BG unit	Conversion factor
Mass $\{M\}$	Kilogram (kg)	Slug	1 slug = 14.5939 kg
Length $\{L\}$	Meter (m)	Foot (ft)	1 ft = 0.3048 m
Time $\{T\}$	Second (s)	Second (s)	1 s = 1 s
Temperature $\{\Theta\}$	Kelvin (K)	Rankine (°R)	1 K = 1.8°R

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[4] If electromagnetic effects are important, a fifth primary dimension must be included, electric current $\{I\}$, whose SI unit is the ampere (A).

Table 1.2 Secondary Dimensions in Fluid Mechanics

Secondary dimension	SI unit	BG unit	Conversion factor
Area $\{L^2\}$	m^2	ft^2	$1\ m^2 = 10.764\ ft^2$
Volume $\{L^3\}$	m^3	ft^3	$1\ m^3 = 35.315\ ft^3$
Velocity $\{LT^{-1}\}$	m/s	ft/s	1 ft/s = 0.3048 m/s
Acceleration $\{LT^{-2}\}$	m/s^2	ft/s^2	$1\ ft/s^2 = 0.3048\ m/s^2$
Pressure or stress $\{ML^{-1}T^{-2}\}$	$Pa = N/m^2$	lbf/ft^2	$1\ lbf/ft^2 = 47.88\ Pa$
Angular velocity $\{T^{-1}\}$	s^{-1}	s^{-1}	$1\ s^{-1} = 1\ s^{-1}$
Energy, heat, work $\{ML^2T^{-2}\}$	$J = N \cdot m$	$ft \cdot lbf$	$1\ ft \cdot lbf = 1.3558\ J$
Power $\{ML^2T^{-3}\}$	W = J/s	$ft \cdot lbf/s$	$1\ ft \cdot lbf/s = 1.3558\ W$
Density $\{ML^{-3}\}$	kg/m^3	$slugs/ft^3$	$1\ slug/ft^3 = 515.4\ kg/m^3$
Viscosity $\{ML^{-1}T^{-1}\}$	$kg/(m \cdot s)$	$slugs/(ft \cdot s)$	$1\ slug/(ft \cdot s) = 47.88\ kg/(m \cdot s)$
Specific heat $\{L^2T^{-2}\Theta^{-1}\}$	$m^2/(s^2 \cdot K)$	$ft^2/(s^2 \cdot {}^\circ R)$	$1\ m^2/(s^2 \cdot K) = 5.980\ ft^2/(s^2 \cdot {}^\circ R)$

EXAMPLE 1.1

A body weighs 1000 lbf when exposed to a standard earth gravity $g = 32.174\ ft/s^2$. (*a*) What is its mass in kg? (*b*) What will the weight of this body be in N if it is exposed to the moon's standard acceleration $g_{moon} = 1.62\ m/s^2$? (*c*) How fast will the body accelerate if a net force of 400 lbf is applied to it on the moon or on the earth?

Solution

Part (a) Equation (1.2) holds with F = weight and $a = g_{earth}$:

$$F = W = mg = 1000\ \text{lbf} = (m\ \text{slugs})(32.174\ \text{ft/s}^2)$$

or

$$m = \frac{1000}{32.174} = (31.08\ \text{slugs})(14.5939\ \text{kg/slug}) = 453.6\ \text{kg} \qquad \textit{Ans. (a)}$$

The change from 31.08 slugs to 453.6 kg illustrates the proper use of the conversion factor 14.5939 kg/slug.

Part (b) The mass of the body remains 453.6 kg regardless of its location. Equation (1.2) applies with a new value of a and hence a new force

$$F = W_{moon} = mg_{moon} = (453.6\ \text{kg})(1.62\ \text{m/s}^2) = 735\ \text{N} \qquad \textit{Ans. (b)}$$

Part (c) This problem does not involve weight or gravity or position and is simply a direct application of Newton's law with an unbalanced force:

$$F = 400\ \text{lbf} = ma = (31.08\ \text{slugs})(a\ \text{ft/s}^2)$$

or

$$a = \frac{400}{31.08} = 12.43\ \text{ft/s}^2 = 3.79\ \text{m/s}^2 \qquad \textit{Ans. (c)}$$

This acceleration would be the same on the moon or earth or anywhere.

Meanwhile, we conclude that dimensionally inconsistent equations, though they abound in engineering practice, are misleading and vague and even dangerous, in the sense that they are often misused outside their range of applicability.

Convenient Prefixes in Powers of 10

Engineering results often are too small or too large for the common units, with too many zeros one way or the other. For example, to write $p = 114{,}000{,}000$ Pa is long and awkward. Using the prefix "M" to mean 10^6, we convert this to a concise $p = 114$ MPa (megapascals). Similarly, $t = 0.000000003$ s is a proofreader's nightmare compared to the equivalent $t = 3$ ns (nanoseconds). Such prefixes are common and convenient, in both the SI and BG systems. A complete list is given in Table 1.3.

Table 1.3 Convenient Prefixes for Engineering Units

Multiplicative factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

EXAMPLE 1.4

In 1890 Robert Manning, an Irish engineer, proposed the following empirical formula for the average velocity V in uniform flow due to gravity down an open channel (BG units):

$$V = \frac{1.49}{n} R^{2/3} S^{1/2} \qquad (1)$$

where R = hydraulic radius of channel (Chaps. 6 and 10)
S = channel slope (tangent of angle that bottom makes with horizontal)
n = Manning's roughness factor (Chap. 10)

and n is a constant for a given surface condition for the walls and bottom of the channel. (*a*) Is Manning's formula dimensionally consistent? (*b*) Equation (1) is commonly taken to be valid in BG units with n taken as dimensionless. Rewrite it in SI form.

Solution

Part (a) Introduce dimensions for each term. The slope S, being a tangent or ratio, is dimensionless, denoted by {unity} or {1}. Equation (1) in dimensional form is

$$\left\{\frac{L}{T}\right\} = \left\{\frac{1.49}{n}\right\}\{L^{2/3}\}\{1\}$$

This formula cannot be consistent unless $\{1.49/n\} = \{L^{1/3}/T\}$. If n is dimensionless (and it is never listed with units in textbooks), then the numerical value 1.49 must have units. This can be tragic to an engineer working in a different unit system unless the discrepancy is properly documented. In fact, Manning's formula, though popular, is inconsistent both dimensionally and physically and does not properly account for channel-roughness effects except in a narrow range of parameters, for water only.

Part (b) From part (*a*), the number 1.49 must have dimensions $\{L^{1/3}/T\}$ and thus in BG units equals 1.49 $\text{ft}^{1/3}/\text{s}$. By using the SI conversion factor for length we have

$$(1.49\ \text{ft}^{1/3}/\text{s})(0.3048\ \text{m/ft})^{1/3} = 1.00\ \text{m}^{1/3}/\text{s}$$

Therefore Manning's formula in SI becomes

$$V = \frac{1.0}{n} R^{2/3} S^{1/2} \qquad \textit{Ans. (b)}\ (2)$$

the acceleration of gravity. In the limit as Δx and Δt become very small, the above estimate reduces to a partial-derivative expression for convective x-acceleration:

$$a_{x,\text{convective}} = \lim_{\Delta t \to 0} \frac{\Delta u}{\Delta t} = u\frac{\partial u}{\partial x}$$

In three-dimensional flow (Sec. 4.1) there are *nine* of these convective terms.

1.6 Thermodynamic Properties of a Fluid

While the velocity field **V** is the most important fluid property, it interacts closely with the thermodynamic properties of the fluid. We have already introduced into the discussion the three most common such properties

1. Pressure p
2. Density ρ
3. Temperature T

These three are constant companions of the velocity vector in flow analyses. Four other thermodynamic properties become important when work, heat, and energy balances are treated (Chaps. 3 and 4):

4. Internal energy e
5. Enthalpy $h = \hat{u} + p/\rho$
6. Entropy s
7. Specific heats c_p and c_v

In addition, friction and heat conduction effects are governed by the two so-called *transport properties:*

8. Coefficient of viscosity μ
9. Thermal conductivity k

All nine of these quantities are true thermodynamic properties which are determined by the thermodynamic condition or *state* of the fluid. For example, for a single-phase substance such as water or oxygen, two basic properties such as pressure and temperature are sufficient to fix the value of all the others:

$$\rho = \rho(p, T) \qquad h = h(p, T) \qquad \mu = \mu(p, T) \tag{1.5}$$

and so on for every quantity in the list. Note that the specific volume, so important in thermodynamic analyses, is omitted here in favor of its inverse, the density ρ.

Recall that thermodynamic properties describe the state of a *system,* i.e., a collection of matter of fixed identity which interacts with its surroundings. In most cases here the system will be a small fluid element, and all properties will be assumed to be continuum properties of the flow field: $\rho = \rho(x, y, z, t)$, etc.

Recall also that thermodynamics is normally concerned with *static* systems, whereas fluids are usually in variable motion with constantly changing properties. Do the properties retain their meaning in a fluid flow which is technically not in equilibrium? The answer is yes, from a statistical argument. In gases at normal pressure (and even more so for liquids), an enormous number of molecular collisions occur over a very short distance of the order of 1 μm, so that a fluid subjected to sudden changes rapidly adjusts itself toward equilibrium. We therefore assume that all the thermodynamic properties listed above exist as point functions in a flowing fluid and follow all the laws and state relations of ordinary equilibrium thermodynamics. There are, of course, important nonequilibrium effects such as chemical and nuclear reactions in flowing fluids which are not treated in this text.

Pressure

Pressure is the (compression) stress at a point in a static fluid (Fig. 1.1). Next to velocity, the pressure p is the most dynamic variable in fluid mechanics. Differences or *gradients* in pressure often drive a fluid flow, especially in ducts. In low-speed flows, the actual magnitude of the pressure is often not important, unless it drops so low as to cause vapor bubbles to form in a liquid. For convenience, we set many such problem assignments at the level of 1 atm $= 2116 \text{ lbf/ft}^2 = 101{,}300$ Pa. High-speed (compressible) gas flows (Chap. 9), however, are indeed sensitive to the magnitude of pressure.

Temperature

Temperature T is a measure of the internal energy level of a fluid. It may vary considerably during high-speed flow of a gas (Chap. 9). Although engineers often use Celsius or Fahrenheit scales for convenience, many applications in this text require *absolute* (Kelvin or Rankine) temperature scales:

$$\begin{aligned} {}^\circ\text{R} &= {}^\circ\text{F} + 459.69 \\ \text{K} &= {}^\circ\text{C} + 273.16 \end{aligned}$$

If temperature differences are strong, *heat transfer* may be important [10], but our concern here is mainly with dynamic effects. We examine heat-transfer principles briefly in Secs. 4.5 and 9.8.

Density

The density of a fluid, denoted by ρ (lowercase Greek rho), is its mass per unit volume. Density is highly variable in gases and increases nearly proportionally to the pressure level. Density in liquids is nearly constant; the density of water (about 1000 kg/m^3) increases only 1 percent if the pressure is increased by a factor of 220. Thus most liquid flows are treated analytically as nearly "incompressible."

In general, liquids are about three orders of magnitude more dense than gases at atmospheric pressure. The heaviest common liquid is mercury, and the lightest gas is hydrogen. Compare their densities at 20°C and 1 atm:

$$\text{Mercury:} \quad \rho = 13{,}580 \text{ kg/m}^3 \qquad \text{Hydrogen:} \quad \rho = 0.0838 \text{ kg/m}^3$$

They differ by a factor of 162,000! Thus the physical parameters in various liquid and gas flows might vary considerably. The differences are often resolved by the use of *dimensional analysis* (Chap. 5). Other fluid densities are listed in Tables A.3 and A.4 (in App. A).

Specific Weight

The *specific weight* of a fluid, denoted by γ (lowercase Greek gamma), is its weight per unit volume. Just as a mass has a weight $W = mg$, density and specific weight are simply related by gravity:

$$\gamma = \rho g \tag{1.6}$$

The units of γ are weight per unit volume, in lbf/ft^3 or N/m^3. In standard earth gravity, $g = 32.174$ ft/s^2 $= 9.807$ m/s^2. Thus, e.g., the specific weights of air and water at 20°C and 1 atm are approximately

$$\gamma_{\text{air}} = (1.205 \text{ kg/m}^3)(9.807 \text{ m/s}^2) = 11.8 \text{ N/m}^3 = 0.0752 \text{ lbf/ft}^3$$

$$\gamma_{\text{water}} = (998 \text{ kg/m}^3)(9.807 \text{ m/s}^2) = 9790 \text{ N/m}^3 = 62.4 \text{ lbf/ft}^3$$

Specific weight is very useful in the hydrostatic-pressure applications of Chap. 2. Specific weights of other fluids are given in Tables A.3 and A.4.

Specific Gravity

Specific gravity, denoted by SG, is the ratio of a fluid density to a standard reference fluid, water (for liquids), and air (for gases):

$$\text{SG}_{\text{gas}} = \frac{\rho_{\text{gas}}}{\rho_{\text{air}}} = \frac{\rho_{\text{gas}}}{1.205 \text{ kg/m}^3} \tag{1.7}$$

$$\text{SG}_{\text{liquid}} = \frac{\rho_{\text{liquid}}}{\rho_{\text{water}}} = \frac{\rho_{\text{liquid}}}{998 \text{ kg/m}^3}$$

For example, the specific gravity of mercury (Hg) is $\text{SG}_{\text{Hg}} = 13{,}580/998 \approx 13.6$. Engineers find these dimensionless ratios easier to remember than the actual numerical values of density of a variety of fluids.

Potential and Kinetic Energies

In thermostatics the only energy in a substance is that stored in a system by molecular activity and molecular bonding forces. This is commonly denoted as *internal energy* $\hat{u}$. A commonly accepted adjustment to this static situation for fluid flow is to add two more energy terms which arise from newtonian mechanics: the potential energy and kinetic energy.

The potential energy equals the work required to move the system of mass m from the origin to a position vector $\mathbf{r} = \mathbf{i}x + \mathbf{j}y + \mathbf{k}z$ against a gravity field $\mathbf{g}$. Its value is $-m\mathbf{g}\cdot\mathbf{r}$, or $-\mathbf{g}\cdot\mathbf{r}$ per unit mass. The kinetic energy equals the work required to change the speed of the mass from zero to velocity V. Its value is $\frac{1}{2}mV^2$ or $\frac{1}{2}V^2$ per unit mass. Then by common convention the total stored energy e per unit mass in fluid mechanics is the sum of three terms:

$$e = \hat{u} + \tfrac{1}{2}V^2 + (-\mathbf{g}\cdot\mathbf{r}) \tag{1.8}$$

Also, throughout this book we shall define z as upward, so that $\mathbf{g} = -g\mathbf{k}$ and $\mathbf{g}\cdot\mathbf{r} = -gz$. Then Eq. (1.8) becomes

$$e = \hat{u} + \tfrac{1}{2}V^2 + gz \tag{1.9}$$

The molecular internal energy $\hat{u}$ is a function of T and p for the single-phase pure substance, whereas the potential and kinetic energies are kinematic properties.

State Relations for Gases

Thermodynamic properties are found both theoretically and experimentally to be related to each other by state relations which differ for each substance. As mentioned, we shall confine ourselves here to single-phase pure substances, e.g., water in its liquid phase. The second most common fluid, air, is a mixture of gases, but since the mixture ratios remain nearly constant between 160 and 2200 K, in this temperature range air can be considered to be a pure substance.

All gases at high temperatures and low pressures (relative to their critical point) are in good agreement with the *perfect-gas law*

$$p = \rho R T \qquad R = c_p - c_v = \text{gas constant} \tag{1.10}$$

Since Eq. (1.10) is dimensionally consistent, R has the same dimensions as specific heat, $\{L^2T^{-2}\Theta^{-1}\}$, or velocity squared per temperature unit (kelvin or degree Rankine). Each gas has its own constant R, equal to a universal constant Λ divided by the molecular weight

$$R_{\text{gas}} = \frac{\Lambda}{M_{\text{gas}}} \tag{1.11}$$

where $\Lambda = 49{,}700 \text{ ft}^2/(\text{s}^2 \cdot {}^\circ\text{R}) = 8314 \text{ m}^2/(\text{s}^2 \cdot \text{K})$. Most applications in this book are for air, with $M = 28.97$:

$$R_{\text{air}} = 1717 \text{ ft}^2/(\text{s}^2 \cdot {}^\circ\text{R}) = 287 \text{ m}^2/(\text{s}^2 \cdot \text{K}) \tag{1.12}$$

Standard atmospheric pressure is 2116 lbf/ft^2, and standard temperature is 60°F = 520°R. Thus standard air density is

$$\rho_{\text{air}} = \frac{2116}{(1717)(520)} = 0.00237 \text{ slug/ft}^3 = 1.22 \text{ kg/m}^3 \tag{1.13}$$

This is a nominal value suitable for problems.

One proves in thermodynamics that Eq. (1.10) requires that the internal molecular energy $\hat{u}$ of a perfect gas vary only with temperature: $\hat{u} = \hat{u}(T)$. Therefore the specific heat c_v also varies only with temperature:

$$c_v = \left(\frac{\partial \hat{u}}{\partial T}\right)_\rho = \frac{d\hat{u}}{dT} = c_v(T)$$

or

$$d\hat{u} = c_v(T)\, dT \tag{1.14}$$

In like manner h and c_p of a perfect gas also vary only with temperature:

$$\begin{aligned} h &= \hat{u} + \frac{p}{\rho} = \hat{u} + RT = h(T) \\ c_p &= \left(\frac{\partial h}{\partial T}\right)_p = \frac{dh}{dT} = c_p(T) \\ dh &= c_p(T)\, dT \end{aligned} \tag{1.15}$$

The ratio of specific heats of a perfect gas is an important dimensionless parameter in compressible-flow analysis (Chap. 9)

$$k = \frac{c_p}{c_v} = k(T) \geq 1 \tag{1.16}$$

The term in parentheses is positive, so $\dot{S}_{\text{Un}} > 0$. This agrees with Clausius's statement of the Second Law of Thermodynamics.

Notice an odd fact here: The rate of heat transfer, Q, and hence $\dot{S}_{\text{Un}}$, is determined by the wall's resistance to heat flow. Although the wall is the agent that causes the entropy of the universe to increase, its own entropy does not changes. Only the entropies of the reservoirs change.

1.3 Modes of heat transfer

Figure 1.3 shows an analogy that might be useful in fixing the concepts of heat conduction, convection, and radiation as we proceed to look at each in some detail.

Heat conduction

Fourier's law. Joseph Fourier (see Fig. 1.4) published his remarkable book *Théorie Analytique de la Chaleur* in 1822. In it he formulated a very complete exposition of the theory of heat conduction.

Hebegan his treatise by stating the empirical law that bears his name: *the heat flux,*[3] q (W/m^2), *resulting from thermal conduction is proportional to the magnitude of the temperature gradient and opposite to it in sign.* If we call the constant of proportionality, k, then

$$q = -k\,\frac{dT}{dx} \tag{1.8}$$

The constant, k, is called the *thermal conductivity*. It obviously must have the dimensions W/m·K, or J/m·s·K, or Btu/h·ft·°F if eqn. (1.8) is to be dimensionally correct.

The heat flux is a vector quantity. Equation (1.8) tells us that if temperature decreases with x, q will be positive—it will flow in the x-direction. If T increases with x, q will be negative—it will flow opposite the x-direction. In either case, q will flow from higher temperatures to lower temperatures. Equation (1.8) is the one-dimensional form of Fourier's law. We develop its three-dimensional form in Chapter 2, namely:

$$\vec{q} = -k\,\nabla T$$

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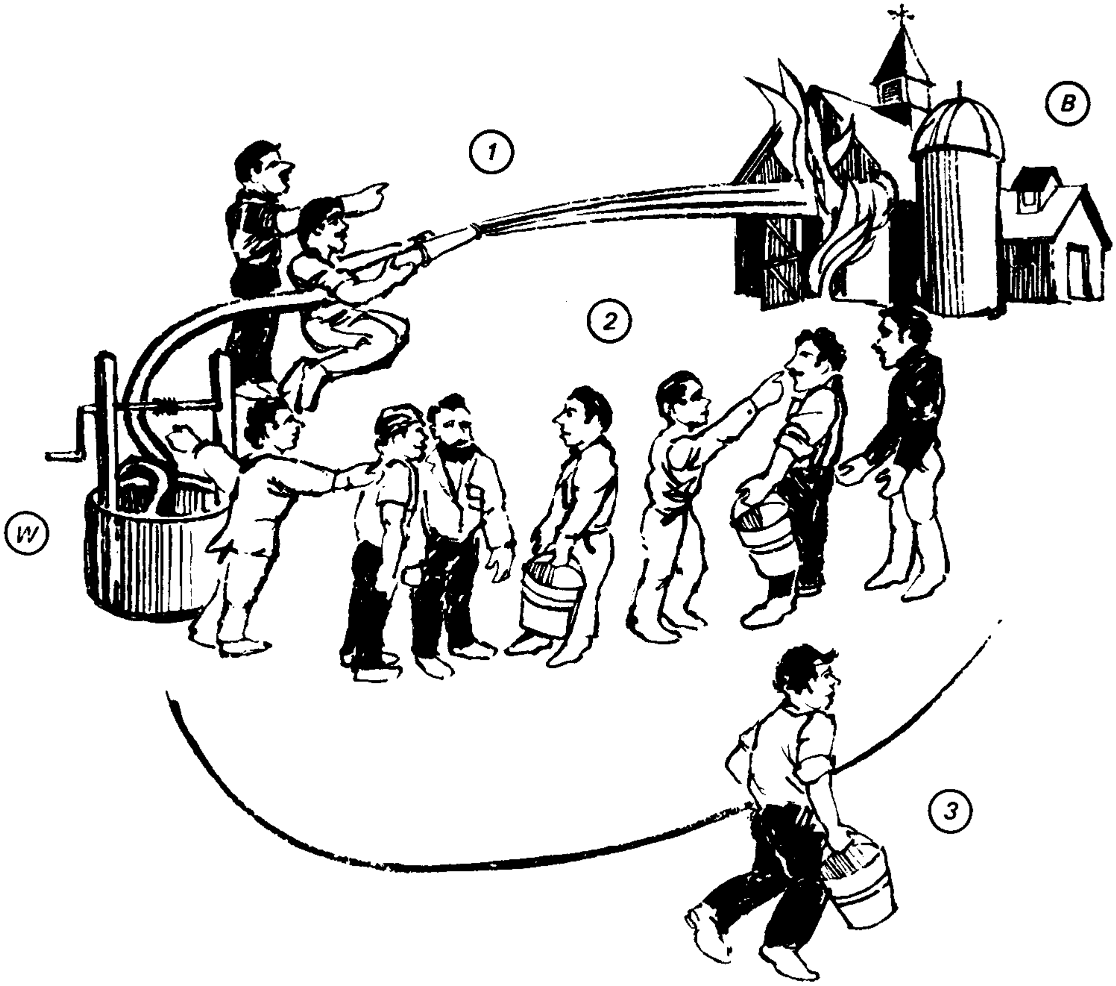
[3] The heat flux, q, is a heat rate per unit area and can be expressed as Q/A, where A is an appropriate area.



Help! The barn is on fire.

Let the ***water*** **be analogous to** ***heat,*** **and let the** ***people*** **be analogous to the** ***heat transfer medium.*** **Then:**

Case 1	**The hose directs water from Ⓦ to Ⓑ independently of the medium. This is analogous to** ***thermal radiation*** **in a vacuum or in most gases.**
Case 2	**In the bucket brigade, water goes from Ⓦ to Ⓑ through the medium. This is analogous to** ***conduction.***
Case 3	**A single runner, representing the medium, carries water from Ⓦ to Ⓑ . This is analogous to** ***convection.***

Figure 1.3 An analogy for the three modes of heat transfer.

Example 1.1

The front of a slab of lead ($k = 35$ W/m·K) is kept at 110°C and the back is kept at 50°C. If the area of the slab is 0.4 m^2 and it is 0.03 m thick, compute the heat flux, q, and the heat transfer rate, Q.

Solution. For the moment, we presume that dT/dx is a constant equal to $(T_{\text{back}} - T_{\text{front}})/(x_{\text{back}} - x_{\text{front}})$; we verify this in Chapter 2. Thus, eqn. (1.8) becomes

$$q = -35\left(\frac{50-110}{0.03}\right) = +70{,}000 \text{ W/m}^2 = 70 \text{ kW/m}^2$$

and

$$Q = qA = 70(0.4) = 28 \text{ kW} \qquad \blacksquare$$

In one-dimensional heat conduction problems, there is never any real problem in deciding which way the heat should flow. It is therefore sometimes convenient to write Fourier's law in simple scalar form:

$$q = k\,\frac{\Delta T}{L} \tag{1.9}$$

where L is the thickness in the direction of heat flow and q and ΔT are both written as positive quantities. When we use eqn. (1.9), we must remember that q always flows from high to low temperatures.

Thermal conductivity values. It will help if we first consider how conduction occurs in, for example, a gas. We know that the molecular velocity depends on temperature. Consider conduction from a hot wall to a cold one in a situation in which gravity can be ignored, as shown in Fig. 1.5. The molecules near the hot wall collide with it and are agitated by the molecules of the wall. They leave with generally higher speed and collide with their neighbors to the right, increasing the speed of those neighbors. This process continues until the molecules on the right pass their kinetic energy to those in the cool wall. Within solids, comparable processes occur as the molecules vibrate within their lattice structure and as the lattice vibrates as a whole. This sort of process also occurs, to some extent, in the electron "gas" that moves through the solid. The

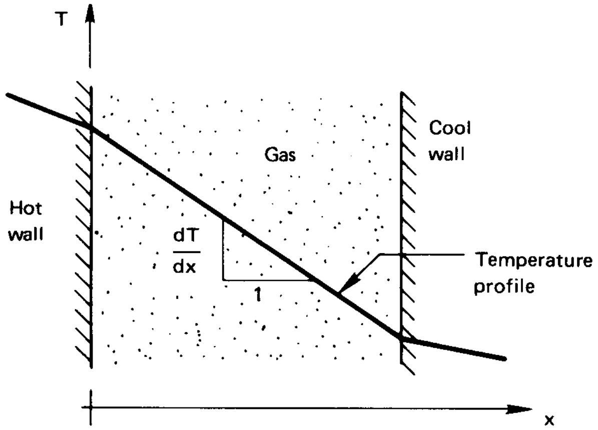


Figure 1.5 Heat conduction through gas separating two solid walls.

processes are more efficient in solids than they are in gases. Notice that

$$-\frac{dT}{dx} = \underbrace{\frac{q}{k} \propto \frac{1}{k}}_{\substack{\text{since, in steady}\\ \text{conduction, } q \text{ is}\\ \text{constant}}} \tag{1.10}$$

Thus solids, with generally higher thermal conductivities than gases, yield smaller temperature gradients for a given heat flux. In a gas, by the way, k is proportional to molecular speed and molar specific heat, and inversely proportional to the cross-sectional area of molecules.

This book deals almost exclusively with S.I. units, or *Système International d'Unités.* Since much reference material will continue to be available in English units, we should have at hand a conversion factor for thermal conductivity:

$$1 = \frac{\text{J}}{0.0009478\ \text{Btu}} \cdot \frac{\text{h}}{3600\ \text{s}} \cdot \frac{\text{ft}}{0.3048\ \text{m}} \cdot \frac{1.8^\circ\text{F}}{\text{K}}$$

Thus the conversion factor from W/m·K to its English equivalent, Btu/h·ft·°F, is

$$\boxed{1 = 1.731\,\frac{\text{W/m}\cdot\text{K}}{\text{Btu/h}\cdot\text{ft}\cdot{}^\circ\text{F}}} \tag{1.11}$$

Consider, for example, copper—the common substance with the highest conductivity at ordinary temperature:

$$k_{\text{Cu at room temp}} = (383\ \text{W/m}\cdot\text{K})\Big/1.731\frac{\text{W/m}\cdot\text{K}}{\text{Btu/h}\cdot\text{ft}\cdot{}^\circ\text{F}} = 221\ \text{Btu/h}\cdot\text{ft}\cdot{}^\circ\text{F}$$

The range of thermal conductivities is enormous. As we see from Fig. 1.6, k varies by a factor of about 10^5 between gases and diamond at room temperature. This variation can be increased to about 10^7 if we include the effective conductivity of various cryogenic “superinsulations.” (These involve powders, fibers, or multilayered materials that have been evacuated of all air.) The reader should study and remember the order of magnitude of the thermal conductivities of different types of materials. This will be a help in avoiding mistakes in future computations, and it will be a help in making assumptions during problem solving. Actual numerical values of the thermal conductivity are given in Appendix A (which is a broad listing of many of the physical properties you might need in this course) and in Figs. 2.2 and 2.3.

Example 1.2

A copper slab (k = 372 W/m·K) is 3 mm thick. It is protected from corrosion by a 2-mm-thick layers of stainless steel (k = 17 W/m·K) on both sides. The temperature is 400°C on one side of this composite wall and 100°C on the other. Find the temperature distribution in the copper slab and the heat conduction through the wall (see Fig. 1.7).

Solution. If we recall Fig. 1.5 and eqn. (1.10), it should be clear that the temperature drop will take place almost entirely in the stainless steel, where k is less than 1/20 of k in the copper. Thus, the copper will be virtually isothermal at the average temperature of $(400 + 100)/2 = 250$°C. Furthermore, the heat conduction can be estimated in a 4 mm slab of stainless steel as though the copper were not even there. With the help of Fourier’s law in the form of eqn. (1.8), we get

$$q = -k\frac{dT}{dx} \simeq 17\ \text{W/m·K} \cdot \left(\frac{400 - 100}{0.004}\right)\ \text{K/m} = 1275\ \text{kW/m}^2$$

The accuracy of this rough calculation can be improved by considering the copper. To do this we first solve for $\Delta T_{\text{s.s.}}$ and ΔT_{Cu} (see Fig. 1.7). Conservation of energy requires that the steady heat flux through all three slabs must be the same. Therefore,

$$q = \left(k\frac{\Delta T}{L}\right)_{\text{s.s.}} = \left(k\frac{\Delta T}{L}\right)_{\text{Cu}}$$

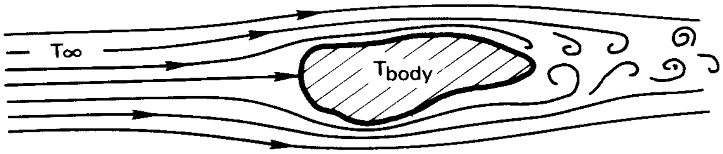


Figure 1.9 The convective cooling of a heated body.

This is the *one-dimensional heat diffusion equation.* Its importance is this: By combining the First Law with Fourier's law, we have eliminated the unknown Q and obtained a differential equation that can be solved for the temperature distribution, $T(x,t)$. It is the primary equation upon which all of heat conduction theory is based.

The heat diffusion equation includes a new property which is as important to transient heat conduction as k is to steady-state conduction. This is the thermal diffusivity, α:

$$\alpha \equiv \frac{k}{\rho c} \; \frac{\mathrm{J}}{\mathrm{m{\cdot}s{\cdot}K}} \; \frac{\mathrm{m^3}}{\mathrm{kg}} \; \frac{\mathrm{kg{\cdot}K}}{\mathrm{J}} = \alpha \;\; \mathrm{m^2/s} \;\; (\text{or } \mathrm{ft^2/hr}).$$

The thermal diffusivity is a measure of how quickly a material can carry heat away from a hot source. Since material does not just transmit heat but must be warmed by it as well, α involves both the conductivity, k, and the volumetric heat capacity, ρc.

Heat Convection

The physical process. Consider a typical convective cooling situation. Cool gas flows past a warm body, as shown in Fig. 1.9. The fluid immediately adjacent to the body forms a thin slowed-down region called a *boundary layer.* Heat is conducted into this layer, which sweeps it away and, farther downstream, mixes it into the stream. We call such processes of carrying heat away by a moving fluid *convection.*

In 1701, Isaac Newton considered the convective process and suggested that the cooling would be such that

$$\frac{dT_{\text{body}}}{dt} \propto T_{\text{body}} - T_{\infty} \tag{1.15}$$

where T_∞ is the temperature of the oncoming fluid. This statement suggests that energy is flowing from the body. But if the energy of the body is constantly replenished, the body temperature need not change. Then with the help of eqn. (1.3) we get, from eqn. (1.15) (see Problem 1.2),

$$Q \propto T_{\text{body}} - T_\infty \tag{1.16}$$

This equation can be rephrased in terms of $q = Q/A$ as

$$\boxed{q = \overline{h}\left(T_{\text{body}} - T_\infty\right)} \tag{1.17}$$

This is the steady-state form of Newton's law of cooling, as it is usually quoted, although Newton never wrote such an expression.

The constant h is the *film coefficient* or *heat transfer coefficient*. The bar over h indicates that it is an average over the surface of the body. Without the bar, h denotes the "local" value of the heat transfer coefficient at a point on the surface. The units of h and $\overline{h}$ are W/m^{2}K or J/s·m^2·K. The conversion factor for English units is:

$$1 = \frac{0.0009478\ \text{Btu}}{\text{J}} \cdot \frac{\text{K}}{1.8^\circ\text{F}} \cdot \frac{3600\ \text{s}}{\text{h}} \cdot \frac{(0.3048\ \text{m})^2}{\text{ft}^2}$$

or

$$\boxed{1 = 0.1761\,\frac{\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}}{\text{W/m}^2\text{K}}} \tag{1.18}$$

It turns out that Newton oversimplified the process of convection when he made his conjecture. Heat convection is complicated and $\overline{h}$ can depend on the temperature difference $T_{\text{body}} - T_\infty \equiv \Delta T$. In Chapter 6 we find that h really *is* independent of ΔT in situations in which fluid is forced past a body and ΔT is not too large. This is called *forced convection*.

When fluid buoys up from a hot body or down from a cold one, h varies as some weak power of ΔT—typically as $\Delta T^{1/4}$ or $\Delta T^{1/3}$. This is called *free* or *natural convection*. If the body is hot enough to boil a liquid surrounding it, h will typically vary as ΔT^2.

For the moment, we restrict consideration to situations in which Newton's law is either true or at least a reasonable approximation to real behavior.

We should have some idea of how large h might be in a given situation. Table 1.1 provides some illustrative values of h that have been

Table 1.1 Some illustrative values of convective heat transfer coefficients

Situation	$\overline{h}$, W/m^{2}K
Natural convection in gases	
• 0.3 m vertical wall in air, $\Delta T = 30$°C	4.33
Natural convection in liquids	
• 40 mm O.D. horizontal pipe in water, $\Delta T = 30$°C	570
• 0.25 mm diameter wire in methanol, $\Delta T = 50$°C	4,000
Forced convection of gases	
• Air at 30 m/s over a 1 m flat plate, $\Delta T = 70$°C	80
Forced convection of liquids	
• Water at 2 m/s over a 60 mm plate, $\Delta T = 15$°C	590
• Aniline-alcohol mixture at 3 m/s in a 25 mm I.D. tube, $\Delta T = 80$°C	2,600
• Liquid sodium at 5 m/s in a 13 mm I.D. tube at 370°C	75,000
Boiling water	
• During film boiling at 1 atm	300
• In a tea kettle	4,000
• At a peak pool-boiling heat flux, 1 atm	40,000
• At a peak flow-boiling heat flux, 1 atm	100,000
• At approximate maximum convective-boiling heat flux, under optimal conditions	10^6
Condensation	
• In a typical horizontal cold-water-tube steam condenser	15,000
• Same, but condensing benzene	1,700
• Dropwise condensation of water at 1 atm	160,000

observed or calculated for different situations. They are only illustrative and should not be used in calculations because the situations for which they apply have not been fully described. Most of the values in the table could be changed a great deal by varying quantities (such as surface roughness or geometry) that have not been specified. The determination of h or $\overline{h}$ is a fairly complicated task and one that will receive a great deal of our attention. Notice, too, that $\overline{h}$ can change dramatically from one situation to the next. Reasonable values of h range over about six orders of magnitude.

Table 1.2 Forms of the electromagnetic wave spectrum

Characterization	*Wavelength, λ*	
Cosmic rays	< 0.3 pm	
Gamma rays	0.3–100 pm	
X rays	0.01–30 nm	
Ultraviolet light	3–400 nm	***Thermal Radiation*** ***0.1–1000 μm***
Visible light	0.4–0.7 μm	
Near infrared radiation	0.7–30 μm	
Far infrared radiation	30–1000 μm	
Millimeter waves	1–10 mm	
Microwaves	10–300 mm	
Shortwave radio & TV	300 mm–100 m	
Longwave radio	100 m–30 km	

The electromagnetic spectrum. Thermal radiation occurs in a range of the electromagnetic spectrum of energy emission. Accordingly, it exhibits the same wavelike properties as light or radio waves. Each quantum of radiant energy has a wavelength, λ, and a frequency, ν, associated with it.

The full electromagnetic spectrum includes an enormous range of energy-bearing waves, of which heat is only a small part. Table 1.2 lists the various forms over a range of wavelengths that spans 17 orders of magnitude. Only the tiniest "window" exists in this spectrum through which we can *see* the world around us. Heat radiation, whose main component is usually the spectrum of infrared radiation, passes through the much larger window—about three orders of magnitude in λ or ν.

Black bodies. The model for the perfect thermal radiator is a so-called *black body*. This is a body which absorbs all energy that reaches it and reflects nothing. The term can be a little confusing, since such bodies *emit* energy. Thus, if we possessed infrared vision, a black body would glow with "color" appropriate to its temperature. of course, perfect radiators *are* "black" in the sense that they absorb all visible light (and all other radiation) that reaches them.

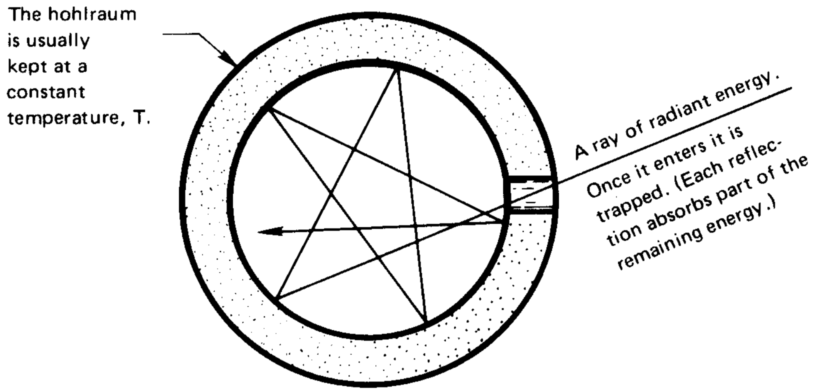


Figure 1.13 Cross section of a spherical hohlraum. The hole has the attributes of a nearly perfect thermal black body.

It is necessary to have an experimental method for making a perfectly black body. The conventional device for approaching this ideal is called by the German term *hohlraum*, which literally means "hollow space". Figure 1.13 shows how a hohlraum is arranged. It is simply a device that traps all the energy that reaches the aperture.

What are the important features of a thermally black body? First consider a distinction between heat and infrared radiation. *Infrared radiation* refers to a particular range of wavelengths, while *heat* refers to the whole range of radiant energy flowing from one body to another. Suppose that a radiant heat flux, q, falls upon a translucent plate that is not black, as shown in Fig. 1.14. A fraction, α, of the total incident energy, called the *absorptance*, is absorbed in the body; a fraction, ρ,

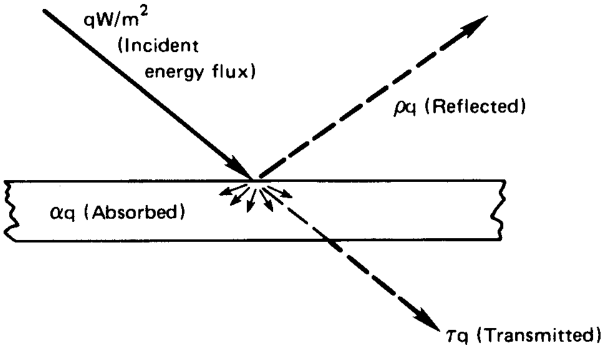


Figure 1.14 The distribution of energy incident on a translucent slab.

called the *reflectance*, is reflected from it; and a fraction, τ, called the *transmittance*, passes through. Thus

$$1 = \alpha + \rho + \tau \tag{1.25}$$

This relation can also be written for the energy carried by each wavelength in the distribution of wavelengths that makes up *heat* from a source at any temperature:

$$1 = \alpha_\lambda + \rho_\lambda + \tau_\lambda \tag{1.26}$$

All radiant energy incident on a black body is absorbed, so that α_b or $\alpha_{\lambda_b} = 1$ and $\rho_b = \tau_b = 0$. Furthermore, the energy emitted from a black body reaches a theoretical maximum, which is given by the Stefan-Boltzmann law. We look at this next.

The Stefan-Boltzmann law. The flux of energy radiating from a body is commonly designated $e(T)$ W/m^2. The symbol $e_\lambda(\lambda, T)$ designates the distribution function of radiative flux in λ, or the *monochromatic emissive power:*

$$e_\lambda(\lambda, T) = \frac{de(\lambda, T)}{d\lambda} \quad \text{or} \quad e(\lambda, T) = \int_0^\lambda e_\lambda(\lambda, T)\, d\lambda \tag{1.27}$$

Thus

$$e(T) \equiv E(\infty, T) = \int_0^\infty e_\lambda(\lambda, T)\, d\lambda$$

The dependence of $e(T)$ on T for a black body was established experimentally by Stefan in 1879 and explained by Boltzmann on the basis of thermodynamics arguments in 1884. The Stefan-Boltzmann law is

$$\boxed{e_b(T) = \sigma T^4} \tag{1.28}$$

where the Stefan-Boltzmann constant, σ, is 5.670400×10^{-8} W/m$^2 \cdot$K^4 or 1.714×10^{-9} Btu/hr$\cdot$ft$^2 \cdot {}^\circ$R^4, and T is the absolute temperature.

e_λ vs. λ. Nature requires that, at a given temperature, a body will emit a unique distribution of energy in wavelength. Thus, when you heat a poker in the fire, it first glows a dull red—emitting most of its energy at long wavelengths and just a little bit in the visible regime. When it is prediction, and his work included the initial formulation of quantum mechanics. He found that

$$e_{\lambda_b} = \frac{2\pi h c_o^2}{\lambda^5 \left[\exp(hc_o/k_B T\lambda) - 1\right]} \tag{1.30}$$

where c_o is the speed of light, 2.99792458×10^8 m/s; h is Planck's constant, $6.62606876 \times 10^{-34}$ J·s; and k_B is Boltzmann's constant, $1.3806503 \times 10^{-23}$ J/K.

Radiant heat exchange. Suppose that a heated object (1 in Fig. 1.16a) radiates only to some other object (2) and that both objects are thermally black. All heat leaving object 1 arrives at object 2, and all heat arriving at object 1 comes from object 2. Thus, the net heat transferred from object 1 to object 2, Q_net, is the difference between $Q_{1\text{ to }2} = A_1 e_b(T_1)$ and $Q_{2\text{ to }1} = A_1 e_b(T_2)$

$$Q_\text{net} = A_1 e_b(T_1) - A_1 e_b(T_2) = A_1 \sigma\left(T_1^4 - T_2^4\right) \tag{1.31}$$

If the first object "sees" other objects in addition to object 2, as indicated in Fig. 1.16b, then a *view factor* (sometimes called a *configuration factor* or a *shape factor*), $F_{1\text{-}2}$, must be included in eqn. (1.31):

$$\boxed{Q_\text{net} = A_1 F_{1\text{-}2}\, \sigma\left(T_1^4 - T_2^4\right)} \tag{1.32}$$

We may regard $F_{1\text{-}2}$ as the fraction of energy leaving object 1 that is intercepted by object 2.

Example 1.5

A black thermocouple measures the temperature in a chamber with black walls. If the air around the thermocouple is at 20°C, the walls are at 100°C, and the heat transfer coefficient between the thermocouple and the air is 15 W/m^{2}K, what temperature will the thermocouple read?

Solution. The heat convected away from the thermocouple by the air must exactly balance that radiated to it by the hot walls if the system is in steady state. Furthermore, $F_{1\text{-}2} = 1$ since the thermocouple (1) radiates all its energy to the walls (2):

$$\overline{h} A_{tc}\left(T_{tc} - T_\text{air}\right) = -Q_\text{net} = -A_{tc}\sigma\left(T_{tc}^4 - T_\text{wall}^4\right)$$

7.3 Fossil Fuels

Coal

Robert Reuther

Coal Composition and Classification

Coal is a sedimentary rock formed by the accumulation and decay of organic substances derived from plant tissues and exudates that have been buried over periods of geological time along with various mineral inclusions. Coal is classified by **type and rank.** Coal type classifies coal by the plant sources from which it was derived. Coal rank classifies coal by its degree of metamorphosis from the original plant sources and is therefore a measure of the age of the coal. The process of metamorphosis or aging is termed **coalification.**

The study of coal by type is known as coal petrography. Coal type is determined from the examination of polished sections of a coal sample using a reflected-light microscope. The degree of reflectance and color of a sample are identified with specific residues of the original plant tissues. These various residues are referred to as **macerals.** Macerals are collected into three main groups: vitrinite, inertinite, and exinite (sometimes referred to as liptinite). The maceral groups and their associated macerals are listed in Table 7.3.1 along with a description of the plant tissue from which each distinct maceral type is derived.

TABLE 7.3.1 Coal Maceral Groups and Macerals

Maceral Group	Maceral	Derivation
Vitrinite	Collinite	Humic gels
	Telinite	Wood, bark, and cortical tissue
	Pseudovitrinite	? (Some observors place in the inertinite group)
Exinite	Sporinite	Fungal and other spores
	Cutinite	Leaf cuticles
	Resinite	Resin bodies and waxes
	Alginite	Algal remains
Inertinite	Micrinite	Unspecified detrital matter, <10 μm
	Macrinite	Unspecified detrital matter, 10–100 μm
	Semifusinite	"Burned" woody tissue, low reflectance
	Fusinite	"Burned" woody tissue, high reflectance
	Sclerotinite	Fungal sclerotia and mycelia

Modified from Berkowitz, N., *An Introduction to Coal Technology.* Academic Press, New York, 1979.

Coal rank is the most important property of coal, since it is rank which initiates the classification of coal for use. Rank is a measure of the age or degree of coalification of coal. Coalification describes the process which the buried organic matter goes through to become coal. When first buried, the organic matter has a certain elemental composition and organic structure. However, as the material becomes subjected to heat and pressure, the composition and structure slowly change. Certain structures are broken down, and others are formed. Some elements are lost through volatilization while others are concentrated through a number of processes, including being exposed to underground flows which carry away some elements and deposit others. Coalification changes the values of various properties of coal. Thus, coal can be classified by rank through the measurement of one or more of these changing properties.

In the United States and Canada, the rank classification scheme defined by the American Society of Testing and Materials (ASTM) has become the standard. In this scheme, the properties of **gross calorific value** and **fixed carbon** or **volatile matter content** are used to classify a coal by rank. Gross calorific value is a measure of the energy content of the coal and is usually expressed m units of energy per unit mass. Calorific value increases as the coal proceeds through coalification. Fixed carbon content is a measure of the mass remaining after heating a dry coal sample under conditions specified by the ASTM.

Fixed carbon content increases with coalification. The conditions specified for the measurement of fixed carbon content result in being able alternatively to use the volatile matter content of the coal measured under dry, ash-free conditions as a rank parameter. The rank of a coal proceeds from lignite, the "youngest" coal, through subbituminous, bituminous, and semibituminous, to anthracite, the "oldest" coal. There exist subdivisions within these rank categories which are defined in Table 7.3.2. (Some rank schemes include meta-anthracite as a rank above, or "older" than, anthracite. Others prefer to classify such deposits as graphite. Graphite is a minimal resource and is valuable primarily for uses other than as a fuel.) According to the ASTM scheme, coals are ranked by calorific value up to the high volatile A bituminous rank, which includes coals with calorific values (measured on a moist, mineral matter-free basis) greater than 14,000 Btu/lb (32,564 kJ/kg). At this point, fixed carbon content (measured on a dry, mineral matter-free basis) takes over as the rank parameter. Thus, a high volatile A bituminous coal is defined as having a calorific value greater than 14,000 Btu/lb, but a fixed carbon content less than 69 wt%. The requirement for having two different properties with which to define rank arises because calorific value increases significantly through the lower-rank coals, but very little (in a relative sense) in the higher-ranks, whereas fixed carbon content has a wider range in higher-rank coals, but little (relative) change in the lower-ranks. The most widely used classification scheme outside of North America is that developed under the jurisdiction of the International Standards Organization, Technical Committee 27, Solid Mineral Fuels.

Coal Analysis

The composition of a coal is typically reported in terms of its **proximate analysis** and its **ultimate analysis.** The proximate analysis of a coal is made up of four constituents: volatile matter content, fixed carbon content, moisture content, and ash content, all of which are reported on a weight percent basis. The measurement of these four properties of a coal must be carried out according to strict specifications codified by the ASTM.

Volatile matter in coal includes carbon dioxide, inorganic sulfur- and nitrogen-containing species, and organic compounds. The percentage of various species present depends on rank. Volatile matter content can typically be reported on a number of bases, such as moist; dry, mineral matter-free (dmmf); moist, mineral matter-free; moist, ash-free; and dry, ash-free (daf); depending on the condition of the coal on which measurements were made.

Mineral matter and ash are two distinct entities. Coal does not contain ash, even though the ash content of a coal is reported as part of its proximate analysis. Instead, coal contains mineral matter, which can be present both as distinct mineral entities or inclusions and intimately bound with the organic matrix of the coal. Ash, on the other hand, refers to the solid inorganic material remaining *after combusting* a coal sample. Proximate ash content is the ash remaining after the coal has been exposed to air under specific conditions (ASTM Standard Test Method D 3174). It is reported as the mass percent remaining upon combustion of the original sample on either a dry or moist basis.

Moisture content refers to the mass of water which is released from the solid coal sample when it is heated under specific conditions of temperature and residence time as codified in ASTM Standard Test Method D 3173.

The fixed carbon content refers to the mass of organic matter remaining in the sample after the moisture and volatile matter are released. It is primarily made up of carbon with lesser amounts of hydrogen, sulfur, and nitrogen also present. It is typically reported by difference from the total of the volatile matter, ash, and moisture contents on a mass percent of the original coal sample basis. Alternatively, it can be reported on a dry basis; a dmmf basis; or a moist, mineral matter-free basis.

The values associated with the proximate analysis vary with rank. In general, volatile matter content decreases with increasing rank, while fixed carbon content correspondingly increases. Moisture and ash also decrease, in general, with rank. Typical values for proximate analysis as a function of the rank of a coal are provided in Table 7.3.3.

The ultimate analysis of a coal reports the composition of the organic fraction of coal on an elemental basis. Like the proximate analysis, the ultimate analysis can be reported on a moist or dry basis and on

Neavel, R. 1981. Origin, petrography, and classification of coal, in *Chemistry of Coal Utilization, Second Supplementary Volume,* M.A. Elliott, Ed., John Wiley & Sons, New York, 91–158.

Villagran, R.A. 1989. *Acid Rain Legislation: Implications for the Coal Industry,* Shearson, Lehman, Hutton, New York, 37–39.

Further Information

An excellent resource for understanding coal, its sources, its uses, and its limitations and potential problems is the book by Elliott referenced above under Averitt (1981), Habermehl et al. (1981), and Neavel (1981). A reader wishing an understanding of coal topics could find no better resource.

Another comprehensive book which includes more-recent information but is not quite as weighty as Elliott's (664 pages vs. 2374 pages) is *The Chemistry and Technology of Coal,* edited (second edition, revised and expanded) by James G. Speight.

For up-to-date information specific to the environmental problems associated with the use of coal, the reader is referred to Norbert Berkowitz's chapter entitled "Environmental Aspects of Coal Utilization" in *An Introduction to Coal Technology.*

For information on the standards for coal analyses and descriptions of the associated procedures, the reader is referred to any recent edition of the American Society for Testing and Materials's *Annual Book of ASTM Standards.* Section 5 covers petroleum products, lubricants, and fossil fuels, including coal and coke.

Oil

Philip C. Crouse, P.E.

Overview

Fossil fuel energy accounted for 86.3% of all world energy in 1990. The Energy Information Administration (EIA) of the U.S. Department of Energy estimates that in the year 2010, fossil fuels will account for 85.9% of all world energy consumption — only a 0.4% percentage decrease in usage (Figure 7.3.2). According to EIA estimates, coal is expected to decline slightly from about a 27% to about a 25% share of consumption, and consumption of natural gas is expected to increase from 21 to 24% over the 20-year period. Over the same period, oil is forecasted to continue to be world major energy source with only slight declines from the present 39% of consumption.

Recent efforts in the United States have been to foster growth in natural gas usage as an energy source, causing an estimated growth of 2.3% per year. Total energy usage is expected to grow from 345.6 to 476.0 quadrillion Btu — or a 38% growth in energy usage over 20 years.

Crude Oil Classification and World Reserves

Obtaining accurate estimates of world petroleum and natural gas resources and reserves is difficult and uncertain. Terminology used by industry to classify resources and reserves has no broadly accepted standard classification. Such classifications have been a source of controversy in the international oil and gas community. Confusion persists in regard to classification. This section uses information provided by the Department of Energy classification system. The next chart shows the relationship of resources to reserves. **Recoverable resources** include discovered and undiscovered resources. **Discovered resources** are those resources that can be economically recovered (Figure 7.3.3).

Discovered resources include all production already out of the ground and reserves. Reserves are further broken down into proved reserves and other reserves. Again, there are many different groups that classify reserves in different ways, such as *measured*, *indicated*, *internal*, *probable*, and *possible*. Most groups break reserves into producing and nonproducing categories. Each of the definitions is quite voluminous and the techniques for qualifying reserves vary globally.

TABLE 7.3.7 Oil Reserves (Year End) — million barrels

	1970	1980	1990
North America	53,160	80,053	84,134
South America	25,557	26,922	69,686
Western Europe	5,698	18,698	21,289
Eastern Europe	59,880	84,140	65,412
Middle East	342,134	357,578	601,987
Africa	46,356	52,650	59,159
Asia-Pacific	21,973	38,517	56,151
Total	554,777	658,557	957,818
OPEC	404,441	428,139	715,502
Non-OPEC	150,336	230,418	242,316

Source: EIA, *International Oil and Gas Exploration and Development 1991*, Washington, D.C., December 1993, 36–39.

TABLE 7.3.8 Annual Oil Production — million barrels

	1970	1980	1990
North America	4,157	4,379	4,136
South America	1,738	1,331	1,574
Western Europe	116	869	1,478
Eastern Europe	2,706	4,550	4,204
Middle East	5,063	6,760	6,120
Africa	2,246	2,265	2,367
Asia-Pacific	651	1774	2371
Total	16,678	21,928	22,049
OPEC	8,545	9,839	8,645
Non-OPEC	8,133	12,089	13,604

Source: EIA, International Oil and Gas Exploration and Development 1991, Washington, D.C., December 1993, 30–33.

Proved reserves are generally defined as: “Those volumes of oil and gas that geological and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under existing economic and operating conditions.”

OPEC (the Organization of Petroleum-Exporting Countries) has been key in setting global fossil fuel prices over the last two decades. With very large reserves, OPEC can provide much of the world future needs for crude oil and petroleum products. About two-thirds of the world known petroleum reserves are located in the Middle East as shown in Table 7.3.7.

Table 7.3.8 shows that the annual world crude oil production has steadily grown from 16.7 billion barrels in 1970 to 22 billion barrels in 1990.

Both crude oil demand and production are forecast to increase over the next 20 years. OPEC production is relatively level at 8.6 billion barrels in 1990 compared with 8.5 billion barrels in 1970. During the same time, non-OPEC production increased from 8.1 to 13.6 billion barrels. As the “swing producer”, OPEC’s production in 1980 increased by over 1 billion barrels when non-OPEC production could not meet total demand. They then decreased production by a similar amount in 1990 when production in the rest of the world increased by 1 billion to a non-OPEC total of 13.6 billion barrels. With a low price environment, OPEC is expected to gain market share in global production over the next 20 years.

Standard Fuels

Petroleum is refined into petroleum products that are used to meet individual product demands. The general classifications of products are

1. NATURAL GAS LIQUIDS AND LIQUEFIED REFINERY GASES
   This category includes ethane (C_2H_6), ethylene (C_2H_4), propane (C_3H_8), propylene (C_3H_6), butane and isobutane (C_4H_{10}), and butylene and isobutylene (C_4H_8).
2. FINISHED PETROLEUM PRODUCTS
   This category includes motor gasoline, aviation gasoline, jet fuel, kerosene, distillate, fuel oil, residual fuel oil, petrochemical feed stock, naphthas, lubricants, waxes, petroleum coke, asphalt and road oil, and still gas.
   - *Motor gasoline* includes reformulated gasoline for vehicles and oxygenated gasoline such as gasohol (a mixture of gasoline and alcohol).
   - *Jet fuel* is classified by use such as industrial or military and naphtha and kerosene-type. Naphtha fuels are used in turbo jet and turbo prop aircraft engines and excludes ram-jet and petroleum rocket fuel.
   - *Kerosene* is used for space heaters, cook stoves, wick lamps, and water heaters.
   - *Distillate fuel oil* is broken into subcategories: No. 1 distillate, No. 2 distillate, and No. 4 fuel oil which is used for commercial burners.
   - *Petrochemical feedstock* is used in the manufacture of chemicals, synthetic rubber, and plastics.
   - *Naphthas* are petroleums with an approximate boiling range of 122 to 400°F.
   - *Lubricants* are substances used to reduce friction between bearing surfaces, used as process materials, and as carriers of other materials. They are produced from distillates or residues. Lubricants are paraffinic or naphthenic and separated by viscosity measurement.
   - *Waxes* are solid or semisolid material derived from petroleum distillates or residues. They are typically a slightly greasy, light colored or translucent, crystallizing mass.
   - *Asphalt and road oil*. Asphalt is a cementlike material containing bitumens. Road oil is any heavy petroleum oil used as a dust pallatine and road surface treatment.
   - *Still Gas* is any refinery by-product gas. It consists of light gases of methane, ethane, ethylene, butane, propane, and the other associated gases. Still gas typically used as a refinery fuel.

World Refining Capacity. Refining capacity grew from 48 million barrels per day in 1970 to about 75 million barrels per day in 1990 — a 55% growth in capacity. Table 7.3.9 shows world refining capacity beginning in 1970. The peak year was 1982 in which capacity was 81.4 million barrels per day. Utilization of refinery capacity was about 80% in 1990, pointing to underutilization.

TABLE 7.3.9 World Refining Capacity

	1970	1980	1990
North America	13.2	20.2	17.4
Latin America	4.8	8.6	7.2
Western Europe	14.7	20.3	14.1
Middle East	2.2	3.6	4.2
Africa	0.7	1.7	2.6
Asia-Pacific	5.1	10.4	10.3
Central Planned Economies	7.5	15.4	17.6
Total world	48.2	80.0	73.4

Natural Gas

Philip C. Crouse, P.E.

Natural gas has been called the environmentally friendly fossil fuel since it releases fewer harmful contaminants. World production of dry natural gas was 73.7 trillion ft^3 and accounted for over 20% of world energy production. In 1990 Russia accounted for about one third of world natural gas. The second largest producer was the United States having about one quarter of world 1990 natural gas production.

Natural Gas Production Measurement

Natural gas production is generally measured as "dry" natural gas production. It is determined as the volume of natural gas withdrawn from a reservoir less (1) the volume returned for cycling and repressuring reservoirs; (2) the shrinkage resulting from the removal of lease condensate and plant liquids; (3) the nonhydrocarbon gases. The parameters for measurement are 60°F and 14.73 lb standard per square inch absolute.

World Production and Reserves of Dry Natural Gas

From 1983 to 1992, dry natural gas production rose from 54.4 to 75 trillion ft^3. The breakdown by region of world is shown in Table 7.3.10.

TABLE 7.3.10 World Dry Natural Gas Production — trillion ft^3

	1983	1992
North, Central, and South America	21.20	25.30
Western Europe	6.20	7.85
Eastern Europe and former U.S.S.R.	21.09	28.60
Middle East and Africa	2.95	6.87
Far East and Oceania	2.96	6.38
World total	54.40	75.00

Source: EIA, *Annual Energy Review 1993*, EIA, Washington, D.C., July 1994, 305.

World natural gas reserves estimated by the *Oil and Gas Journal* as of December 31, 1991 are in Table 7.3.11. OPEC accounted for 40% of world reserves yet processes only about 12% of the world production. The former U.S.S.R. accounts for about 40% and Iran another 15% of world reserves.

TABLE 7.3.11 World Natural Gas Reserves — billion ft^3

North America	343,677
South America	166, 850
Western Europe	177,844
Eastern Europe	1,766,358
Middle East	1,319,823
Africa	310,241
Asia-Pacific	299,288
Total	4,384,081
OPEC	1,729,205
Non-OPEC	2,654,876

Compressed Natural Gas

Environmental issues have countries examining and supporting legislation to subsidize the development of cleaner vehicles that use compressed natural gas (CNG). Even with a push toward the use of CNG-burning vehicles, the numbers are quite small when compared with gasoline vehicles. Italy has used

CNG since 1935 and has the largest usage with 300,000 vehicles. The United States ranked fifth with an estimated 30,000 vehicles in 1994. Argentina, which ranked sixth, had 15,000 vehicles.

Liquefied Natural Gas (LNG)

Natural gas can be liquefied by lowering temperature until a liquid state is achieved. It can be transported by refrigerated ships. The process of using ships and providing special-handling facilities adds significantly to the final LNG cost. If oil prices stay low, prospects for LNG development will remain low in the future. However, LNG projects planned by OPEC member countries may become significant over the next 20 years with shipments of LNG exports ultimately accounting for up to 25% of all gas exports.

Physical Properties of Hydrocarbons

The most important physical properties from a crude oil classification standpoint are density or specific gravity and the viscosity of liquid petroleum. Crude oil is generally lighter than water. A Baume-type scale is predominantly used by the petroleum industry and is called the **API** (American Petroleum Institute) **gravity** scale (see Table 7.3.12). It is related directly to specific gravity by the formula:

$$\varphi = (141.5)\big/(131.5 + \ ^{\circ}\text{API})$$

where φ = specific gravity. Temperature and pressure are standardized at 60°F and 1 atm pressure.

TABLE 7.3.12 Relation of API Gravity, Specific Gravity, and Weight per Gallon of Gasoline

Degree API	Specific Gravity	Weight of gallon in lbs.
8	1.014	8.448
9	1.007	8.388
10	1.000	8.328
15	0.966	8.044
20	0.934	7.778
25	0.904	7.529
30	0.876	7.296
35	0.850	7.076
40	0.825	6.870
45	0.802	6.675
50	0.780	6.490
55	0.759	6.316
58	0.747	6.216

Note: The specific gravity of crude oils ranges from about 0.75 to 1.01.

Other key physical properties involve the molecular weight of the hydrocarbon compound and the boiling point and liquid density. Table 7.3.13 shows a summation of these properties.

Defining Terms

API Gravity: A scale used by the petroleum industry for specific gravity.

Discovered resources: Discovered resources include all production already out of the ground and reserves.

Proved resources: Resources that geological and engineering data demonstrate with reasonable certainly to be recoverable in future years from known reservoirs under existing economic and operating conditions.

Recoverable resources: Recoverable resources include discovered resources.

7.6 Solar Energy Resources

D. Yogi Goswami

The sun is a vast nuclear power plant of the fusion variety which generates power in the form of radiant energy at a rate of 3.8×10^{23} kW. An extremely small fraction of this is intercepted by Earth, but even this small fraction amounts to the huge quantity of 1.8×10^{14} kW. On the average, about 60% of this energy, incident at the outer edge of the atmosphere, reaches the surface. To compare these numbers with our energy needs, consider the present electrical-generating capacity in the United States, which is approximately of 7×10^{8} kW. This is equivalent to an average solar radiation falling on only 1000 square miles in a cloudless desert area. It must, however, be remembered that solar energy is distributed over the entire surface of Earth facing the sun, and it seldom exceeds 1.0 kW/m^2. Compared to other sources, such as fossil fuels or nuclear power plants, solar energy has a very low energy density. However, solar radiation can be concentrated to achieve very high energy densities. Indeed, temperatures as high as 3000 K have been achieved in solar furnaces.

Solar energy technology has been developed to a point where it can replace most of the fossil fuels or fossil fuel-derived energy. In many applications it is already economical, and it is a matter of time before it becomes economical for other applications as well.

This section deals in the availability of solar radiation, including methods of measurement, calculation, and available data.

Solar Energy Availability

Detailed information about solar radiation availability at any location is essential for the design and economic evaluation of a solar energy system. Long-term measured data of solar radiation are available for a large number of locations in the United States and other parts of the world. Where long-term measured data are not available, various models based on available climatic data can be used to estimate the solar energy availability. The solar energy is in the form of electromagnetic radiation with the wavelengths ranging from about 0.3 μm (10^{-6} m) to over 3 μm, which correspond to ultraviolet (less than 0.4 μm), visible (0.4 and 0.7 μm), and infrared (over 0.7 μm). Most of this energy is concentrated in the visible and the near-infrared wavelength range (see Figure 7.6.1). The incident solar radiation, sometimes called **insolation,** is measured as irradiance, or the energy per unit time per unit area (or power per unit area). The units most often used are watts per square meter (W/m^2), British thermal units per hour per square foot (Btu/hr-ft^2), and Langleys (calories per square centimeter per minute, cal/cm^2-min).

The amount of solar radiation falling on a surface normal to the rays of the sun outside the atmosphere of the earth (extraterrestrial) at mean Earth-sun distance (D) is called the **solar constant**, I_o. Measurements by NASA indicated the value of solar constant to be 1353 W/m^2 (±1.6%). This value was revised upward and the present accepted value of the solar constant is 1377 W/m^2 (Quinlan, 1979) or 437.1 Btu/hr-ft^2 or 1.974 langleys. The variation in seasonal solar radiation availability at the surface of Earth can be understood from the geometry of the relative movement of Earth around the sun.

Earth-Sun Relationships

Figure 7.6.2 shows the annual motion of Earth around the sun. The **extraterrestrial solar radiation** varies throughout the year because of the variation in the Earth-sun distance (D) as:

$$I = I_o \left(D / D_o \right)^2 \tag{7.6.1}$$

which may be approximated as (Spencer, 1971)

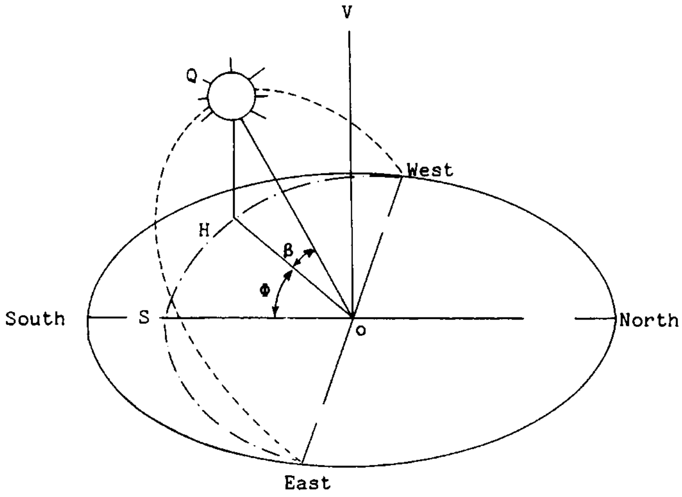


FIGURE 7.6.3 Apparent daily path of the sun across the sky from sunrise to sunset, showing the solar altitude and azimuth angles.

$$\delta = 23.45° \sin\left[360(284 + N)/365°\right] \tag{7.6.4}$$

The apparent motion of the sun around the earth is shown in Figure 7.6.3. The **solar altitude angle**, β, and the **solar azimuth angle**, Φ, describe the position of the sun at any time.

Solar Time

The sun angles are found from the knowledge of solar time, which differs from the local time. The relationship between solar time and local standard time (LST) is given by

$$\text{Solar Time} = \text{LST} + \text{ET} + 4\left(L_{\text{st}} - L_{\text{loc}}\right) \tag{7.6.5}$$

where ET is the **equation of time**, which is a correction factor in minutes that accounts for the irregularity of the motion of the Earth around the sun. L_{st} is the standard time meridian and L_{loc} is the local longitude. ET can be calculated from the following empirical equation:

$$\text{ET}(\text{in minutes}) = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B \tag{7.6.6}$$

where $B = 360(N - 81)/365°$.
The sun angles β (altitude) and Φ (azimuth) can be found from the equations:

$$\sin\beta = \cos\ell \cos\delta \cos H + \sin\ell \sin\delta \tag{7.6.7}$$

where ℓ = latitude angle,

$$\sin\Phi = \cos\delta \sin H / \cos\beta \tag{7.6.8}$$

and

$$H = \text{Hour angle} = \frac{\text{Number of minutes from local solar noon}}{4\ \text{min/degree}} \tag{7.6.9}$$

(At solar noon, $H = 0$, so $\beta = 90 - |\ell - \delta|$ and $\Phi = 0$.)

Solar Radiation on a Surface

As solar radiation, I, passes through the atmosphere, some of it is absorbed by air and water vapor, while some gets scattered by molecules of air, water vapor, aerosols, and dust particles. The part of solar radiation that reaches the surface of the Earth with essentially no change in direction is called **direct or beam normal radiation**, I_{bN}. The scattered radiation reaching the surface from the atmosphere is called **diffuse radiation**, I_d.

I_{bN} can be calculated from the extraterrestrial solar irradiance, I, and the atmospheric optical depth τ as (Goswami et al., 1981; ASHRAE, 1995)

$$I_{\text{bN}} = Ie^{-\tau \sec \theta_z} \tag{7.6.10}$$

where θ_z is the solar zenith angle (angle between the sun rays and the vertical). The atmospheric optical depth determines the attenuation of the solar radiation as it passes through the atmosphere. Threlkeld and Jordan (1958) calculated values of τ for average atmospheric conditions at sea level with a moderately dusty atmosphere and amounts of precipitable water vapor equal to the average value for the United States for each month. These values are given in Table 7.6.1. To account for the differences in local conditions from the average sea level conditions Equation (7.6.10) is modified by a parameter called Clearness Number, Cn, introduced by Threlkeld and Jordan (1958):

$$I_{\text{bN}} = \text{Cn}Ie^{-\tau \sec \theta_z} \tag{7.6.11}$$

values of Cn vary between 0.85 and 1.15.

TABLE 7.6.1 Average Values of Atmospheric Optical Depth (τ) and Sky Diffuse Factor (C) for 21st Day of Each Month

Month	1	2	3	4	5	6	7	8	9	10	11	12
τ	0.142	0.144	0.156	0.180	0.196	0.205	0.207	0.201	0.177	0.160	0.149	0.142
C	0.058	0.060	0.071	0.097	0.121	0.134	0.136	0.122	0.092	0.073	0.063	0.057

Source: Threlkeld, J.L. and Jordan, R.C., *ASHRAE Trans.*, 64, 45, 1958.

Solar Radiation on a Horizontal Surface

Total incident solar radiation on a horizontal surface is given by

$$I_{t,\text{Horizontal}} = I_{\text{bN}} \cos \theta_z + CI_{\text{bN}} \tag{7.6.12}$$

$$= I_{\text{bN}} \sin \beta + CI_{\text{bN}} \tag{7.6.13}$$

where θ_z is called the solar zenith angle and C is called the sky diffuse factor, as given in Table 7.6.1.

Solar Radiation on a Tilted Surface

For a surface of any orientation and tilt as shown in Figure 7.6.4, the angle of incidence, θ, of the direct solar radiation is given by

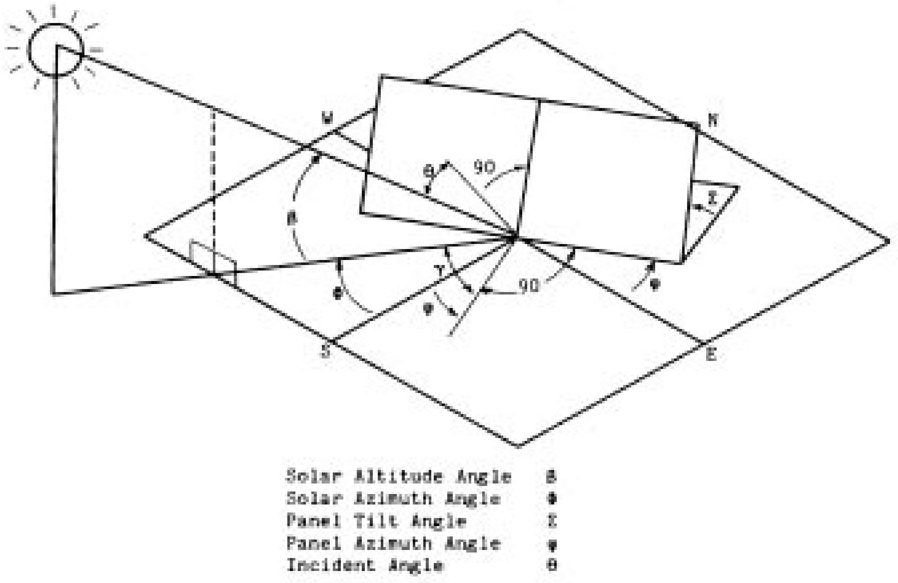


FIGURE 7.6.4 Definitions of solar angles for a tilted surface.

$$\cos\theta = \cos\beta\cos\gamma\sin\Sigma + \sin\beta\cos\Sigma \tag{7.6.14}$$

where γ is the angle between horizontal projections of the rays of the sun and the normal to the surface. Σ is the tilt angle of the surface from the horizontal.

For a tilted surface with angle of incidence θ, the total incident solar radiation is given by

$$I_b = I_{\mathrm{bN}}\cos\theta + I_{\mathrm{diffuse}} + I_{\mathrm{reflected}} \tag{7.6.15}$$

where

$$I_{\mathrm{diffuse}} = CI_{\mathrm{bN}}(1+\cos\Sigma)/2 \tag{7.6.16}$$

and

$$I_{\mathrm{reflected}} = \rho I_{\mathrm{bN}}(C+\sin\beta)(1-\cos\Sigma)/2 \tag{7.6.17}$$

where ρ is the reflectivity of the surroundings. For ordinary ground or grass, ρ is approximately 0.2 while for ground covered with snow it is approximately 0.8.

Solar Radiation Measurements

Two basic types of instruments are used in measurements of solar radiation. These are (see Figure 7.6.5):

1. *Pyranometer:* An instrument used to measure global (direct and diffuse) solar radiation on a surface. This instrument can also be used to measure the diffuse radiation by blocking out the direct radiation with a shadow band.
2. *Pyrheliometer:* This instrument is used to measure only the direct solar radiation on a surface normal to the incident beam. It is generally used with a tracking mount to keep it aligned with the sun.

More-detailed discussions about these and other solar radiation measuring instruments can be found in Zerlaut (1989).

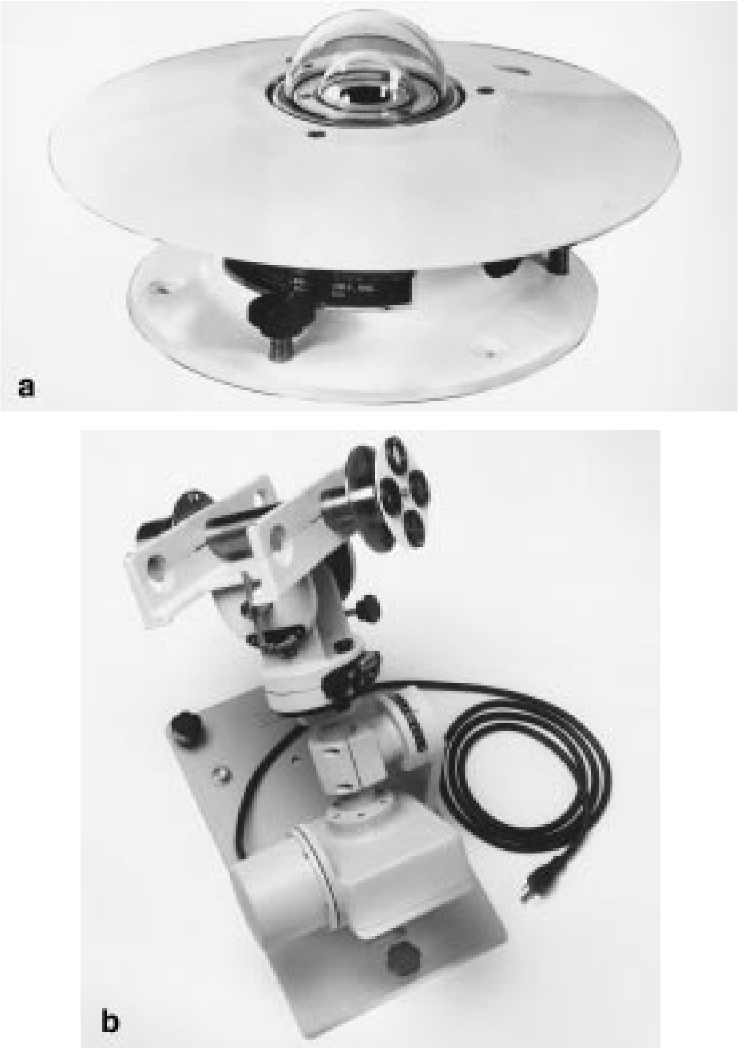


FIGURE 7.6.5 Two basic instruments for solar radiation: (a) pyranometer; (b) pyrheliometer.

Solar Radiation Data

Measured values of solar radiation data for locations in the United States are available from the National Climatic Center in Asheville, NC. A number of states have further presented solar radiation data for locations in those states in readily usable form. Weather services and energy offices in almost all the countries have available some form of solar radiation data or climatic data that can be used to derive solar radiation data for locations in those countries. Tables 7.6.2 to 7.6.8 give solar radiation data for clear days for south-facing surfaces in the Northern Hemisphere (and northern-facing surfaces in the Southern Hemisphere) tilted at 0°, 15°, 30°, 45°, 60°, 75°, and vertical, for latitudes 0°, 10°, 20°, 30°, 40°, 50°, and 60°. The actual average solar radiation data at a location is less than the values given in these tables because of the cloudy and partly cloudy days in addition to the clear days. The actual data can be obtained either from long-term measurements or from modeling based on some climatic parameters, such as percent sunshine. Tables 7.6.9 to 7.6.12 give hourly solar angles for northern latitudes 0°, 20°, 40°, and 60°.

7.7 Wind Energy Resources[*]

Dale E. Berg

The mechanical devices that are used to convert kinetic energy in the wind into useful shaft power are known as windmills (the earliest machines were used to mill grain), wind machines, or wind turbines. The earliest use of wind machines appears to have been in ancient Persia, where they were used for grinding grain and pumping water. By the 14th century, completely different types of mills known as post and cap mills had become a major source of energy for milling, water pumping, and other tasks throughout northern Europe, and they remained so well into the 19th century, when the steam engine displaced them in many applications.

A new form of windmill appeared in United States in the second half of the 19th century — the multivane or annular windmill, also sometimes known as the American windmill (see Figure 7.7.1). These small, lightweight machines were designed to survive high winds with no human intervention by automatically shedding power, and they played a large role in the settlement of the American West — an arid country where little surface water is available. Many windmills of this basic type are still in use for water pumping around the world today.

FIGURE 7.7.1 The multiblade American windmill Photograph by Paul Gipe. (Adapted from *Wind Power for Home & Business*, Chelsea Green Publishing. 1993).

By the end of the 19th century, efforts to adapt wind power to electricity generation were underway in several countries. In the early 20th century, small wind turbine generators utilizing only two or three aerodynamic blades and operating at a higher rotational speed than the multibladed windmills were developed. Many thousands of generators of this type have been used to provide electricity in the remote areas of the world over the past 85 years.

Large-scale wind turbines designed to generate electrical power were built and tested in several European countries and the U.S. between 1935 and 1970. However, economic studies showed that the electricity generated by the machines would be every expensive, and no effort was made to develop the machines as a serious alternative energy source.

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[*] This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

As a result of research and development since the mid 1970s, the cost of energy or wind-generated electricity has decreased from around 30¢ per kilowatt-hour (kWhr) in the early 1980s to less than 5¢/kWhr for a modern wind farm at a good site in 1995, and wind turbine availability (the fraction of time the machine is operational; i.e., not disabled for repairs or maintenance) has increased from 50 to 60% to better than 95% over the same period. At the end of 1995, there were over 26,000 wind turbines operating worldwide with an installed capacity of over 5000 MW. Twenty-five percent of that capacity was installed in 1995, and plans for 1996 call for the installation of an additional 25%. About 2500 MW of the 5000 MW was in Europe, 1700 MW was in the U.S., and over 400 MW was in India.

Wind Characteristics

Wind Speed and Shear

The primary cause of atmospheric air motion, or wind, is uneven heating of Earth by solar radiation. For example, land and water along a coastline absorb radiation differently, and this creates the light winds or breezes normally found along a coast. Earth's rotation is also an important factor in creating winds.

Wind moving across Earth's surface is slowed by trees, buildings, grass, rocks, and other obstructions in its path. The effect of these obstructions decreases with increasing height above the surface, typically resulting in a wind speed that varies with height above the Earth's surface — phenomenon known as **wind shear**. For most situations, wind shear is positive and wind speed increases with height, but situations in which the wind shear is negative or inverse are not unusual. In the absence of actual data for a specific site, a commonly used approximation for wind shear is

$$U/U_o = \left(h/h_o\right)^{\alpha} \tag{7.7.1}$$

where U is the velocity at a height h, U_o is the measured velocity at height h_o, and α is the non-dimensional wind shear exponent.

The wind shear, α, varies with terrain characteristics, but usually is between 0.10 and 0.25. Over a smooth, level, grass-covered terrain such as the United States Great Plains, α is normally about 0.14. For wind over row crops or low bushes with a few scattered trees, a value of 0.20 is more common while a value of 0.25 is normally a good value for wind over a heavy stand of trees, several buildings, or hilly or mountainous terrain.

A specific site may display much different wind shear behavior than that given in Equation 7.7.1, and that will dramatically affect site energy capture, making it important to measure the wind resource at the specific site and height where the wind turbine will be located, if at all possible.

Wind Energy Resource

The available power in the wind passing through a given area at any given velocity is due to the kinetic energy of the wind and is given by

$$\text{Power} = \frac{1}{2}\rho A U^3 \tag{7.7.2}$$

where the power is in watts, ρ is the air density in kg/m^3, A is the area of interest perpendicular to the wind in m^2, and U is the wind velocity in m/sec.

Air density decreases with increasing temperature and increasing altitude. The effect of temperature on density is relatively weak and is normally ignored, as these variations tend to average out over the period of a year. The density difference due to altitude, however, is significant and does not average out. For example, the air density at sea level is approximately 14% higher than that at Denver, CO (elevation 1600 m or 5300 ft above sea level), so wind of any velocity at sea level contains 14% more power than wind of the same velocity at Denver.

7.8 Geothermal Energy

Joel L. Renner and Marshall J. Reed

The word *Geothermal* comes from the combination of the Greek words *gê*, meaning Earth, and *thérm*, meaning heat. Quite literally, geothermal energy is the heat of the Earth. Geothermal resources are concentrations of the Earth's heat, or geothermal energy, that can be extracted and used economically now or in the reasonable future. Currently, only concentrations of heat associated with water in permeable rocks can be exploited. Heat, fluid, and permeability are the three necessary components of all exploited geothermal fields. This section of Energy Resources will discuss the mechanisms for concentrating heat near the surface, the types of geothermal systems, and the environmental aspects of geothermal production.

Heat Flow

Temperature within the Earth increases with depth at an average of about 25°C/km. Spatial variations of the thermal energy within the deep crust and mantle of the Earth give rise to concentrations of thermal energy near the surface of the Earth that can be used as an energy resource. Heat is transferred from the deeper portions of the Earth by conduction of heat through rocks, by the movement of hot, deep rock toward the surface, and by deep circulation of water. Most high-temperature geothermal resources are associated with concentrations of heat caused by the movement of magma (melted rock) to near-surface positions where the heat is stored.

In older areas of continents, such as much of North America east of the Rocky Mountains, heat flow is generally 40 to 60 $\mathrm{mWm^{-2}}$ (milliwatts per square meter). This heat flow coupled with the thermal conductivity of rock in the upper 4 km of the crust yields subsurface temperatures of 90 to 110°C at 4 km depth in the Eastern United States. Heat flow within the Basin and Range (west of the Rocky Mountains) is generally 70 to 90 $\mathrm{mWm^{-2}}$, and temperatures are generally greater than 110°C at 4 km. There are large variations in the Western United States, with areas of heat flow greater than 100 $\mathrm{mWm^{-2}}$ and areas which have generally lower heat flow such as the Cascade and Sierra Nevada Mountains and the West Coast. A more detailed discussion of heat flow in the United States is available in Blackwell et al. (1991).

Types of Geothermal Systems

Geothermal resources are hydrothermal systems containing water in pores and fractures. Most hydrothermal resources contain liquid water, but higher temperatures or lower pressures can create conditions where steam and water or only steam are the continuous phases (White et al., 1971; Truesdell and White, 1973). All commercial geothermal production is expected to be restricted to hydrothermal systems for many years because of the cost of artificial addition of water. Successful, sustainable geothermal energy usage depends on reinjection of the maximum quantity of produced fluid to augment natural recharge of hydrothermal systems.

Other geothermal systems that have been investigated for energy production are (1) geopressured-geothermal systems containing water with somewhat elevated temperatures (above normal gradient) and with pressures well above hydrostatic for their depth; (2) magmatic systems, with temperature from 600 to 1400°C; and (3) hot dry rock geothermal systems, with temperatures from 200 to 350°C, that are subsurface zones with low initial permeability and little water. These types of geothermal systems cannot be used for economic production of energy at this time.

Geothermal Energy Potential

The most recent report (Huttrer, 1995) shows that 6800 $\mathrm{MW_e}$ (megawatts electric) of geothermal electric generating capacity is on-line in 21 countries (Table 7.8.1). The expected capacity in the year 2000 is

CHAPTER 1

INTRODUCTION

1.1 AIR CONDITIONING

Air conditioning is a combined process that performs many functions simultaneously. It conditions the air, transports it, and introduces it to the conditioned space. It provides heating and cooling from its central plant or rooftop units. It also controls and maintains the temperature, humidity, air movement, air cleanliness, sound level, and pressure differential in a space within predetermined limits for the comfort and health of the occupants of the conditioned space or for the purpose of product processing.

The term *HVAC&R* is an abbreviation of *heating, ventilating, air conditioning, and refrigerating*. The combination of processes in this commonly adopted term is equivalent to the current definition of air conditioning. Because all these individual component processes were developed prior to the more complete concept of air conditioning, the term *HVAC&R* is often used by the industry.

1.2 COMFORT AND PROCESSING AIR CONDITIONING SYSTEMS

Air Conditioning Systems

An air conditioning, or HVAC&R, system is composed of components and equipment arranged in sequence to condition the air, to transport it to the conditioned space, and to control the indoor environmental parameters of a specific space within required limits.

Most air conditioning systems perform the following functions:

1. Provide the cooling and heating energy required
2. Condition the supply air, that is, heat or cool, humidify or dehumidify, clean and purify, and attenuate any objectionable noise produced by the HVAC&R equipment
3. Distribute the conditioned air, containing sufficient outdoor air, to the conditioned space
4. Control and maintain the indoor environmental parameters – such as temperature, humidity, cleanliness, air movement, sound level, and pressure differential between the conditioned space and surroundings — within predetermined limits

Parameters such as the size and the occupancy of the conditioned space, the indoor environmental parameters to be controlled, the quality and the effectiveness of control, and the cost involved determine the various types and arrangements of components used to provide appropriate characteristics.

Air conditioning systems can be classified according to their applications as (1) comfort air conditioning systems and (2) process air conditioning systems.

Comfort Air Conditioning Systems

Comfort air conditioning systems provide occupants with a comfortable and healthy indoor environment in which to carry out their activities. The various sectors of the economy using comfort air conditioning systems are as follows:

1. The commercial sector includes office buildings, supermarkets, department stores, shopping centers, restaurants, and others. Many high-rise office buildings, including such structures as the World Trade Center in New York City and the Sears Tower in Chicago, use complicated air conditioning systems to satisfy multiple-tenant requirements. In light commercial buildings, the air conditioning system serves the conditioned space of only a single-zone or comparatively smaller area. For shopping malls and restaurants, air conditioning is necessary to attract customers.

2. The institutional sector includes such applications as schools, colleges, universities, libraries, museums, indoor stadiums, cinemas, theaters, concert halls, and recreation centers. For example, one of the large indoor stadiums, the Superdome in New Orleans, Louisiana, can seat 78,000 people.

3. The residential and lodging sector consists of hotels, motels, apartment houses, and private homes. Many systems serving the lodging industry and apartment houses are operated continuously, on a 24-hour, 7-day-a-week schedule, since they can be occupied at any time.

4. The health care sector encompasses hospitals, nursing homes, and convalescent care facilities. Special air filters are generally used in hospitals to remove bacteria and particulates of submicrometer size from areas such as operating rooms, nurseries, and intensive care units. The relative humidity in a general clinical area is often maintained at a minimum of 30 percent in winter.

5. The transportation sector includes aircraft, automobiles, railroad cars, buses, and cruising ships. Passengers increasingly demand ease and environmental comfort, especially for long-distance travel. Modern airplanes flying at high altitudes may require a pressure differential of about 5 psi between the cabin and the outside atmosphere. According to the *Commercial Buildings Characteristics* (1994), in 1992 in the United States, among 4,806,000 commercial buildings having 67.876 billion ft^2 (6.31 billion m^2) of floor area, 84.0 percent were cooled, and 91.3 percent were heated.

Process Air Conditioning Systems

Process air conditioning systems provide needed indoor environmental control for manufacturing, product storage, or other research and development processes. The following areas are examples of process air conditioning systems:

1. In textile mills, natural fibers and manufactured fibers are hygroscopic. Proper control of humidity increases the strength of the yarn and fabric during processing. For many textile manufacturing processes, too high a value for the space relative humidity can cause problems in the spinning process. On the other hand, a lower relative humidity may induce static electricity that is harmful for the production processes.

2. Many electronic products require clean rooms for manufacturing such things as integrated circuits, since their quality is adversely affected by airborne particles. Relative-humidity control is also needed to prevent corrosion and condensation and to eliminate static electricity. Temperature control maintains materials and instruments at stable condition and is also required for workers who wear dust-free garments. For example, a class 100 clean room in an electronic factory requires a temperature of 72 ± 2°F (22.2 ± 1.1°C), a relative humidity at 45 ± 5 percent, and a count of dust particles of 0.5-μm (1.97×10^{-5} in.) diameter or larger not to exceed 100 particles/ft^3 (3531 particles/m^3).

3. Precision manufacturers always need precise temperature control during production of precision instruments, tools, and equipment. Bausch and Lomb successfully constructed a constant-temperature control room of 68 ± 0.1°F (20 ± 0.56°C) to produce light grating products in the 1950s.

4. Pharmaceutical products require temperature, humidity, and air cleanliness control. For instance, liver extracts require a temperature of 75°F (23.9°C) and a relative humidity of 35 percent. If the temperature exceeds 80°F (26.7°C), the extracts tend to deteriorate. High-efficiency air filters must be installed for most of the areas in pharmaceutical factories to prevent contamination.

5. Modern refrigerated warehouses not only store commodities in coolers at temperatures of 27 to 32°F (−2.8 to 0°C) and frozen foods at −10 to −20°F (−23 to −29°C), but also provide relative-humidity control for perishable foods between 90 and 100 percent. Refrigerated storage is used to prevent deterioration. Temperature control can be performed by refrigeration systems only, but the simultaneous control of both temperature and relative humidity in the space can only be performed by process air conditioning systems.

1.3 CLASSIFICATION OF AIR CONDITIONING SYSTEMS ACCORDING TO CONSTRUCTION AND OPERATING CHARACTERISTICS

Air conditioning systems can also be classified according to their construction and operating characteristics as follows.

Individual Room Air Conditioning Systems

Individual room, or simply individual air conditioning systems employ a single, self-contained room air conditioner, a packaged terminal, a separated indoor-outdoor split unit, or a heat pump. A heat pump extracts heat from a heat source and rejects heat to air or water at a higher temperature for heating. Unlike other systems, these systems normally use a totally independent unit or units in each room. Individual air conditioning systems can be classified into two categories:

- Room air conditioner (window-mounted)
- Packaged terminal air conditioner (PTAC), installed in a sleeve through the outside wall

The major components in a factory-assembled and ready-for-use room air conditioner include the following: An evaporator fan pressurizes and supplies the conditioned air to the space. In tube-and-fin coil, the refrigerant evaporates, expands directly inside the tubes, and absorbs the heat energy from the ambient air during the cooling season; it is called a direct expansion (DX) coil. When the hot refrigerant releases heat energy to the conditioned space during the heating season, it acts as a heat pump. An air filter removes airborne particulates. A compressor compresses the refrigerant from a lower evaporating pressure to a higher condensing pressure. A condenser liquefies refrigerant from hot gas to liquid and rejects heat through a coil and a condenser fan. A temperature control system senses the space air temperature (sensor) and starts or stops the compressor to control its cooling and heating capacity through a thermostat (refer to Chap. 26).

The difference between a room air conditioner and a room heat pump, and a packaged terminal air conditioner and a packaged terminal heat pump, is that a four-way reversing valve is added to all room heat pumps. Sometimes room air conditioners are separated into two split units: an outdoor condensing unit with compressor and condenser, and an indoor air handler in order to have the air handler in a more advantageous location and to reduce the compressor noise indoors.

Individual air conditioning systems are characterized by the use of a DX coil for a single room. This is the simplest and most direct way of cooling the air. Most of the individual systems do not employ connecting ductwork. Outdoor air is introduced through an opening or through a small air damper. Individual systems are usually used only for the perimeter zone of the building.

Evaporative-Cooling Air Conditioning Systems

Evaporative-cooling air conditioning systems use the cooling effect of the evaporation of liquid water to cool an airstream directly or indirectly. It could be a factory-assembled packaged unit or a field-built system. When an evaporative cooler provides only a portion of the cooling effect, then it becomes a component of a central hydronic or a packaged unit system.

An evaporative-cooling system consists of an intake chamber, filter(s), supply fan, direct-contact or indirect-contact heat exchanger, exhaust fan, water sprays, recirculating water pump, and water sump. Evaporative-cooling systems are characterized by low energy use compared with refrigeration cooling. They produce cool and humid air and are widely used in southwest arid areas in the United States (refer to Chap. 27).

Desiccant-Based Air Conditioning Systems

A desiccant-based air conditioning system is a system in which latent cooling is performed by desiccant dehumidification and sensible cooling by evaporative cooling or refrigeration. Thus, a considerable part of expensive vapor compression refrigeration is replaced by inexpensive evaporative cooling. A desiccant-based air conditioning system is usually a hybrid system of dehumidification, evaporative cooling, refrigeration, and regeneration of desiccant (refer to Chap. 29).

There are two airstreams in a desiccant-based air conditioning system: a process airstream and a regenerative airstream. Process air can be all outdoor air or a mixture of outdoor and recirculating air. Process air is also conditioned air supplied directly to the conditioned space or enclosed manufacturing process, or to the air-handling unit (AHU), packaged unit (PU), or terminal for further treatment. Regenerative airstream is a high-temperature airstream used to reactivate the desiccant.

A desiccant-based air conditioned system consists of the following components: rotary desiccant dehumidifiers, heat pipe heat exchangers, direct or indirect evaporative coolers, DX coils and vapor compression unit or water cooling coils and chillers, fans, pumps, filters, controls, ducts, and piping.

Thermal Storage Air Conditioning Systems

In a thermal storage air conditioning system or simply thermal storage system, the electricity-driven refrigeration compressors are operated during off-peak hours. Stored chilled water or stored ice in tanks is used to provide cooling in buildings during peak hours when high electric demand charges and electric energy rates are in effect. A thermal storage system reduces high electric demand for HVAC&R and partially or fully shifts the high electric energy rates from peak hours to off-peak hours.

A thermal storage air conditioning system is always a central air conditioning system using chilled water as the cooling medium. In addition to the air, water, and refrigeration control systems, there are chilled-water tanks or ice storage tanks, storage circulating pumps, and controls (refer to Chap. 31).

Clean-Room Air Conditioning Systems

Clean-room or clean-space air conditioning systems serve spaces where there is a need for critical control of particulates, temperature, relative humidity, ventilation, noise, vibration, and space pressurization. In a clean-space air conditioning system, the quality of indoor environmental control directly affects the quality of the products produced in the clean space.

A clean-space air conditioning system consists of a recirculating air unit and a makeup air unit—both include dampers, prefilters, coils, fans, high-efficiency particulate air (HEPA) filters, ductwork, piping work, pumps, refrigeration systems, and related controls except for a humidifier in the makeup unit (refer to Chap. 30).

Space Conditioning Air Conditioning Systems

Space conditioning air conditioning systems are also called *space air conditioning systems*. They have cooling, dehumidification, heating, and filtration performed predominately by fan coils, water-source heat pumps, or other devices within or above the conditioned space, or very near it. A fan coil consists of a small fan and a coil. A water-source heat pump usually consists of a fan, a finned coil to condition the air, and a water coil to reject heat to a water loop during cooling, or to extract heat from the same water loop during heating. Single or multiple fan coils are always used to serve a single conditioned room. Usually, a small console water-source heat pump is used for each control zone in the perimeter zone of a building, and a large water-source heat pump may serve several rooms with ducts in the core of the building (interior zone, refer to Chap. 28).

Space air conditioning systems normally have only short supply ducts within the conditioned space, and there are no return ducts except the large core water-source heat pumps. The pressure drop required for the recirculation of conditioned space air is often equal to or less than 0.6 in. water column (WC) (150 Pa). Most of the energy needed to transport return and recirculating air is saved in a space air conditioning system, compared to a unitary packaged or a central hydronic air conditioning system. Space air conditioning systems are usually employed with a dedicated (separate) outdoor ventilation air system to provide outdoor air for the occupants in the conditioned space.

Space air conditioning systems often have comparatively higher noise level and need more periodic maintenance inside the conditioned space.

Unitary Packaged Air Conditioning Systems

Unitary packaged air conditioning systems can be called, in brief, packaged air conditioning systems or packaged systems. These systems employ either a single, self-contained packaged unit or two split units. A single packaged unit contains fans, filters, DX coils, compressors, condensers, and other accessories. In the split system, the indoor air handler comprises controls and the air system, containing mainly fans, filters, and DX coils; and the outdoor condensing unit is the refrigeration system, composed of compressors and condensers. Rooftop packaged systems are most widely used (refer to Chap. 29).

Packaged air conditioning systems can be used to serve either a single room or multiple rooms. A supply duct is often installed for the distribution of conditioned air, and a DX coil is used to cool it. Other components can be added to these systems for operation of a heat pump system; i.e., a centralized system is used to reject heat during the cooling season and to condense heat for heating during the heating season. Sometimes perimeter baseboard heaters or unit heaters are added as a part of a unitary packaged system to provide heating required in the perimeter zone.

Packaged air conditioning systems that employ large unitary packaged units are central systems by nature because of the centralized air distributing ductwork or centralized heat rejection systems. Packaged air conditioning systems are characterized by the use of integrated, factory-assembled, and ready-to-use packaged units as the primary equipment as well as DX coils for cooling, compared to chilled water in central hydronic air conditioning systems. Modern large rooftop packaged units have many complicated components and controls which can perform similar functions to the central hydronic systems in many applications.

1.4 CENTRAL HYDRONIC AIR CONDITIONING SYSTEMS

Central hydronic air conditioning systems are also called central air conditioning systems. In a central hydronic air conditioning system, air is cooled or heated by coils filled with chilled or hot water distributed from a central cooling or heating plant. It is mostly applied to large-area buildings with many zones of conditioned space or to separate buildings.

Water has a far greater heat capacity than air. The following is a comparison of these two media for carrying heat energy at 68°F (20°C):

	Air	Water
Specific heat, Btu/lb · °F	0.243	1.0
Density, at 68°F, lb/ft^3	0.075	62.4
Heat capacity of fluid at 68°F, Btu/ft^3 · °F	0.018	62.4

The heat capacity per cubic foot (meter) of water is 3466 times greater than that of air. Transporting heating and cooling energy from a central plant to remote air-handling units in fan rooms is far more efficient using water than conditioned air in a large air conditioning project. However, an additional water system lowers the evaporating temperature of the refrigerating system and makes a small- or medium-size project more complicated and expensive.

A central hydronic system of a high-rise office building, the NBC Tower in Chicago, is illustrated in Fig. 1.1. A central hydronic air conditioning system consists of an air system, a water system, a central heating/cooling plant, and a control system.

Air System

An air system is sometimes called the *air-handling system*. The function of an air system is to condition, to transport, to distribute the conditioned, recirculating, outdoor, and exhaust air, and to control the indoor environment according to requirements. The major components of an air system

11.1 INTRODUCTION

A *heat exchanger* can be defined as any device that transfers heat from one fluid to another or from or to a fluid and the environment. Whereas in *direct contact* heat exchangers, there is no intervening surface between fluids, in *indirect contact* heat exchangers, the customary definition pertains to a device that is employed in the transfer of heat between two fluids or between a surface and a fluid. Heat exchangers may be classified (Shah, 1981, or Mayinger, 1988) according to (1) transfer processes,

(2) number of fluids, (3) construction, (4) heat transfer mechanisms, (5) surface compactness, (6) flow arrangement, (7) number of fluid passes, and (8) type of surface.

Recuperators are direct-transfer heat exchangers in which heat transfer occurs between two fluid streams at different temperature levels in a space that is separated by a thin solid wall (a parting sheet or tube wall). Heat is transferred by convection from the hot (hotter) fluid to the wall surface and by convection from the wall surface to the cold (cooler) fluid. The recuperator is a surface heat exchanger.

Regenerators are heat exchangers in which a hot fluid and a cold fluid flow alternately through the same surface at prescribed time intervals. The surface of the regenerator receives heat by convection from the hot fluid and then releases it by convection to the cold fluid. The process is transient; that is, the temperature of the surface (and of the fluids themselves) varies with time during the heating and cooling of the common surface. The regenerator is a also surface heat exchanger.

In *direct-contact* heat exchangers, heat is transferred by partial or complete mixing of the hot and cold fluid streams. Hot and cold fluids that enter this type of exchanger separately leave together as a single mixed stream. The temptation to refer to the direct-contact heat exchanger as a mixer should be resisted. Direct contact is discussed in Chapter 19. In the present chapter we discuss the shell-and-tube heat exchanger, the compact heat exchanger, the longitudinal high-fin exchanger, the transverse high-fin exchanger including the air-fin cooler, the plate-and-frame heat exchanger, the regenerator, and fouling.

11.2 GOVERNING RELATIONSHIPS

11.2.1 Introduction

Assume that there are two *process streams* in a heat exchanger, a hot stream flowing with a *capacity rate* $C_h = \dot{m}_h C_{ph}$ and a cooler (or cold stream) flowing with a capacity rate $C_c = \dot{m}_c c_{ph}$. Then, conservation of energy demands that the heat transferred between the streams be described by the enthalpy balance

$$q = C_h(T_1 - T_2) = C_c(t_2 - t_1) \tag{11.1}$$

where the subscripts 1 and 2 refer to the inlet and outlet of the exchanger and where the T's and t's are employed to indicate hot- and cold-fluid temperatures, respectively.

Equation (11.1) represents an ideal that must hold in the absence of losses, and while it describes the heat that will be transferred (the *duty* of the heat exchanger) for the case of prescribed flow and temperature conditions, it does not provide an indication of the size of the heat exchanger necessary to perform this duty. The size of the exchanger derives from a statement of the *rate equation*:

$$q = U\eta S\theta_m = U_h\eta_{\text{ov},h}S_h\theta_m = U_c\eta_{\text{ov},c}S_c\theta_m \tag{11.2}$$

where S_h and S_c are the surface areas on the hot and cold sides of the exchanger, U_h and U_c are the *overall heat transfer coefficients* referred to the hot and cold sides of

4. The bond resistance given by the tube manufacturer or calculated from the procedure of Section 11.2.3 is transferred appropriately via

$$r_{Bo} = r_B \frac{d_b}{d_g} \tag{11.180}$$

5. The tube metal resistance is based on the mean tube diameter, and with the metal thickness

$$\delta_t = \frac{d_b - d_g}{2}$$

the tube metal resistance is

$$r_{mot} = \frac{\delta_t}{k_t} \frac{2d_b}{d_b + d_g} \tag{11.181}$$

The sum of these resistances is $\sum R_{io}$:

$$\sum R_{io} = r_{io} + r_{dio} + r_{mol} + r_{Bo} + r_{mot}$$

and it is noted that $\sum R_{io}$ is based on the equivalent bare outside tube surface. The gross outside surface to bare tube surface is $S'/\pi d_b$, so that the total resistance referred to the gross outside surface will be

$$\sum R_{is} = \sum R_{io} \frac{S'}{\pi d_b} \tag{11.182}$$

The air-side coefficient is h_o and the fin efficiency is computed from eq. (11.9b). Then, with no provision for fouling,

$$r_{o\eta} = \frac{1}{h_o \eta_{\text{ov},o}} \tag{11.183}$$

where $\eta_{\text{ov},o}$ is obtained from eq. (11.9b):

$$\eta_{\text{ov},o} = 1 - \frac{S_f}{S}(1 - \eta_f)$$

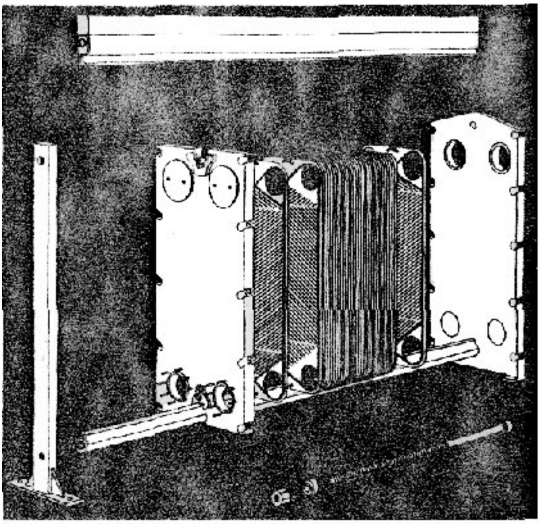
The overall heat transfer coefficient is then given by

$$U_o = \frac{1}{\sum R_{is} + r_{o\eta f}} \tag{11.184}$$

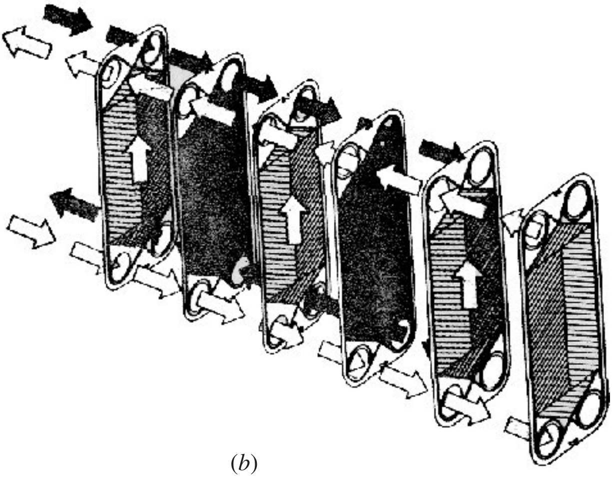
11.8 PLATE AND FRAME HEAT EXCHANGER

11.8.1 Introduction

An exploded view of the *plate and frame heat exchanger,* also referred to as a *gasketed plate heat exchanger,* is shown in Fig. 11.31*a*. The terminology *plate fin heat*



(*a*)



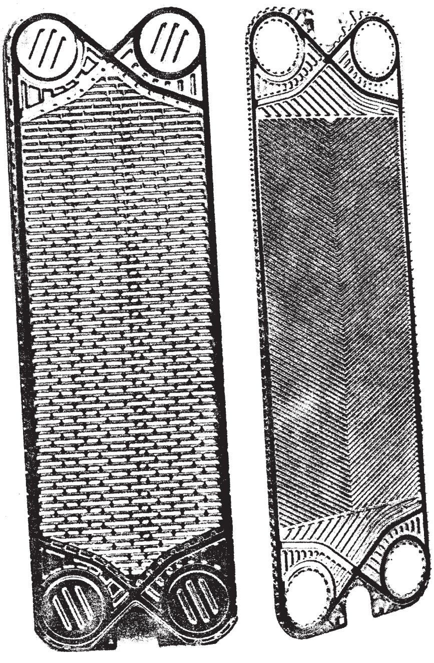
(*b*)

Figure 11.31 (*a*) Exploded view of a typical plate and frame (gasketed-plate) heat exchanger and (*b*) flow pattern in a plate and frame (gasketed-plate) heat exchanger. (From Saunders, 1988, with permission.)

exchanger is also in current use but is avoided here because of the possibility of confusion with the plate fin surfaces in compact heat exchangers. The exchanger is composed of a series of corrugated plates that are formed by precision pressing with subsequent assembly into a mounting frame using full peripheral gaskets. Figure 11.31*b* illustrates the general flow pattern and indicates that the spaces between the plates form alternate flow channels through which the hot and cold fluids may flow, in this case, in counterflow.

Plate and frame heat exchangers have several advantages. They are relatively inexpensive and they are easy to dismantle and clean. The surface area enhancement due to the many corrugations means that a great deal of surface can be packed into a rather small volume. Moreover, plate and frame heat exchangers can accommodate a wide range of fluids.

There are three main disadvantages to their employment. Because of the gasket, they are vulnerable to leakage and hence must be used at low pressures. The rather small equivalent diameter of the passages makes the pressure loss relatively high, and the plate and frame heat exchanger may require a substantial investment in the pumping system, which may make the exchanger costwise noncompetitive.



(*a*) (*b*)

Figure 11.32 Typical plates in plate and frame (gasketed-plate) heat exchanger (*a*) Intermating or washboard type and (*b*) Chevron or herringbone type. (From Saunders, 1988, with permission.)

4

HVAC Equipment and Systems

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4.1 Heating Systems

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This chapter discusses equipment used for producing heat from fossil fuels, electricity, or solar power. The emphasis is on design-oriented information, including system characteristics, operating efficiency, the significance of part load characteristics, and criteria for selecting from among the vast array of heat producing equipment available.

The heating plants discussed in this chapter are often called the *primary systems*. Systems intended to distribute heat produced by the primary systems are called *secondary systems* and include ducts and pipes, fans and pumps, terminal devices, and auxiliary components. Such secondary systems for heating and cooling are described in Chapter 4.3. The terms *primary* and *secondary* are equivalent to the terms *plant* and *system* used by some building analysts and HVAC system modelers.

The goal of this chapter is to have the reader understand the operation of various heat generation or transfer systems and their performance:

- Furnaces
- Boilers
- Heat pumps
- Heat exchangers
- Part load performance and energy calculations for each

In addition to energy consumption, the designer must also be concerned with a myriad of other factors in furnace selection. These include:

- Air side temperature rise — affects duct design and air flow rate
- Air flow rate — affects duct design
- Control operation — for example, will night or unoccupied day/night setback be used or not? Is fan control by thermal switch or time delay relay?
- Safety issues — combustion gas control, fire hazards, high temperature limit switch

4.1.2 Boilers

A boiler is a device made from copper, steel, or cast iron to transfer heat from a combustion chamber (or electric resistance coil) to water in either the liquid phase, vapor phase, or both. Boilers are classified both by the fuel used and by the operating pressure. Fuels include gas, fuel oils, wood, coal, refuse-derived fuels, or electricity. This section focuses on fossil fuel fired boilers.

Boilers produce either hot water or steam at various pressures. Although water does not literally boil in hot water "boilers," they are called boilers, nevertheless. Steam is an exceptionally effective heat transport fluid due to its very large heat of vaporization and coefficient of heat transfer, as noted in Chapter 2.1.

Pressure classifications for boilers for buildings are

- *Low Pressure:* Steam boilers with operating pressures below 15 psig (100 kPa). Hot water boilers with pressures below 150 psig (1000 kPa); temperatures are limited to 250°F (120°C).
- *High Pressure:* Steam boilers with operating pressures above 15 psig (100 kPa). Hot water boilers with pressures above 150 psig (1000 kPa); temperatures are above 250°F (120°C).

Heat rates for steam boilers are often expressed in lb_m of steam produced per hour (or kW). The heating value of steam for these purposes is rounded off to 1000 Btu/lb_m. Steam boilers are available at heat rates of 50 to 50,000 lb_m of steam per hour (15 to 15,000 kW). This overlaps the upper range of furnace sizes noted in the previous section. Steam produced by boilers is used in buildings for space heating, water heating, and absorption cooling. Water boilers are available in the same range of sizes as are steam boilers: 50 to 50,000 MMBtu/hr (15 to 15,000 kW). Hot water is used in buildings for space and water heating.

Since the energy contained in steam and hot water within and flowing through boilers is very large, an extensive codification of regulations has evolved to assure safe operation. In the U.S. the ASME Boiler and Pressure Vessel Code governs construction of boilers. For example, the Code sets the limits of temperature and pressure on low pressure water and steam boilers listed above.

Large boilers are constructed from steel or cast iron. Cast iron boilers are modular and consist of several identical heat transfer sections bolted and gasketed together to meet the required output rating. Steel boilers are not modular but are constructed by welding various components together into one assembly. Heat transfer occurs across tubes containing either the fire or the water to be heated. The former are called *fire-tube boilers* and the latter *water-tube boilers*. Either material of construction can result in equally efficient designs. Small, light boilers of moderate capacity are sometimes needed for use in buildings. For these applications, the designer should consider the use of copper boilers.

Figure 4.1.2 shows a cross-section of a steam boiler of the type used in buildings.

Boiler Design and Selection for Buildings

The HVAC engineer must specify boilers based on a few key criteria. This section lists these but does not discuss the internal design of boilers and their construction. Boiler selection is based on the following criteria:

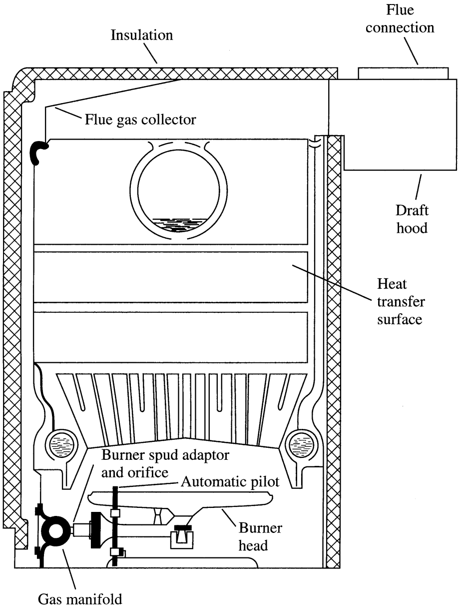

FIGURE 4.1.2 Boiler cross-sectional drawing showing burner, heat exchanger, and flue connection. (From Rabl, A. and Kreider J.F., *Heating and Cooling of Buildings*, McGraw-Hill, New York, NY, 1994. With permission.)

- *Boiler fuel* — type, energy content, heating value including altitude effects if gas fired (no effect for coal or fuel oil boilers).
- *Required heat output* — net output rating in MMBtu/hr (kW)
- Operating pressure and working fluid
- Efficiency and part load characteristics
- *Other* — space needs, control system, combustion air requirements, safety requirements, ASME code applicability

The boiler heat output required for a building is determined by summing the *maximum heating requirement* of all zones or loads serviced by the boiler during peak demand for steam or hot water and adding to that (1) parasitic losses including piping losses and (2) initial loop fluid warm-up. Simply adding all of the *peak heating unit capacities* of all the zones in a building can result in an oversized boiler since the zones do not all require peak heating simultaneously. The ratio of the total of all zone loads under peak conditions to the total heating capacity installed in a building is called the *diversity.*

Additional boiler capacity may be needed to recover from night setback in massive buildings. This transient load is called the *pickup* load and must be accounted for in both boiler and terminal heating unit sizing.

Boilers are often sized by their *sea-level input* fuel ratings. Of course, this rating must be multiplied by the applicable efficiency to determine the gross output of the boiler. In addition, if a gas boiler is not to be located at sea level, the effect of altitude must be accounted for in the rating. Some boiler designs use a forced draft burner to force additional combustion air into the firebox to offset part of the effect of altitude. Also, enriched or pressurized gas may be provided at high altitude so that the heating value per unit volume is the same as at sea level. If no accommodation to altitude is made, the output of a gas boiler drops by approximately 4% per 1000 ft (13% per km) of altitude above sea level. For example, a gas boiler located in Denver, Colorado (5000 ft, 1500 m) will have a capacity of only 80% of its sea level rating.

Table 4.1.2 shows the type of data provided by manufacturers for the selection of boilers for a specific project. Reading across the table, the fuel input needs are first tabulated for the 13 boiler models listed. The fifth column is the sea level boiler output at the maximum design heat rate. The next four columns

One method of avoiding the poor efficiency of this system would be to use two (or more) smaller boilers, the combined capacity of which would total the needed 7000 kBtu/h. Properly chosen, the smaller boilers would have operated more nearly at full load more of the time resulting in higher seasonal efficiency. However, smaller boilers cost more than one large boiler with the capacity equal to the total of the smaller boilers. Multiple boiler systems also offer standby security; if one boiler should fail, the other could carry at least part of the load. A single boiler system would entirely fail to meet the load.

The final decision must be made based on economics, giving proper account to the increased reliability of a system composed of several smaller boilers. Constraints are imposed on such decisions by initial budget, fuel type, owner and architect decisions, and available space.

4.1.3 Service Hot Water

Heated water is used in buildings for various purposes, including basins, sinks for custodial service, showers, and specialty services including kitchens in restaurants and the like. This section overviews service (or domestic) water heating methods for buildings. For details refer to ASHRAE (1999).

Water is heated by equipment that is either part of the space heating system, i.e., the boiler, or by a standalone water heater. The standalone equipment is similar to a small boiler except that water chemistry must be accounted for by use of anodic protection for the tank and by water softening in geographic areas where hardness can cause scale (lime) deposits in the water heater tank.

Two types of systems are used for water heating — *instantaneous* or *storage*. The former heats water on demand as it passes through the heater which uses either steam or hot water. Output temperatures can vary with this system unless a control valve is used on the heated water (not the heat supply) side of the water heater (usually a heat exchanger). Instantaneous water heaters are best suited to relatively uniform loads. They avoid the cost and heat losses of the storage tank but require larger and more expensive heating elements.

Storage type systems are used to accommodate varying loads or loads where large peak demands make it impractical to use instantaneous systems. Water in the storage tank is heated by an immersion steam coil, by direct firing, or by an external heat exchanger. In sizing this system, the designer must account for standby losses from the tank jacket and connected hot water piping. For any steam-based system cold supply water can be preheated using the steam condensate.

In order to size the equipment two items must be known:

- Hourly peak demand for the year — gal/hr, l/hr
- Daily consumption — gal/day, l/d

Of course, the volumetric usage rates must be converted to energy terms by multiplying by the specific heat and water temperature rise.

$$\dot{Q}_{water} = \dot{m}_{water} c_{water} (T_{set} - T_{source}) \qquad (4.1.13)$$

where

$\dot{Q}_{water}$ is the water heat rate, either on a daily or hourly basis; Btu/d or Btu/hr, kJ/d or W

$\dot{m}_{water}$ is the water mass flow rate, either on a daily or hourly basis, calculated from the volumetric flow listed above

$(T_{set} - T_{source})$ are the required hot water supply temperature and water source temperatures, respectively.

c_{water} is the specific heat of water

Table 4.1.6 summarizes water demands for various types of buildings, and Table 4.1.7 lists nominal set points of water heaters for several end uses. When using the lower settings in the table, the designer must be aware of the potential for *Legionella pneumophila* (Legionnaire's Disease). This microbe has been

TABLE 4.1.6 Hot Water Demands and Use for Various Types of Buildings

Type of building[a]	Maximum hour	Maximum day	Average day
Men's dormitories	3.8 gal (14.4 L)/student	22.0 gal (83.4 L)/student	13.1 gal (49.7 L)/student
Women's dormitories	5.0 gal (19 L)/student	26.5 gal (100.4 L)/student	12.3 gal (46.6 L)/student
Motels: No. of units[a]			
20 or less	6.0 gal (22.7 L)/unit	35.0 gal (132.6 L)/unit	20.0 gal (75.8 L)/unit
60	5.0 gal (19.7 L)/unit	25.0 gal (94.8 L)/unit	14.0 gal (53.1 L)/unit
100 or more	4.0 gal (15.2 L)/unit	15.0 gal (56.8 L)/unit	10.0 gal (37.9 L)/unit
Nursing homes	4.5 gal (17.1 L)/bed	30.0 gal (113.7 L)/bed	18.4 gal (69.7 L)/bed
Office buildings	0.4 gal (1.5 L)/person	2.0 gal (7.6 L)/person	1.0 gal (3.8 L)/person
Food service establishments:			
Type A: full-meal restaurants and cafeterias	1.5 gal (5.7 L)/max meals/h	11.0 gal (41.7 L)/max meals/h	2.4 gal (9.1 L)/average meals/h[c]
Type B: drive-ins, grilles, luncheonettes, sandwich and snack shops	0.7 gal (2.6 L)/max meals/h	6.0 gal (22.7 L)/max meals/h	0.7 gal (2.6 L)/average meals/day[c]
Apartment houses: No. of apartments			
20 or less	12.0 gal (45.5 L)/apt.	80.0 gal (303.2 L)/apt.	42.0 gal (159.2 L)/apt.
50	10.0 gal (37.9 L)/apt.	73.0 gal (276.7 L)/apt.	40.0 gal (151.6 L)/apt.
75	8.5 gal (32.2 L)/apt.	66.0 gal (250 L)/apt.	38.0 gal (144 L)/apt.
100	7.0 gal (26.5 L)/apt.	60.0 gal (227.4 L)/apt.	37.0 gal (140.2 L)/apt.
200 or more	5.0 gal (19 L)/apt.	50.0 gal (195 L)/apt.	35.0 gal (132.7 L)/apt.
Elementary schools	0.6 gal (2.3 L)/student	1.5 gal (5.7 L)/student	0.6 gal (2.3 L)/student[b]
Junior and senior high schools	1.0 gal (3.8 L)/student	3.6 gal (13.6 L)/student	1.8 gal (6.8 L)/student[b]

[a] The average usage of a U.S. residence is 60 gal/day (227 L/h) with a peak usage of 6 gal/h (22.7 L/h) (ASHRAE, 1987).

[b] Interpolate for intermediate values.

[c] Per day of operation. Temperature basis: 140°F.

Source: From ASHRAE. With permission.

TABLE 4.1.7 Representative Hot Water Use Temperatures

	Temperature	
Use	°F	°C
Lavatory		
Handwashing	105	40
Shaving	115	45
Showers and tubs	110	43
Therapeutic baths	95	35
Commercial and institutional laundry	180	82
Residential dishwashing and laundry	140	60
Surgical scrubbing	110	43
Commercial spray-type dishwashing		
Single or multiple tank hood(s) or rack(s)		
Wash	150 min	65 min
Final rinse	180–195	82–90
Single tank conveyor		
Wash	160 min	71 min
Final rinse	180–195	82–90

Note: Table values are water use temperatures, not necessarily water heater set points.
Source: From ASHRAE. With permission.

traced to infestations of shower heads; it is able to grow in water maintained at 115°F (46°C). This problem can be limited by using domestic water temperatures in the 140°F (60°C) range.

Hot water can be supplied from a storage type system at the maximum rate

$$\dot{V}_{water} = \dot{V}_r + \frac{f_{useful} V_{tank}}{\Delta t} \tag{4.1.14}$$

where

$\dot{V}_{water}$ is the volumetric hot water supply rate; gal/hr, l/s
$\dot{V}_r$ is the water heater recovery rate; gal/hr, l/s
f_{useful} is the useful fraction of the hot water in the tank before dilution lowers temperature excessively; 0.60–0.80
V_{tank} is the tank volume; gal, (L)
Δt is the duration of peak demand, h, (s)

Jacket losses are assumed to be small.

4.1.4 Electric Resistance Heating

Electricity can be used as the heat source in both furnaces and boilers. Electric units are available in the full range of sizes from small residential furnaces (5 to 15 kW) to large boilers for commercial buildings (200 kW to 20 MW). Electric units have four attractive features:

- Relatively lower initial cost
- Efficiency near 100%
- Near zero part load penalty
- Flue gas vents are not needed

The cost of electricity (both energy and demand charges, see Chapters 3.1 and 3.2) diminishes the apparent advantage of electric boilers and furnaces, however. Nevertheless, they continue to be installed where first cost is a prime concern. However, the prudent designer should consider the overwhelming life cycle costs of electric systems. Electric boiler and furnace sizing follows the methods outlined above for fuel-fired systems. In many cases, the thermodynamic and economic penalties of pure resistance heating can be reduced by using electric heat pumps, the subject of the next section.

Environmental concerns must also be considered when considering electric heating. Low conversion and transmission efficiencies (relative to direct combustion of fuels for water heating) result in relatively higher CO_2 emissions. SO_2 emissions from coal power plants are also an environmental concern.

4.1.5 Electric Heat Pumps

A *heat pump* extracts heat from environmental or other medium temperature sources (such as the ground, groundwater, or building heat recovery systems), raises its temperature sufficiently to be of value in meeting space heating or other loads, and delivers it to the load. This chapter emphasizes heat pumps used for space heating with outdoor air or groundwater as the heat source.

Figure 4.1.5 shows a heat pump cycle on the *T-s* diagram; Figure 4.1.6 shows it on the more frequently used p-h diagram. It is exactly the refrigeration cycle discussed in Chapter 2. Vapor is compressed in step 3-4 and heat is extracted from the condenser in step 4–1. This heat is used for space heating in the systems discussed in this section. In step 1-2, isenthalpic throttling takes place to the low side pressure. Finally, heat extracted from the environment, or other low temperature heat source, is used to boil the refrigerant in the evaporator in step 2-3.

An ideal Carnot heat pump would appear as a rectangle in the *T-s* diagram. The coefficient of performance (COP) of a Carnot heat pump is given in Chapter 2.1 which shows there to be inversely proportional to the difference between the high and low temperature reservoirs. The same result applies generally to heat pumps using real fluids. Although the high side temperature (T_1) remains essentially fixed (ignoring for now the effect of night thermostat setback), the low side temperature closely tracks the widely varying outdoor temperature. As a result, the *capacity and COP of air source heat pumps are strong functions of outdoor temperature.* This feature of heat pumps must be accounted for by the designer since heat pump capacity diminishes as the space heating load on it increases. Heat pumps can be

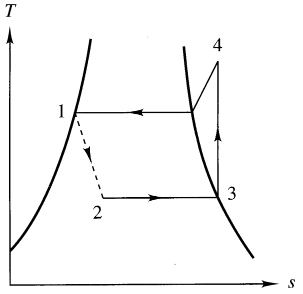

FIGURE 4.1.5 Heat pump T-s diagram showing four steps of the simple heat pump process. (From Rabl, A. and Kreider J.F., *Heating and Cooling of Buildings*, McGraw-Hill, New York, NY, 1994. With permission.)

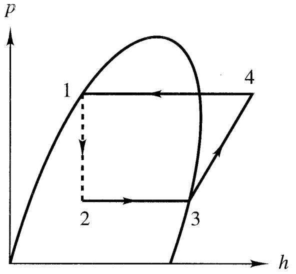

FIGURE 4.1.6 Heat pump p-h diagram showing four steps of the simple heat pump process. (From Rabl, A. and Kreider J.F., *Heating and Cooling of Buildings*, McGraw-Hill, New York, NY, 1994. With permission.)

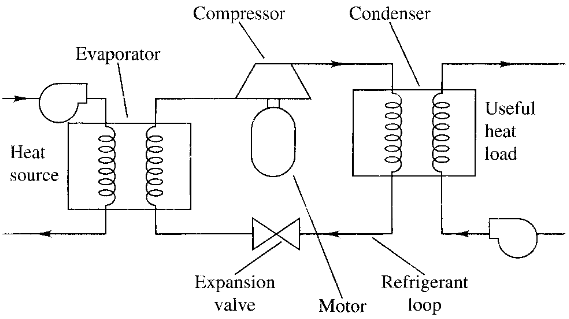

FIGURE 4.1.7 Liquid source heat pump mechanical equipment schematic diagram showing motor driven centrifugal compressor, condenser, and evaporator. (From Rabl, A. and Kreider J.F., *Heating and Cooling of Buildings*, McGraw-Hill, New York, NY, 1994. With permission.)

supplemented by fuel heat or electric resistance heating depending on the cost of each. Figure 4.1.7 shows a water source heat pump system that is not subject to outdoor temperature variations if groundwater or a heat recovery loop is used as the heat source.

The attraction of heat pumps is that they can deliver more thermal power than they consume electrically during an appreciable part of the heating season. In moderate climates requiring both heating and cooling, the heat pump can also be operated as an air conditioner, thereby avoiding the additional cost of a separate air conditioning system. Figure 4.1.8 shows one way to use a heat pump system for both heating and cooling by reversing flow through the system.

Typical Equipment Configurations

Heat pumps are available in sizes ranging from small residential units (10 kW) to large central systems (up to 15 MW) for commercial buildings. Large systems produce heated water at temperatures up to

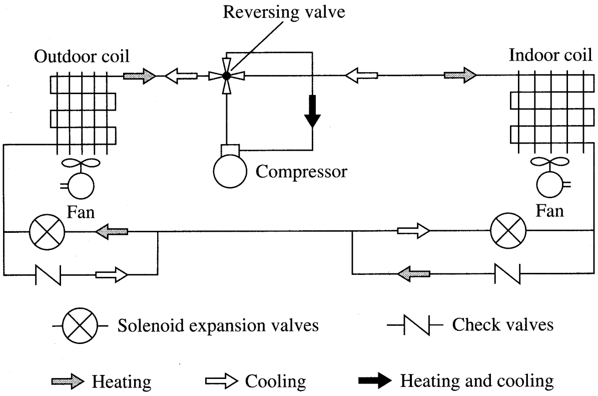

FIGURE 4.1.8 Air-to-air heat pump diagram. A reciprocating compressor is used. This design allows operation as a heat pump or an air conditioner by reversing the refrigerant flow. (From Rabl, A. and Kreider J.F., *Heating and Cooling of Buildings*, McGraw-Hill, New York, NY, 1994. With permission.)

220°F (105°C). Central systems can use both environmental and internal building heat sources. In many practical circumstances the heat gains in the core zones of a commercial building could satisfy the perimeter heat losses in winter. A heat pump could be used to efficiently condition both types of zones simultaneously.

Heat pumps require a compressor and two heat exchangers. In the energy bookkeeping that one does for heat pumps, the power input to the compressor is added to the heat removed from the low temperature heat source to find the heat delivered to the space to be heated. Increased heating capacity at low air source temperatures can be achieved by oversizing the compressor. To avoid part load penalties in moderate weather, a variable speed compressor drive can be used.

The outdoor and indoor heat exchangers use forced convection on the air side to produce adequate heat transfer coefficients. In the outdoor exchanger, the temperature difference between the boiling refrigerant and the air is between 10 and 25°F (6–14°C). If the heat source is internal building heat, water is used to transport heat to the heat pump evaporator and smaller temperature differences can be used.

A persistent problem with air source heat pumps is the accumulation of frost on the outdoor coil at coil surface temperatures just above the freezing point. The problem is most severe in humid climates; little defrosting is needed for temperatures below 20°F (–7°C) where humidities are below 60%. *Reverse cycle defrosting* can be accomplished by briefly operating the heat pump as an air conditioner (by reversing the flow of refrigerant) and turning the outdoor fan off. Hot refrigerant flowing through the outside melts the accumulated frost. This energy penalty must be accounted for in calculating the COP of heat pumps. Defrost control can be initiated either by time clock or, better, by a sensor measuring either the refrigerant condition (temperature or pressure) or, ideally, by the air pressure drop across the coil.

The realities of heat pump performance, as discussed above, reduce the capacity of real systems from the Carnot ideal. Figure 4.1.9 shows ideal Carnot COP values as a function of source temperature for a high side temperature of 70°F (21°C). The intermediate curve shows performance for a Carnot heat pump with real (i.e., finite temperature difference) heat exchangers. Finally, the performance of a real heat pump is shown in the lower curve. Included in the lower curve are the effects of heat exchanger losses, use of real fluids, compressor inefficiencies, and pressure drops. The COP of real machines is much lower (about 50%) than that for an ideal Carnot cycle with heat exchanger penalties.

The *energy efficiency ratio* EER is the ratio of heating capacity (Btu per hour) to the electric input rate (watts). EER thus has the units of Btu per watt-hour. The dimensionless COP is found from the EER by dividing it by the conversion factor 3.413 Btu/W · h.

Heat Pump Selection

The strong dependence of heat pump output on ambient temperature must be accounted for when selecting central plant equipment. If outdoor air is used as the heat source, peak heating requirements

TABLE 4.1.9 Heat Pump and Building Load Data – Example 4

Bin temp. °F	Heating load Btu/h	Heat pump COP	Heat pump output Btu/h	Heat pump input Btu/h	Auxiliary power Btu/h	Heating system COP
62	1,950	2.64	1,950	739	0	2.64
57	5,200	2.68	5,200	1,940	0	2.68
52	8,450	2.64	8,450	3,201	0	2.64
47	11,700	2.63	11,700	4,449	0	2.63
42	14,950	2.50	14,950	5,980	0	2.50
37	18,200	2.39	18,200	7,615	0	2.39
32	21,450	2.23	21,450	9,619	0	2.23
27[a]	24,700	2.07	24,700	11,932	0	2.07
22	27,950	1.97	25,100	12,741	2,850	1.79
17	31,200	1.80	22,400	12,444	8,800	1.47
12	34,450	1.70	19,900	11,706	14,550	1.31
7	37,700	1.54	17,600	11,429	20,100	1.20
2	40,950	1.39	15,400	11,079	25,550	1.12
–3	44,200	1.30	13,500	10,385	30,700	1.08
–8	47,450	1.17	11,700	10,000	35,750	1.04

[a] Heat pump balance point.

resistance heating. Use the bin data and heat pump performance data given in Table 4.1.9. The house heating base temperature is 65°F (18.3°C) accounting for internal gains. Figure 4.1.11 shows the energy flows as a function of outdoor temperature.

The preceding table includes these data in order:

1. Center point of temperature bin, T_{bin}
2. Heating demand, $\dot{Q} = K_{tot}(65°\text{F} - T_{bin})$
3. COP from manufacturer's data, a function of temperature, including defrost
4. Heat pump output; above the balance point, $\dot{Q}$; below the heat pump balance point, manufacturer's data
5. Heat pump input, the heat pump output divided by COP
6. Auxiliary power; the positive difference, if any, between $\dot{Q}$ and heat pump output
7. *Heating system* COP given by $\dot{Q}$ divided by the sum of auxiliary power and heat pump input

The energy calculations are summarized in Table 4.1.10. The bottom line in the table contains energy totals. With the heat pump, the total electricity requirement is 48.7 MBtu/yr (51.4 GJ/yr). If pure resistance heating were used, the total electricity requirement would be 98.36 MBtu/yr (103.8 GJ/yr).

The SPF for the heat pump is the seasonal output divided by the seasonal input to the heat pump:

$$\text{SPF}_{\text{hp}} = \frac{Q_{o,\text{yr}}}{Q_{i,\text{yr}}} = \frac{90.33\ \text{MBtu}}{40.66\ \text{MBtu}} = 2.22$$

The SPF for the heating system is the seasonal heat load divided by the seasonal input to the heat pump and the auxiliary heater:

$$\text{SPF}_{\text{sys}} = \frac{Q_{o,\text{yr}}}{Q_{i,\text{yr}} + Q_{i,\text{aux,yr}}} = \frac{98.36\ \text{MBtu}}{(40.66 + 8.03)\ \text{MBtu}} = 2.02$$

The advantage of a constant temperature heat source is apparent from this example. If ground water or building exhaust air (both essentially at constant temperature) were used as the heat source rather than outdoor air, there would not be a drop off in capacity as with the outdoor air source device just when heat is most needed.

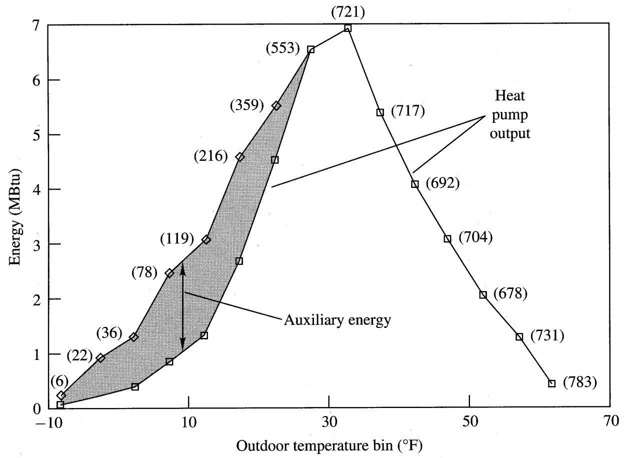

FIGURE 4.1.11 Heat pump energy use for the bin method example. The numbers at each bin temperature indicate the number of hours of occurrence in each bin. (From Rabl, A. and Kreider J.F., *Heating and Cooling of Buildings*, McGraw-Hill, New York, NY, 1994. With permission.)

TABLE 4.1.10 Heat Pump Energy Calculations – Example 4

Bin temp. °F	Bin hours h	Heating energy MBtu	Heat pump output MBtu	Heat pump input MBtu	Aux. heat input MBtu	Total input MBtu
62	783	1.53	1.53	0.58	0.00	0.58
57	731	3.80	3.80	1.42	0.00	1.42
52	678	5.73	5.73	2.17	0.00	2.17
47	704	8.24	8.24	3.13	0.00	3.13
42	692	10.35	10.35	4.14	0.00	4.14
37	717	13.05	13.05	5.46	0.00	5.46
32	721	15.47	15.47	6.94	0.00	6.94
27[a]	553	13.66	13.66	6.60	0.00	6.60
22	359	10.03	9.01	4.57	1.02	5.60
17	216	6.74	4.84	2.69	1.90	4.59
12	119	4.10	2.37	1.39	1.73	3.12
7	78	2.94	1.37	0.89	1.57	2.46
2	36	1.47	0.55	0.40	0.92	1.32
–3	22	0.97	0.30	0.23	0.68	0.90
–8	6	0.28	0.07	0.06	0.21	0.27
Total		98.36	90.33	40.66	8.03	48.70

[a] Heat pump balance point.

4.1.6 Low Temperature Radiant Heating

Heating systems in many parts of the world use warmed floors and/or ceilings for space heating in buildings. Although this system is unusual in the U.S., the good comfort and quiet operation provided by this approach make it worth considering for some applications. In Europe it is far more common. Radiant systems are well suited to operation with heat pump, solar, and other low temperature systems. This section discusses the principles of low temperature space heating. This form of heating is distinct from high temperature radiant heating using either electricity or natural gas to provide a high temperature source from which radiation can be directed for localized heating.

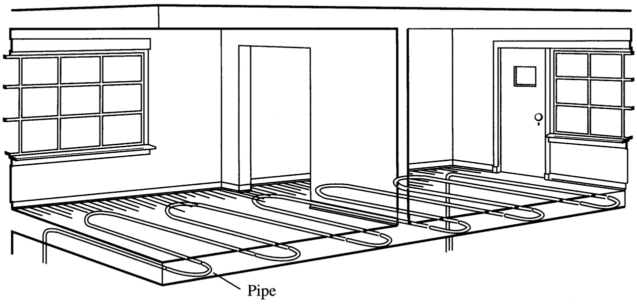

FIGURE 4.1.12 Residential radiant floor heating system. (From Rabl, A. and Kreider J.F., *Heating and Cooling of Buildings*, McGraw-Hill, New York, NY, 1994. With permission.)

Figure 4.1.12 shows how a radiant floor might be configured in a residence. The same concept can also be used in the ceiling in both residential and commercial buildings. The term *radiant* is a misnomer since between 30% (ceilings) and 50% (floors) of heat transferred from radiant panels is actually by convection. However, we will use the industry's nomenclature for this heating system.

The radiation heat output of radiant panels is given by the Stefan-Boltzmann equation as discussed in Chapter 2.1.

$$\dot{Q} = \in_{eff} F_{h,\,u}\sigma(T_h^4 - T_u^4) \tag{4.1.15}$$

where

$\in_{eff}$ is $1/[(1/\in_h + 1/\in_u) - 1]$, the effective emittance of the space, and the subscripts h and u refer to the unheated and heated (by radiant panels) surfaces of the space; the effective emittance is approximately 0.8.

$F_{h,u}$ is the view factor between the heating surface and the unheated surfaces; its value is 1.0 in the present case.

T_h is the heating surface temperature.

T_u is the mean of the unheated surface temperatures.

σ is the Stefan-Boltzmann constant (see Chapter 2).

Convection from the heating surface can be found using the standard free convection expressions in Chapter 2.1.

The designer's job is to determine the panel area needed, its operating temperature, the heating liquid flow rate, and construction details. The panel size is determined based on standard heat load calculations (Chapter 6.1). Proper account should be made of any losses from the back of the radiant panels to unheated spaces. Panel temperatures should not exceed 85°F (29.5°C) for floors and 115°F (46°C) for ceilings.

Water temperatures are typically 120°F (49°C) for floors and up to 155°F (69°C) for ceilings. Panels can be piped in a series configuration if pipe runs are not excessively long (the final panels in a long series run will not perform up to specifications due to low fluid temperatures). Long series loops also have excessively high pressure drops. If large areas are to be heated, a combination of series and parallel connections can be used. Manufacturers can advise regarding the number of panels that can be connected in series without performance penalties.

If radiant floors are to be built during building construction rather than using prefabricated panels in ceilings, the following guidelines can be used. Tubing spacing for a system of the type shown above should be between 6 and 12 in (15 and 30 cm). The tubing diameter ranges between 0.5 and 1.0 in (0.6 and 2.5 cm). Flow rates are determined by the rate of heat loss from the panel, which in turn depends on the surface temperature and hence the fluid temperature. This step in the design is iterative. Panel design follows this process:

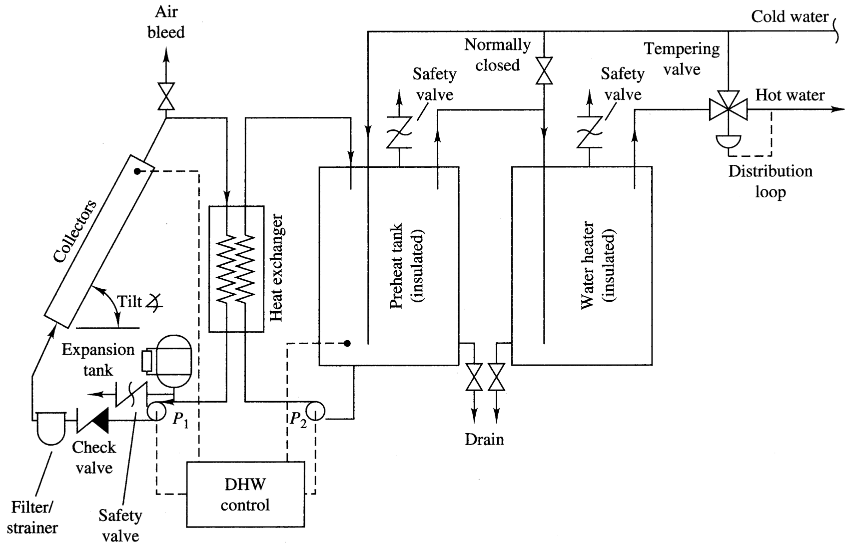

FIGURE 4.1.13 Solar water heating system including collectors, pumps, heat exchanger, and storage tanks along with piping and ancillary fittings. Collectors are tilted up from the horizontal at a fixed angle roughly equal to the local latitude. (From Rabl, A. and Kreider J.F., *Heating and Cooling of Buildings*, McGraw-Hill, New York, NY, 1994. With permission.)

- Determine room heat load.
- Decide on location of panels (roof or floor).
- Find panel heat flux including both radiation and convection contributions at 80°F (27°C) for floor panels and 110°F (43°C) for ceiling panels.
- Divide heat load by heat flux to find needed panel area.
- If panel area exceeds available floor or ceiling area, raise panel temperature (not exceeding temperatures noted earlier) and repeat steps 3 and 4.
- If the panel area is still insufficient, consider both floor and ceiling panels.

Control of radiant heating systems has proven to be a challenge in the past due to the large time constant of these systems. Both under- and overheating are problems. If the outdoor temperature drops rapidly, this system will have difficulty responding quickly. On the other hand, after a morning warmup followed by high solar gains on a sunny winter day, the radiant system may overshoot. The current generation of "smart" controls should help improve the comfort control of these systems.

4.1.7 Solar Heating

Solar energy is a source of low temperature heat that has selected applications to buildings. Solar water heating is a particularly effective method of using this renewable resource since low to moderate temperature water (up to 140°F, 60°C) can be produced by readily available, flat plate collectors (Goswami, Kreider, and Kreith, 2000).

Figure 4.1.13 shows one system for heating service water for residential or commercial needs using solar collectors. The system consists of three loops; it is instructive to describe the system's operation based on these three.

First, the collector loop (filled with a nonfreezing solution if needed) operates whenever the DHW controller determines that the collector is warmer, by a few degrees, than the storage tank. Heat is transferred from the solar-heated fluid by a counterflow or plate heat exchanger to the storage tank in the second loop of the system. Storage is needed since the availability of solar heat rarely matches the water heating load. The check valve in the collector loop is needed to prevent reverse flow at night in systems where the collectors (which are cold at night) are mounted above the storage tank.

The third fluid loop is the hot water delivery loop. Hot water drawn off to the load is replaced by cold water supplied to the solar preheat tank, where it is heated as much as possible by solar heat. If solar energy is insufficient to heat the water to its setpoint, conventional fuels can finish the heating in the water heater tank, as shown on the right of Figure 4.1.13. The tempering valve in the distribution loop is used to limit the temperature of water dispatched to the building if the solar tank should be above the water heater setpoint in summer.

The energy delivery of DHW systems can be found using the *f*-chart method described in Duffie and Beckman (1992). As a rough rule of thumb, one square foot of collector can provide one gallon of hot water per day (45 L/m^2) on the average in sunny climates. Design pump flows are to be 0.02 gal/min per square foot of collector [$0.01\ L/(s \cdot m^2)$], and heat exchanger effectivenesses of at least 0.75 can be justified economically. Tanks should be insulated so that no more than 2% of the stored heat is lost overnight.

Solar heating should be assessed on an economic basis. If the cost of delivered solar heat, including the amortized cost of the delivery system and its operation, is less than that of competing energy sources, an incentive exists for using the solar resource. The collector area needed on commercial buildings can be large; if possible, otherwise unused roof space can be used to hold the collector arrays. See Chapter 6.4 for a complete and detailed description of solar system analysis and design.

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4.2 Air Conditioning Systems

Dennis L. O'Neal and John A. Bryant

Air conditioning has rapidly grown over the past 50 years, from a luxury to a standard system included in most residential and commercial buildings. In 1970, 36% of residences in the U.S. were either fully air conditioned or utilized a room air conditioner for cooling (Blue, et al., 1979). By 1997, this number had more than doubled to 77%, and that year also marked the first time that over half (50.9%) of residences in the U.S. had central air conditioners (Census Bureau, 1999). An estimated 83% of all new homes constructed in 1998 had central air conditioners (Census Bureau, 1999). Air conditioning has also grown rapidly in commercial buildings. From 1970 to 1995, the percentage of commercial buildings with air conditioning increased from 54 to 73% (Jackson and Johnson, 1978, and DOE, 1998).

Air conditioning in buildings is usually accomplished with the use of mechanical or heat-activated equipment. In most applications, the air conditioner must provide both cooling and dehumidification to maintain comfort in the building. Air conditioning systems are also used in other applications, such as automobiles, trucks, aircraft, ships, and industrial facilities. However, the description of equipment in this chapter is limited to those commonly used in commercial and residential buildings.

Commercial buildings range from large high-rise office buildings to the corner convenience store. Because of the range in size and types of buildings in the commercial sector, there is a wide variety of equipment applied in these buildings. For larger buildings, the air conditioning equipment is part of a total system design that includes items such as a piping system, air distribution system, and cooling tower.

13.1 Introduction

Jay Lee and Robert Shafrik

Manufacturing is the means by which the technical and industrial capability of a nation is harnessed to transform innovative designs into well-made products that meet customer needs. This activity occurs through the action of an integrated network that links many different participants with the goals of developing, making, and selling useful things.

Manufacturing is the conversion of raw materials into desired end products. The word derives from two Latin roots meaning *hand* and *make*. Manufacturing, in the broad sense, begins during the design phase when judgments are made concerning part geometry, tolerances, material choices, and so on. Manufacturing operations start with manufacturing planning activities and with the acquisition of required resources, such as process equipment and raw materials. The manufacturing function extends throughout a number of activities of design and production to the distribution of the end product and, as necessary, life cycle support. Modern manufacturing operations can be viewed as having six principal components: materials being processed, process equipment (machines), manufacturing methods, equipment calibration and maintenance, skilled workers and technicians, and enabling resources.

There are three distinct categories of manufacturing:

- *Discrete item manufacturing*, which encompasses the many different processes that bestow physical shape and structure to materials as they are fashioned into products. These processes can be grouped into families, known as unit manufacturing processes, which are used throughout manufacturing.
- *Continuous materials processing*, which is characterized by a continuous production of materials for use in other manufacturing processes or products. Typical processes include base metals production, chemical processing, and web handing. Continuous materials processing will not be further discussed in this chapter.
- *Micro- and nano-fabrication*, which refers to the creation of small physical structures with a characteristic scale size of microns (millionths of a meter) or less. This category of manufacturing is essential to the semiconductor and mechatronics industry. It is emerging as very important for the next-generation manufacturing processes.

Manufacturing is a significant component of the U.S. economy. In 1995, 19% of the U.S. gross domestic product resulted from production of durable and nondurable goods; approximately 65% of total U.S. exports were manufactured goods; the manufacturing sector accounted for 95% of industrial research and development spending; and manufacturing industries employed a work force of over 19 million people in 360,000 companies. In the modern economy, success as a global manufacturer requires the development and application of manufacturing processes capable of economically producing high-quality products in an environmentally acceptable manner.

Modern Manufacturing

Manufacturing technologies address the capabilities to design and to create products, and to manage that overall process. Product quality and reliability, responsiveness to customer demands, increased labor productivity, and efficient use of capital were the primary areas that leading manufacturing companies throughout the world emphasized during the past decade to respond to the challenge of global competitiveness. As a consequence of these trends, leading manufacturing organizations are flexible in management and labor practices, develop and produce virtually defect-free products quickly (supported with global customer service) in response to opportunities, and employ a smaller work force possessing multidisciplinary skills. These companies have an optimal balance of automated and manual operations.

To meet these challenges, the manufacturing practices must be continually evaluated and strategically employed. In addition, manufacturing firms must cope with design processes (e.g., using customers' requirements and expectations to develop engineering specifications, and then designing components), production processes (e.g., moving materials, converting materials properties or shapes, assembling products or components, verifying processes results), and business practices (e.g., turning a customer order into a list of required parts, cost accounting, and documentation of procedures). Information technology will play an indispensable role in supporting and enabling the complex practices of manufacturing by providing the mechanisms to facilitate and manage the complexity of manufacturing processes and achieving the integration of manufacturing activities within and among manufacturing enterprises. A skilled, educated work force is also a critical component of a state-of-the-art manufacturing capability. Training and education are essential, not just for new graduates, but for the existing work force.

Manufacturing is evolving from an art or a trade into a science. The authors believe that we must understand manufacturing as a technical discipline. Such knowledge is needed to most effectively apply capabilities, quickly incorporate new developments, and identify the best available solutions to solve problems. The structure of the science of manufacturing is very similar across product lines since the same fundamental functions are performed and the same basic managerial controls are exercised.

13.2 Unit Manufacturing and Assembly Processes

Robert E. Schafrik

There are a bewildering number of manufacturing processes able to impart physical shape and structure to a workpiece. However, if these processes are broken down into their basic elements and then examined for commonality, only a few fundamental processes remain. These are the building blocks, or unit processes, from which even the most complicated manufacturing system is constructed. This section describes these unit processes in sufficient detail that a technically trained person, such as a design engineer serving as a member of an integrated product and process design team comprised of members from other specialties, could become generally knowledgeable regarding the essential aspects of manufacturing processes. Also, the information presented in this section will aid such an individual in pursuing further information from more specialized manufacturing handbooks, publications, and equipment/tool catalogs.

Considering the effect that a manufacturing process has on workpiece configuration and structure, the following five general types of unit manufacturing process can be identified (Altan et al., 1983; NRC, 1995):

Material removal processes — Geometry is generated by changing the mass of the incoming material in a controlled and well-defined manner, e.g., milling, turning, electrodischarge machining, and polishing.

Deformation processes — The shape of a solid workpiece is altered by plastic deformation without changing its mass or composition, e.g., rolling, forging, and stamping.

Primary shaping processes — A well-defined geometry is established by bulk forming material that initially had no shape, e.g., casting, injection molding, die casting, and consolidation of powders.

Structure-change processes — The microstructure, properties, or appearance of the workpiece are altered without changing the original shape of the workpiece, e.g., heat treatment and surface hardening.

Joining and assembly processes — Smaller objects are put together to achieve a desired geometry, structure, and/or property. There are two general types: (1) consolidation processes which use mechanical, chemical, or thermal energy to bond the objects (e.g., welding and diffusion bonding) and (2) strictly mechanical joining (e.g., riveting, shrink fitting, and conventional assembly).

Unit Process Selection

Each component being manufactured has a well-defined geometry and a set of requirements that it must meet. These typically include

- Shape and size
- Bill-of-material
- Accuracy and tolerances
- Appearance and surface finish
- Physical (including mechanical) properties
- Production quantity
- Cost of manufacture

In order to satisfy these criteria, more than one solution is usually possible and trade-off analyses should be conducted to compare the different approaches that could be used to produce a particular part.

Control and Automation of Unit Processes

Every unit process must be controlled or directed in some way. The need for improved accuracy, speed, and manufacturing productivity has spurred the incorporation of automation into unit processes regarding both the translation of part design details into machine instructions, and the operation of the unit process itself and as a subsystem of the overall production environment. The section of this chapter on computer-aided design/computer-aided manufacturing (CAD/CAM) discusses the technology involved in creating and storing CAD files and their use in CAM. The expectations of precision are continuing to change, as indicated in Figure 13.2.1. This drive for ever-tighter tolerances is helping spur interest in continual improvements in design and manufacturing processses.

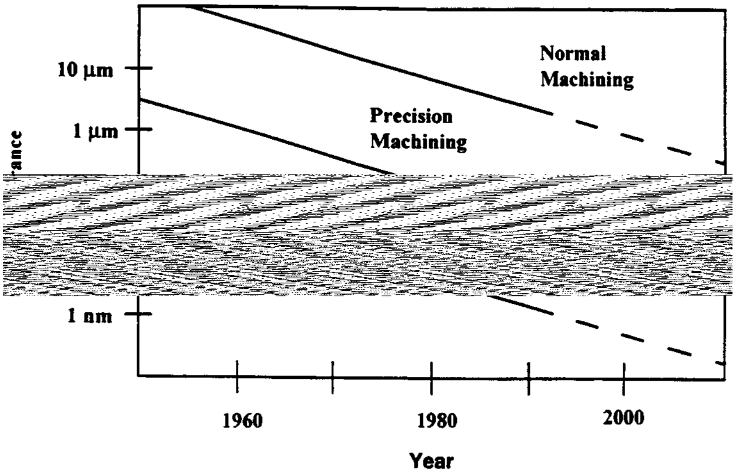

FIGURE 13.2.1 Precision machining domains. (From NRC, *Unit Manufacturing Processes,* National Academy Press, Washington, D.C., 1995, 169. With permission.)

Modern machine tool controls are emphasizing two areas: adaptive control and communication. For *adaptive control* the controller must adapt its control gains so that the overall system remains at or near the optimal condition in spite of varying process dynamics. Expanded *communication* links the data collected by a unit process controller to other segments of the manufacturing operation. Data regarding production time and quantity of parts produced can be stored in an accessible database for use by inventory control and quality monitoring. This same database can then be used by production schedulers to avoid problems and costs associated with redundant databases.

At the factory level, machining operations employing two or more numerically controlled (NC) machine tools may use a separate mainframe computer that controls several machine tools or an entire shop. The system is often referred to as *distributed numerical control* (DNC).

Today many factories are implementing *flexible manufacturing systems* (FMS), an evolution of DNC. An FMS consists of several NC unit processes (not necessarily only machine tools) which are interconnected by an automated materials handling system and which employ industrial robots for a variety of tasks requiring flexibility, such as loading/unloading the unit process queues. A single computer serves as master controller for the system, and each process may utilize a computer to direct the lower-order tasks. Advantages of FMS include:

- A wide range of parts can be produced with a high degree of automation
- Overall production lead times are shortened and inventory levels reduced
- Productivity of production employees is increased
- Production cost is reduced
- The system can easily adapt to changes in products and production levels

Unit Processes

In the following discussion, a number of unit processes are discussed, organized by the effect that they have on workpiece configuration and structure. Many of the examples deal with processing of metals since that is the most likely material which users of this handbook will encounter. However, other materials are readily processed with the unit processes described in this chapter, albeit with suitable modifications or variations.

Mechanical assembly and material handling are also discussed in this section. On average, mechanical assembly accounts for half of the manufacturing time, and processes have been developed to improve the automation and flexibility of this very difficult task. Material handling provides the integrating link between the different processes — material-handling systems ensure that the required material arrives at the proper place at the right time for the various unit processes and assembly operations.

The section ends with a case study that demonstrates how understanding of the different unit processes can be used to make engineering decisions.

- Material removal (machining) processes
  - Traditional machining
    Drill and reaming
    Turning and boring
    Planing and shaping
    Milling
    Broaching
    Grinding
    Mortality
  - Nontraditional machining
    Electrical discharge machining
    Electrical chemical machining
    Laser beam machining
    Jet machining (water and abrasive)
    Ultrasonic machining
- Phase-change processes
  - Green sand casting
  - Investment casting
- Structure-change processes
  - Normalizing steel
  - Laser surface hardening
- Deformation processes
  - Die forging
  - Press-brake forming
- Consolidation processes
  - Polymer composite consolidation
  - Shielded metal-arc welding
- Mechanical assembly
- Material handling
- Case study: Manufacturing and inspection of precision recirculating ballscrews

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1

Manufacturing Systems and Their Design Principles

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1.1 Introduction

Manufacturing has always been the key to success among nations in the world economy (Figure 1.1). A responsive manufacturing system working in harmony with the rest of an enterprise has a major impact on its competitiveness; it plays a vital role in the successful introduction of new products or continuous improvements of existing products in response to demands of the market (Cohen, 1987).

A wide variety of items are produced by manufacturing firms, depending upon the market demands they may be custom made or mass produced. Manufacturing systems used for their production are designed and tailored to specific requirements. Consequently, several manufacturing techniques are adopted to address new market demands.

This chapter is devoted to a high-level overview of manufacturing techniques, their objectives and design principles. In this regard, some of the available manufacturing techniques are explained and their achievements, advantages, and limitations are discussed. Due to the significant impact of computers on manufacturing, an effort is made to introduce the role of computers and information technology in modern manufacturing systems. In this regard, applications and functions of computers in various stages of product design, generation of the sequence of operations and process planning, control of the machines and monitoring of the processes (on/off line), automation, networking and communication systems, and quality control of the production systems are explained. Later in the chapter, the design principles of manufacturing systems and their components

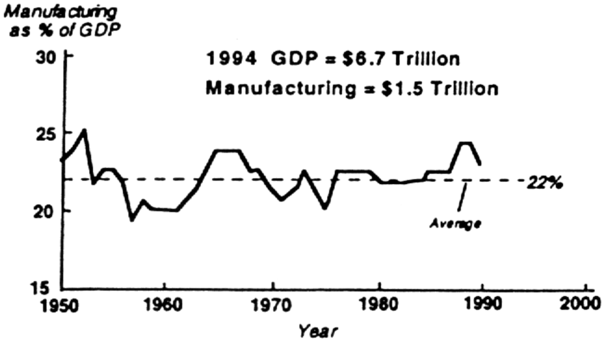

FIGURE 1.1 Despite assertions that the U.S. is becoming a service industry, manufacturing has consistently accounted for about 22% of GDP. (Source: U.S. Bureau of Labor Statistics.)

are presented as well as some of the issues related to their enabling technologies and barriers. The chapter concludes with a discussion of some of the future directions in manufacturing systems.

1.2 Major Manufacturing Paradigms and Their Objectives

New technological developments and market demands have major impacts on manufacturing. As a result, several shifts in the focus of manufacturing processes can be observed, which can be conveniently divided into three major epochs: (1) precomputer numerical control, (2) computer numerical control (CNC), and (3) knowledge epochs (Mehrabi and Ulsoy, 1997; Mehrabi, Ulsoy, and Koren, 1998). In the pre-CNC epochs (before the 1970s), the emphasis was on increased production rate; little demand existed for product variations and the market was characterized by local competition. Mass production uses dedicated lines designed for production of a specific part; it uses transfer line technology with fixed tooling and automation. The objective is to cost-effectively produce one specific part type at high volumes and with the required quality.

The emphasis on cost-effective production was supplemented with a focus on improved product quality in the CNC epoch (the 1970s and 1980s). Manufacturing was dramatically affected by the invention of CNC machines as they provide more accurate control and means for better quality. Japanese production techniques such as Kaizen (continuous improvement); just-in-time (JIT) (elimination/minimization of inventory as the ideal goal to reduce costs); lean manufacturing (efficiently eliminate waste, reduce cost, and improve quality control; and total quality management (TQM) (increased and faster communications with customers to meet their requirements) attracted considerable attention. Furthermore, CNC machines provided necessary tools for easier integration/automation which, in turn, contributed to manufacturing of a product family on the same system. Consequently, flexible manufacturing systems (FMSs) were introduced to address changes in work orders, production schedules, part programs, and tooling for the production of a family of parts. The economic objective of an FMS (see Figure 1.2) is to make possible the cost-effective manufacture of several types of parts that can change over time, with shortened changeover time, on the same system at the required volume and quality. It has a fixed hardware and fixed (but programmable) software (see Figure 1.3). In terms of design, the system possesses an integral architecture (hardware/software), i.e., the boundaries between the components and their functionalities are often difficult to identify and are tightly linked together. This type of architecture does not allow for reconfiguration changes to be made. Therefore, an FMS has limited capabilities for upgrading, add-ons, customization, and changes in production capacity.

In the knowledge epoch (i.e., starting in the 1990s), focus shifted to the responsiveness of a manufacturing system characterized by intensified global competition, the fast pace of technological innovations, and enormous progress in computer and information technology (Jaikumar, 1993; Mehrabi

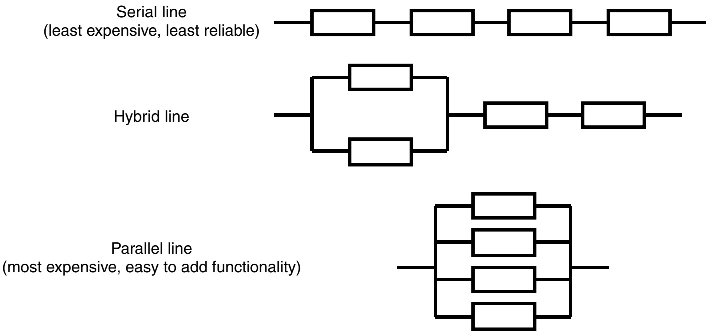

FIGURE 1.6 Several possible configurations with four machines.

1.5.2 Process Planning and System Design of Manufacturing Systems

Once a product design is completed, it is produced by using machines and other equipment (e.g., material handling) and resources. Computers are used extensively to identify optimal machining configurations by taking into account the cost, quality, and reliability of the entire system (see Figure 1.6), control the activities of planning and distributing the sequence of operations among the machines, and to specify machining parameters such as feed, speed, etc., computer-aided process planning (CAPP) (Bedworth, Handerson, and Wolfe, 1991; Vajpayee, 1995).

Two basic approaches to CAPP exist, variant and regenerative. The variant technique is used mostly for process planning of a family of products. With this technique, group technology (GT) is used to create and classify the plans (for a family of parts), and store them in a database. For the next design, the required plans are retrieved from the database already created for this family of parts (Groover and Zimmers, 1984). With the regenerative method, process plans are produced for every new product and as such, no database of plans exists (Gyorki, 1989; Vajpayee, 1995). It is more sophisticated than the variant method and has the advantage of facilitating integration of process planning stage with product design while the needs for human experts are minimized or totally eliminated.

1.5.3 Software/Hardware Architecture and Communications in Manufacturing Systems

An integral part of a manufacturing system is the software required to handle tasks at various levels such as control, monitoring, and communications among mechanical, electrical, and electronic components (low level) as well as higher level tasks such as process planning, user interface, process control, data collection/report from the process, etc. Therefore, the structure and functionality of the control software are very critical and directly affect the performance of the entire system. The controllers of the machines, networking and data communication between CNC controller/PLC (programmable logic controllers) or PLC/PLC, have been through proprietary networks (similar situation as with controllers); i.e., related control systems, communication systems, protocols, and software/hardware are not open to users or other vendors (Aronson, 1997; Altintas and Munasinghe, 1996). Therefore, further system enhancements, integration of sensors, and new technologies are severely restricted. Open-architecture principles and systems are introduced to accommodate these features (see Figure 1.7).

Another critical issue in the design of modern intelligent manufacturing systems is communication. Let us consider a set of sensors/devices communicating with a central computer/controller. Traditionally, they should be hard-wired to the central controller/PLC; therefore, the costs associated with wiring, connections, control cabinet, space, labor, maintenance, and trouble shooting are quite

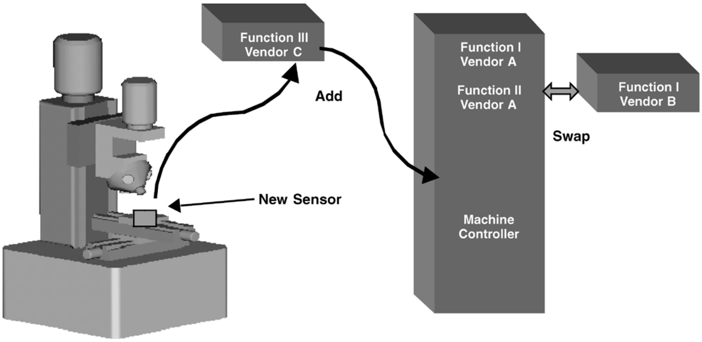

FIGURE 1.7 Open-architecture principle in machine tool control systems.

high. With a proper communication system, the same sensor/device is connected to a network (locally) which takes care of all data reporting and condition monitoring of the entire manufacturing system.

Recent developments in built-in intelligent control devices and communication networks, such as Devicenet, address some of these issues (Proctor and Albus, 1997; Proctor and Micholski, 1993). In the Devicenet network, local devices have built-in intelligence (with little cost) and their communication capabilities are enhanced. Therefore, control decisions/actions are made locally and the entire control system for manufacturing is decentralized. Also, progress is made in the development of standard terminology for message and instruction sets, such as manufacturing message specification (MMS), which is necessary for shop floor communication.

1.5.4 Monitoring and Control of Manufacturing Systems

One of the key factors in evaluating product quality is precision in machining. To achieve that, the cutting operation is tightly controlled by using real-time data collected from sensors located at different locations of the workpiece, tool, and machine. Also, some measurements are made for process monitoring purposes with the objective of preventing irrepairable damages to the workpiece and the machine. In general, real-time measurements of the following variables are required: dimensional errors, quality of surface finish, thermal deformations during machining, and dynamic deformations of the workpiece; chatter vibration, cutting force, condition of the chip, and identification of the cutting for process monitoring; thermal deformation, dynamic deformation of the machine elements, and structural vibration of the machine tool and wear, failure, and thermal deformations of the tool (Rangwala and Dornfeld, 1990; Li and Elbestawi, 1996).

Currently, commercially available controllers of CNC machines have been equipped with proprietary control systems; i.e., the users do not have access to the controller and further modifications/enhancements of the system (by the users) are either impossible or very costly. This has significantly hindered the applications of efficient control algorithms, addition of new sensors for process improvement/monitoring purposes, and has suppressed the automation of the entire production system. PC-based control systems (Koren et al., 1998; Hollenback, 1996) are the answer to the limitations mentioned above; they are very suitable for operating in an open-architecture environment (see Figure 1.7).

The same view is valid for programmable logic controllers (PLCs). To date, PLCs have been used in industrial automation to control and monitor discrete event systems. The functionality of PLCs can be enhanced, however, by proper implementation of available I/O boards (and compatible software) on a much more compact and industrial PC platform such as PC/104. This offers the advantage of integrating the functional logic (discrete) of PLCs and machine-tools' motion control (continuous) by utilizing modeling capabilities of Petri nets (Park et al., 1998) (see Figure 1.8).

Materials

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12.1 Metals

Victor A. Greenhut

Introduction — Nature and Properties of Pure Metals

Metals achieve engineering importance because of their abundance, variety, and unique properties as conferred by metallic bonding. Twenty-four of the 26 most abundant elements in the Earth's crust are

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0-8493-9418-X/98/$0.00+$.50

metals, with only two nonmetallic elements, oxygen and silicon, exceeding metals in frequency. The two most abundant metallic elements, iron (5.0%) and aluminum (8.1%), are also the most commonly used structural metals. Iron is the most-used metal, in part because it can be extracted from its frequently occurring, enriched ores with considerably less energy penalty than aluminum, but also because of the very wide range of mechanical properties its alloys can provide (as will be seen below). The next 15 elements in frequency, found at least in parts per thousand, include most common engineering metals and alloys: calcium (3.6%), magnesium (2.1%), titanium (0.63%), manganese (0.10), chromium (0.037%), zirconium (0.026%), nickel (0.020%), vanadium (0.017%), copper (0.010%), uranium (0.008%), tungsten (0.005%), zinc (0.004%), lead (0.002%), cobalt (0.001%), and beryllium (0.001%). The cost of metals is strongly affected by strategic abundance as well as secondary factors such as extraction/processing cost and perceived value. Plain carbon steels and cast irons, iron alloys with carbon, are usually most cost-effective for ordinary mechanical applications. These alloys increase in cost with alloying additions.

A variety of metal properties are unique among materials and of importance technologically. These properties are conferred by metallic bonding, in which the "extra" outer valence electrons are "shared" among all metal ion cores. This bonding is different from other types of solids in that the electrons are free to acquire energy, and the metallic ions are relatively mobile, and quite interchangeable with regard to their positions in the crystal lattice, the three-dimensional repeating arrangement of atoms in a solid. This section of the chapter will concentrate on the mechanical properties of metals, for which metallic bonding provides ductile deformation, i.e., shows substantial permanent shape change under mechanical load prior to fracture. The ductility of metals at low and moderate temperature makes them formable as solids and also confers safety (fracture toughness) in mechanical applications, in that under impact loading the metal will absorb energy rather than break catastrophically.

Metals are good conductors of heat and electricity because thermal and electrical energy can be transferred by the free electrons. These two properties tend to parallel each other. For example, the pure noble metals (e.g., copper, silver, gold, platinum) are among the best electrical and thermal conductors. As a broad generalization, metallic elements with an odd number of valence electrons tend to be better conductors than those with an even number. These behaviors can be seen in Table C.6A of the Appendix. Thermal conductivity and electrical resistivity (inverse conductivity) have a reciprocal relationship and follow the indicted trends. As metals are alloyed with other elements, are deformed, contain multiple phases, and contain crystalline imperfections, their electrical and thermal conductivity usually decreases significantly from that of the pure, perfect, unalloyed metal. The specific values of thermal conductivity and electrical resistivity for several common engineering alloys is given in Table C.6B of the Appendix. Electrical and thermal conductivities tend to decrease proportionately to each other with increasing temperature for a specific metal. These conductivities may be altered if heating introduces metallurgical change during annealing (see subsection on mechanical forming).

Metals are opaque to and reflective of light and most of the electromagnetic spectrum, because electromagnetic energy is transferred to the free electrons and immediately retransmitted. This gives most metals a characteristic reflective "metallic color" or sheen, which if the metal is very smooth yields a mirror surface. At very short wavelengths (high energies) of the electromagnetic spectrum, such as X rays, the radiant energy will penetrate the material. This is applied in radiographic analysis of metals for flaws such as cracks, casting porosity, and inclusions.

Metals are almost always crystalline solids with a regular repeating pattern of ions. A number of atomic-level defects occur in this periodic array. A large number of atomic sites are "vacancies" (point defects) not occupied by atoms (Figure 12.1.1). The number and mobility of vacant sites increase rapidly with temperature. The number and mobility of vacancies in metals are quite high compared with other materials because there are no charge balance or local electron bond considerations. This means that solid metal can undergo significant changes with only moderate thermal excitation as vacancy motion (diffusion) provides atom-by-atom reconstruction of the material. Vacancies allow solid metals to homogenize in a "soaking pit" after casting and permit dissimilar metals to diffusion bond at moderate temperatures and within short times. In the process, substitutional metallic atoms (ions) shown in Figure can vary over a very wide range. It is possible to manipulate the properties of a single metal composition over a very wide range in the solid state — a behavior which can be used to mechanically form a particular metal and then use it in a demanding load-bearing application. The use of minor alloying additions can provide a yet wider range of properties with appropriate thermal and mechanical treatment.

Casting

One of the important technological advantages of metals is their ability to incorporate a wide variety of secondary elements in a particular metal and thereby create alloys of the metal. Alloying can increase the strength of a metal by several orders of magnitude and permit the strength and ductility to be varied over a wide range by thermal and/or mechanical treatment, resulting in ease of mechanical forming or resistance to deformation.

Several metal phases may exist together in the solid as grains (crystals), or secondary phases may occur as smaller entities on grain (intercrystal) boundaries or within grains. Often the strengthening phase is submicroscopic and cannot be detected by optical metallography (reflection optical microscopy). The size and distribution of secondary phases is manipulated by thermomechanical (thermal and/or mechanical) treatment of the solid metal as well as the original casting procedure.

Casting methods include expendable mold casting (investment/precision, plaster mold, dry sand, and wet sand casting), permanent mold casting (ingot, permanent mold, centrifugal, and die casting), and continuous casting (direct chill and “splat” casting). These are listed in approximate order of cooling rate in Figure 12.1.2. As cooling rate increases, the grain (crystal) size tends to be smaller and the strength increases while compositional segregation decreases, providing more uniform properties. At the extremely high casting rates (10^5 to 10^6/sec) of continuous splat casting, it is possible to produce homogeneous metals not possible in terms of phase diagrams, and many metals have been produced in the amorphous state, yielding unusual metallic glasses. Ingot casting and continuous direct chill casting are primarily used to produce solid metal which will be extensively mechanically formed to final shape. The other casting methods are used to produce shapes near final dimensions, but to varying extends may receive extensive machining, forming, or finishing prior to use. For the latter group, grain refiners are frequently added to reduce solidification grain size. Metal tends to solidify directionally, with grains elongated in the direction of heat flow. This gives rise to directional mechanical properties which should be accounted for in design.

Comparison of Casting Methods

	Solidification Rate	Grain Size	Strength	Segregation
Expendable mold	Slow	Coarse	Low	Most
Investment	↓	↑	↓	↑
Plaster mold				
Dry sand				
Green sand				
Reusable mold				
Ingot				
Permanent mold				
Centrifugal				
Die cast				
Continuous — direct chill				
Continuous — splat cast	Fast	Fine	High	Least

FIGURE 12.1.2 The effects of casting speed (solidification rate) are compared.

To obtain optimum properties and prevent flaws which may cause failure, the casting procedure must avoid or control compositional segregation, shrinkage cavities, porosity, improper texture (grain directionality), residual (internal) stresses, and flux/slag inclusions. This can be accomplished with good casting practice. With the exception of investment (lost wax, precision) casting and to a lesser extent die casting, it is difficult to achieve very exacting tolerances and fine surface finish without postfinishing or forming of a casting.

Strength and Deformation, Fracture Toughness

Figure 12.1.3 shows a typical stress–strain diagram for a metal. The first portion is a linear, spring-type behavior, termed *elastic,* and attributable to stretching of atomic bonds. The slope of the curve is the "stiffness" (given for various metals in Table C.3 of the Appendix). The relative stiffness is low for metals as contrasted with ceramics because atomic bonding is less strong. Similarly, high-melting-point metals tend to be stiffer than those with weaker atomic bonds and lower melting behavior. The stiffness behavior is frequently given quantitatively for uniaxial loading by the simplified expressions of Hooke's law:

$$\varepsilon_x = \sigma_x / E \qquad \varepsilon_y = \varepsilon_z = -\upsilon \sigma_x / E \tag{12.1.1}$$

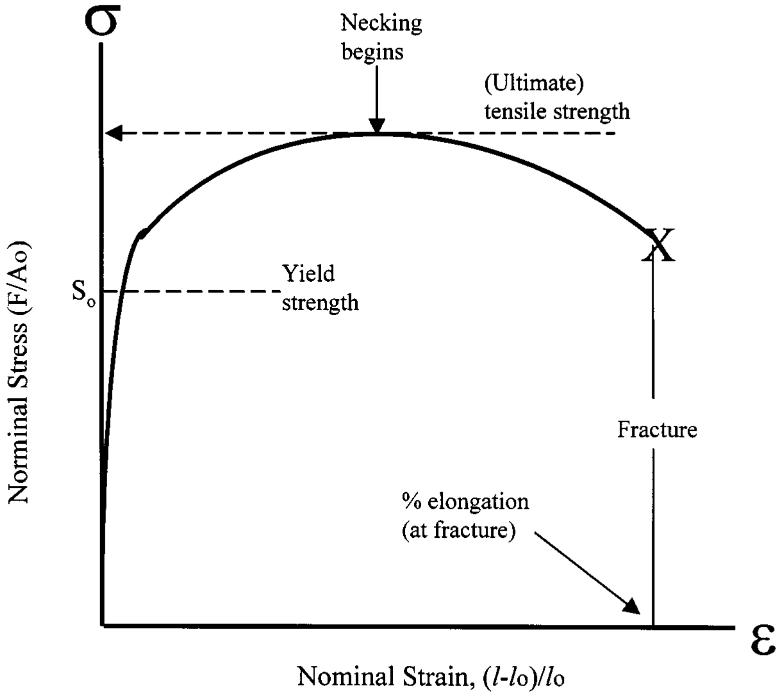

FIGURE 12.1.3 Typical engineering stress–strain curve for a metal.

Where σ_x is the stress (force per unit area, psi or Pa) in the *x* direction of applied unidirectional tensile load, ε_x is the strain (length per unit length or percent) in the same direction ε_y and ε_z are the contracting strains in the lateral directions, *E* is Young's modulus (the modulus of elasticity), and υ is Poisson's ratio. Values of the modulus of elasticity and Poisson's ratio are given in Table C.6A of the Appendix for pure metals and in C.6B for common engineering alloys. It may be noted that another property which depends on atomic bond strength is thermal expansion. As the elastic modulus (stiffness) increases with atomic bond strength, the coefficient of linear expansion tends to decrease, as seen in Table C.6.

The relationship of Equation (12.1.1) is for an isotropic material, but most engineering metals have some directionality of elastic properties and other structure-insensitive properties such as thermal expansion coefficient. The directionality results from directional elongation or preferred crystal orientation, which result from both directional solidification and mechanical forming of metals. In most cases two elastic moduli and a Poisson's ratio are required to fully specify behavior. A principal modulus might be given in the rolling direction of sheet or plate with a secondary modulus in the transverse direction. A difference of 2 to 5% should ordinarily be expected, but some metals can show an elastic modulus difference as great as a factor of 2 in the principal directions of heavily formed material. Such directional differences should be accounted for when spring force or dimensional tolerance under load (or change of temperature) is critical in a design.

At a critical stress the metal begins to deform permanently, as seen as a break in the straight-line behavior in the stress-strain diagram of Figure 12.1.3. The stress for this onset is termed the yield stress or elastic limit. For engineering purposes it is usually taken at 0.2% plastic strain in order to provide a predictable, identifiable value. An extensive table of yield values and usual applications for commercial metals and alloys is given in Appendix C.5. In the case of steel a small yield drop allows for clear identification of the yield stress and this value is used. The onset of yield is a structure-sensitive property. It can vary over many orders of magnitude and depends on such factors as grain size and structure, phases present, degree of cold work, and secondary phases in grains or on grain boundaries as affected by the thermal and mechanical treatment of the alloy. The extension to failure, the ductility, and maximum in the stress–strain curve, the "ultimate stress" or "tensile strength" (see Appendix C.5) are also structure-sensitive properties. The strength and specific strength (strength-to-weight ratio) generally decrease with temperature.

The ductility usually decreases as the strength (yield or ultimate) increases for a particular metal. Reduction in the grain size of the metal will usually increase yield stress while decreasing ductility (Figure 12.1.4). Either yield or ultimate strength are used for engineering design with an appropriate safety factor, although the former may be more objective because it measures the onset of permanent deformation. Ductility after yield provides safety, in that, rather than abrupt, catastrophic failure, the metal deforms.

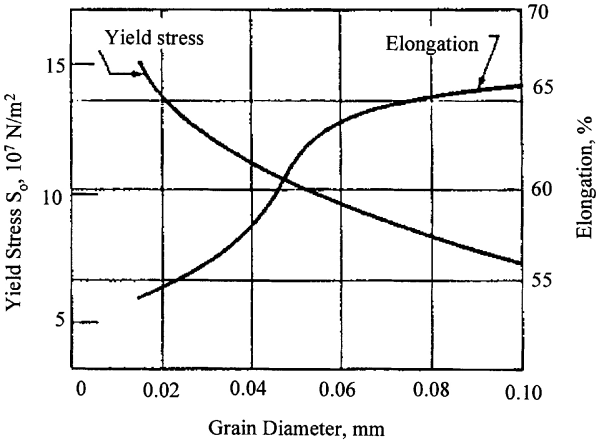

FIGURE 12.1.4 The effect of grain (crystal) size on yield stress and elongation to failure (ductility) for cartridge brass (Cu–30 Zn) in tension.

A different, independent measure is needed for impact loads — "toughness." This is often treated in design, materials selection, and flaw evaluation by extending Griffith's theory of critical flaw size in a brittle material:

$$\sigma_f = K_{1c}/\gamma c^{1/2} \tag{12.1.2}$$

where σ_f is the failure stress, K_{Ic} is a structure-sensitive materials property, the "fracture toughness" or "stress intensity factor" for a normal load, γ is a constant depending on orientation, and c is the depth of a long, narrow surface flaw or crack (or half that of an internal flaw). This is a separate design issue from that of strength. It is of particular importance when a metal shows limited ductility and catastrophic failure must be avoided. In some applications the growth of cracks, c is monitored to prevent catastrophic failure. Alternatively, as a performance test sufficient energy absorption as characteristic of a metal is determined when it is fractured in a Charpy or Izod impact test. Many metals will show a rapid decline in such energy absorption below a nil ductility temperature (NDT), which may establish a lowest use temperature for a particular metal in a particular state and for a particular application. Welds are often qualified by impact tests as well as strength testing. Care must be taken to apply the impact test appropriate to an application.

Hardness, the resistance of the near surface of a metal to penetration by an indentor, is also employed as a mechanical test. Increased hardness can often be correlated with an increase in yield and ultimate strengths. Typical hardness values for a large number of commercial metals and alloys are provided in Appendix C.5. A hardness indent is frequently done to "determine" the strength of a steel, using "equivalency" tables. Great caution must be taken in applying such tables because while hardness is an easy test to perform, it measures a complex and interactive set of properties, increasing with strength, elastic modulus, and work hardening rate. It is also an observation of surface properties which may not be characteristic of the bulk metal — particularly thick-gauge steel used in tension. Surface-hardening treatments can make the simplistic use of an "equivalency" table particularly dangerous. Application to nonferrous metals is also problematic. If a hardness tested part is to be put into service, the placement of hardness indents (surface flaws) can cause permanent failure.

A summary of important engineering metals can be found in Appendix C.5. This extensive table provides strength, hardness, and applications information for many commercial metals in varied heat treatments.

Mechanical Forming

Hot working is used when major shape change, cross-section reduction, or texture (directional) properties are desired. Cold working is preferred when close tolerances and fine surface finish are needed. The cold-worked form of a metal typically shows higher yield and tensile strength, as can be seen for several alloys listed in Appendix C.5. Rolling, forging, and extrusion are primarily done hot, while shape drawing, extrusion, deep drawing, stretching, spinning, bending, and high-velocity forming are more commonly performed cold. Hot rolling between parallel rollers is used to reduce ingots to plates, sheets, strips, and skelp, as well as structural shapes, rail, bar, round stock (including thick-walled pipe), and wire. Sheet metal and threads on round or wire stock may be rolled to shape cold. Closed die hot forging employs dies with the final part shape, while open die forging (including swaging and roll forging) uses less-shaped dies. Coining, embossing, and hobbing are cold-forging operations used to obtain precision, detailed surface relief or dimensions. Generally, extrusion and die drawing require careful control of die configuration and forming rate and, in the latter case, lubricant system. Impact extrusion, hydrostatic extrusion, and deep drawing (thin-walled aluminum cans) permit very large precise dimensional and cross-section changes to be made cold in a single pass. Stretching, spinning, bending are usually used to shape sheet or plate metal and the spring-back of the metal due to elastic modulus must be accounted for to obtain a precise shape.

Solute, Dispersion, and Precipitation Strengthening and Heat Treatment

Alloying additions can have profound consequences on the strength of metals. Major alloying additions can lead to multiphase materials which are stronger than single-phase materials. Such metal alloys may also give very fine grain size with further strengthening of material. Small alloying additions may also substantially increase strength by solute strengthening as solid solution substitutional or interstitial atoms and or by particle strengthening as dispersion or precipitation hardening alloys.

Substitutional solute strengthening of copper by various atoms is shown in Figure 12.1.5. As the amount of an alloying element in solution increases, the strength increases as disloctions are held in place by the "foreign" atoms. The greater the ionic misfit (difference in size — Sn is a much larger ion than Ni), the greater the strengthening effect. The strength increase can be quite dramatic — as much as a 20-fold increase with a 1.5% addition to copper. Alternatively, a large addition of a very soluble element such as nickel can give major strengthening — monel, the Cu–70Ni alloy is more than four times stronger than pure copper (Figure 12.1.6). Interstitial solid solution carbon contributes to the strength of iron and is one contributor to strength in steels and cast irons. Solute strengthening can become ineffective in strengthening at elevated temperature relative to the absolute melting point of a metal as a result of rapid diffusion of substitutional and interstitial elements. The addition of more than one solute element can lead to synergistic strengthening effects, as this and other strengthening mechanisms can all contribute to the resistance of a metal to deformation.

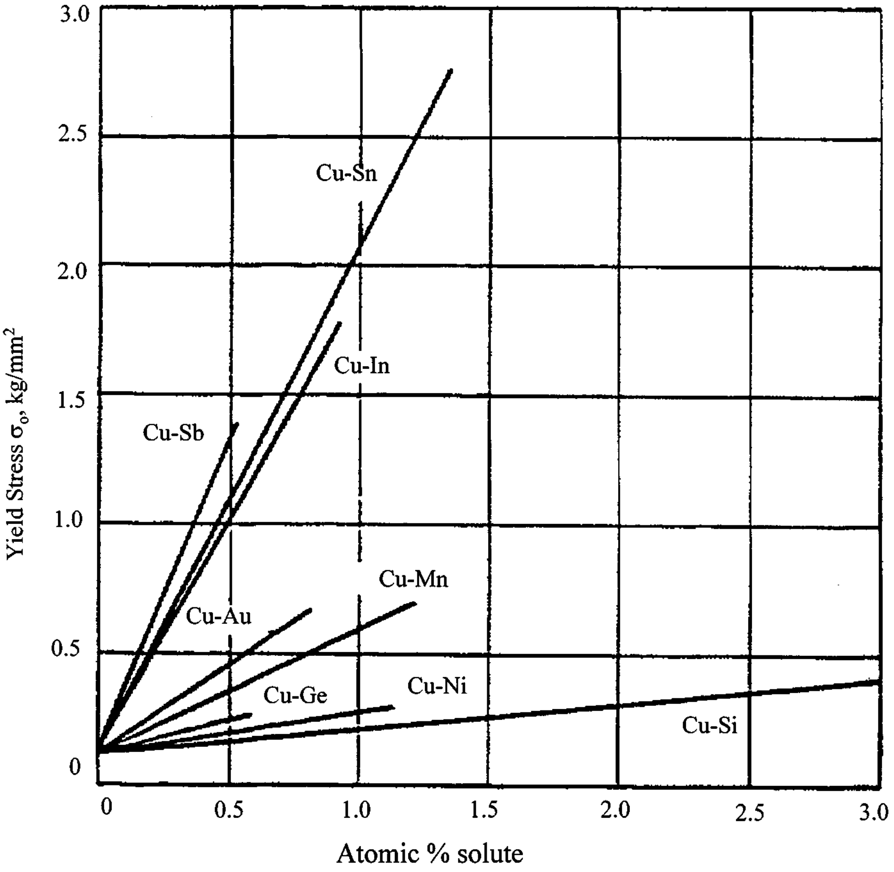

FIGURE 12.1.5 Effect of various substitutional atoms on the strength of copper. Note that as the ionic size of the substitutional atom becomes larger the strengthening effect becomes greater.

Ultrafine particles can also provide strengthening. A second phase is introduced at submicroscopic levels within each crystal grain of the metal. This may be done by a variety of phase-diagram reactions, the most common being precipitation. In this case the solid alloy is heated to a temperature at which the secondary elements used to produce fine second-phase particles dissolve in the solid metal — this is termed *solution heat treatment*. Then the metal is usually quenched (cooled rapidly) to an appropriate

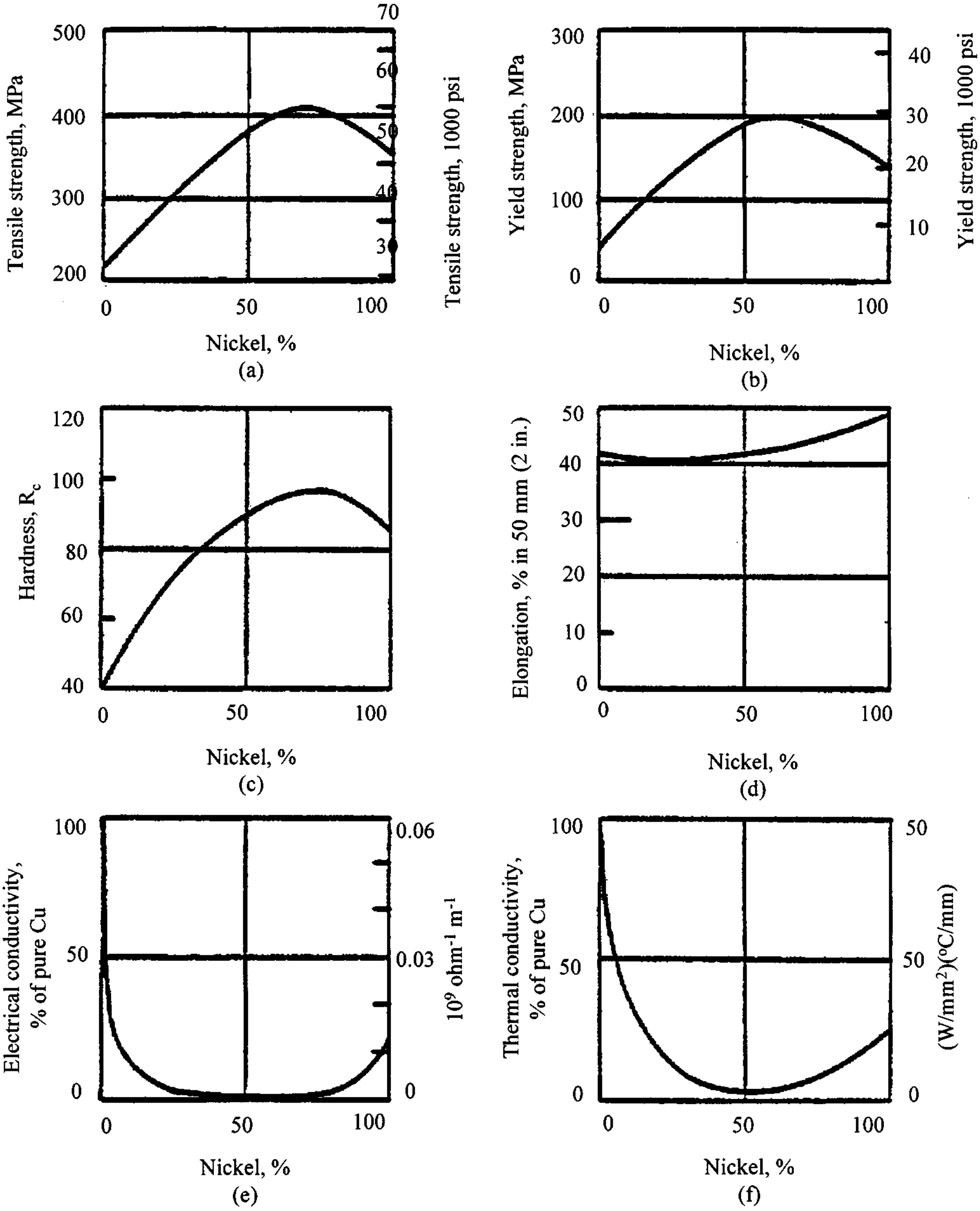

FIGURE 12.1.6 Variation in properties for copper–nickel random solid solution alloys. Note that over time at low temperature alloys (monel) may become nonrandom with significant strength increases.

temperature (e.g., room temperature or ice brine temperature) and subsequently held at an elevated temperature for a specified "aging" time during which particles precipitate and grow in size at near atomic levels throughout the solid metal. Temperature, time, alloy composition, and prior cold work affect the size and distribution of second-phase particles. The combination of treatments can be quite complex, and recently "thermomechanical treatments" combining temperature, time, and dynamic working have resulted in substantial property improvements. Heat treatment can be performed by the user, but it is difficult to achieve the optimum properties obtained by a sophisticated metallurgical mill. The heat treatment can manipulate structure and properties to obtain maximum strength or impact resistance. When metal is to be cold worked, a "softening treatment" can be employed which provides low yield stress and high ductility. The difference between the “dead soft” and maximum strength conditions can be over an order of magnitude — a useful engineering property change.

Alternative surface diffusion methods such as nitriding and carburizing, which introduce particles for fracture and wear resistance, are presented in the subsection on metal surface treatments.

In the case of dispersion strengthening (hardening), the fine strengthening particles are a discontinuous second phase without atomic continuity with the matrix. The behavior of such particles is shown schematically in Figure 12.1.7a as a function of increasing aging time or aging temperature (fixed time) which result in larger, more widely spaced dispersed-phase particles. Under stress, dislocations must move around (bypass) such particles, so that yield strength decreases with increased aging. Long aging times may be used to decrease yield strength (“soften”) of the metal for fabrication. A short aging time, would be used for maximum strength. The dispersed phase can also provide some enhancement of ductility. A dispersion-strengthened metal for which the dispersed phase is stable at elevated temperatures can provide both high-temperature strength and creep resistance (subsection on high-temperature effects). Surface diffusion treatments usually produce dispersion hardening.

Precipitation strengthening (hardening) employs particles which have at least some atomic continuity with the matrix metal. Thus, when the metal is deformed, dislocations can either bypass or pass through (cut) the particles. The resulting behavior is shown in Figure 12.1.7b. As aging time or temperature increases (particles grow larger and more widely spaced), the yield stress increases to a maximum and then decreases. The maximum is termed *critically aged*, and when this designation is part of an alloy treatment, precipitation strengthening may be assumed. For fabrication by cold working, the lower-strength, higher-ductility *underaged* condition is usually employed. There are different possible combinations of thermal and mechanical treatment which will provide a maximum critical aging treatment. Usually the best optimum for strength is given in handbooks and data sheets. However, improved treatments may be available, particularly of the combined thermomechanical type.

Strengthening of Steels and Steel Heat Treatment

Steels, perhaps the most important of all engineering metals, are alloys of iron and carbon usually containing about 0.02 to 1.0 $^w/_o$ carbon. The binary Fe–C phase diagram is important in describing this behavior and is shown in Figure 12.1.8. This diagram shows what phases and structures will occur in quasi equilibrium at various carbon contents and temperatures (under atmospheric pressure). Steel forming and heat treatment center on the transformation from austenite, γ phase, at elevated temperature to ferrite (α phase) plus cementite (iron carbide, Fe_3C) below 727°C (1340°F), the Ac_1 temperature, a eutectoid transformation. If there are no other intentional alloying elements, the steel is a “plain carbon” steel and has an AISI (American Iron and Steel Institute) designation 1002 to 10100. The first two characters indicate that it is a plain carbon steel, while the latter characters indicate the “points” of carbon.[*] Alloy steels, containing intentional alloying additions, also indicate the points of carbon by the last digits and together with the first digits provide a unique designation of alloy content. In the phase diagram (Figure 12.1.8) iron carbide (Fe_3C, cementite) is shown as the phase on the right. This is for all practical purposes correct, but the true thermodynamically stable phase is graphite (C) — relevant when the eutectic at 1148°C (2048°F) is used to produce cast irons (alloys greater than 2 $^w/_o$ C).

The solid-state eutectoid transformation is promoted by the magnetic effect in iron as nonmagnetic austenite transforms below the eutectoid (Ac_1) temperature to the two magnetic solid phases ferrite (iron with solid solution carbon) and cementite solid phase.[**] At the eutectoid composition, 0.77 $^w/_o$ carbon,

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[*] Plain carbon steels contain about 0.2 $^w/_o$ Si, 0.5 $^w/_o$ Mn, 0.02 $^w/_o$ P, and 0.02 $^w/_o$ S.

[**] It should be noted that austenitic stainless steels (300 and precipitation hardening, PH, series designations), nonmagnetic alloys with considerable chromium and nickel content to provide corrosion resistance, do not ordinarily transform from austenite to the lower-temperature phases. They are not intentionally alloyed with carbon, are not magnetic, and do not show the phase transformation strengthening mechanisms of steels. The term *steel* is something of a misnomer for these alloys.

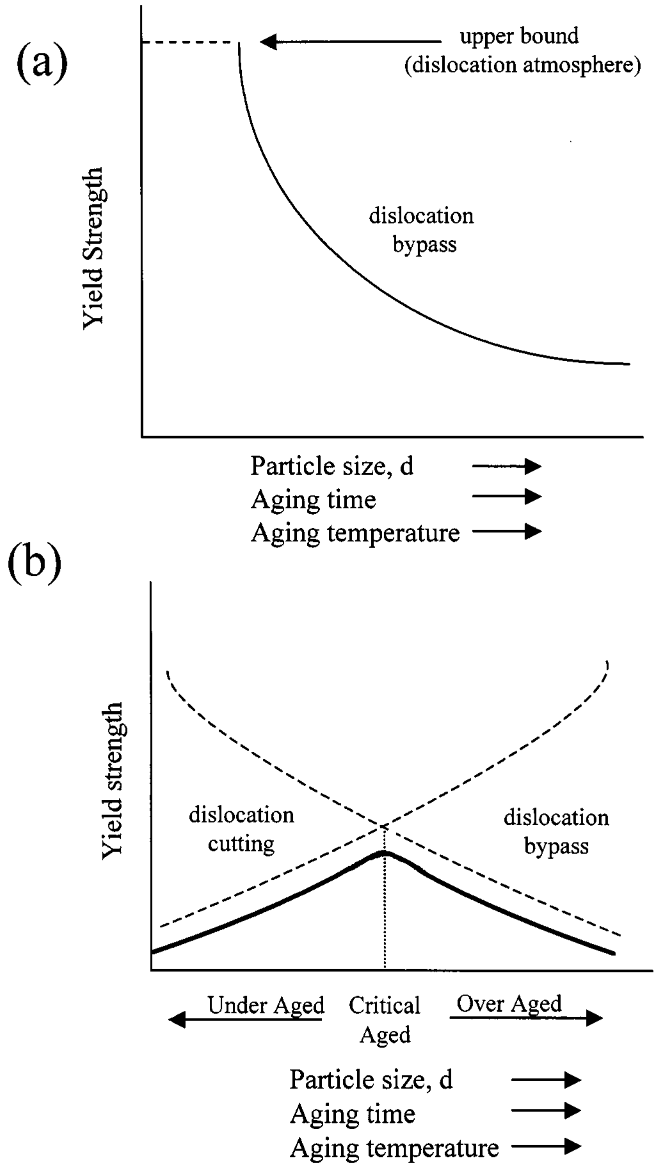

FIGURE 12.1.7 Effect of aging on dispersion- and precipitation-strengthened alloys for a fixed second–phase addition. (a) Dispersion strengthening: as aging time or temperature increases (dispersed phase particles larger and more separated), yield strength increases. A lower bound exists for near atomic size particles. (b) Precipitation hardening: two behaviors can occur giving a composite curve with a maximum at the critical aging time or temperature (optimum size and spacing of particles).

the two phases form as a fine alternating set of plates (lamellae) termed *pearlite* because of their pearllike appearance in a metallographic microscope. This two-phase structure of metal (ferrite) and carbide (cementite) provides strength (very slowly cooled — about 65 ksi, 14% tensile elongation), which increases as a more-rapid quenching yields a finer pearlite microstructure (to about 120 ksi). As strength increases, ductility and fracture toughness decrease. With yet more rapid quenching and more local atomic diffusion, the austenite transforms to bainite, a phase of alternating carbon and iron-rich atomic planes. This has yet higher strength (to about 140 ksi) and lower ductility. When the metal is quenched so rapidly that carbon diffusion is prevented, the austenite becomes unstable. Below a critical temperature,

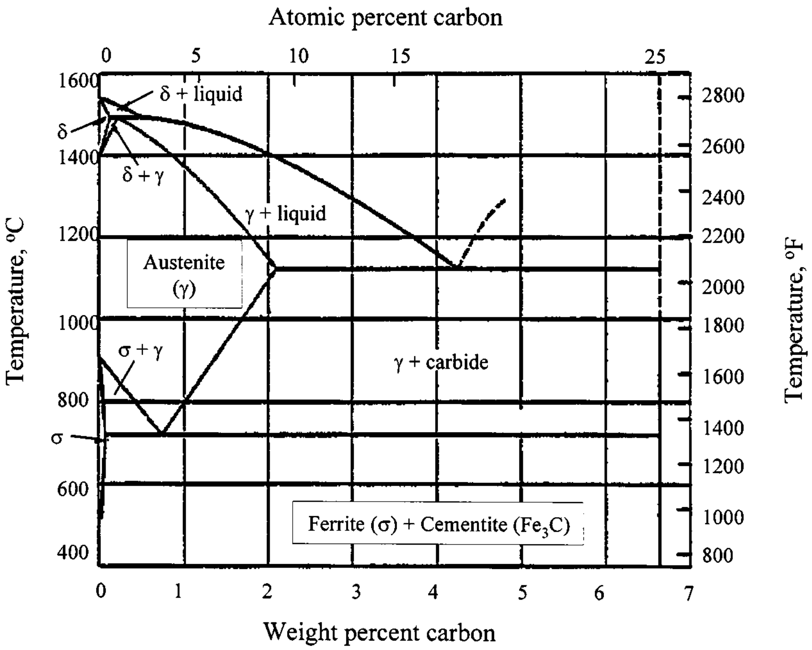

FIGURE 12.1.8 Iron–carbon phase diagram relevant for steel. The steel composition range is from about 0.02 to 1.00 ${}^{w}/_{o}$ carbon. Steel strengthening treatments require heating into the austenite region (above the Ac_3) and then quenching.

the martensitic start temperature (M_s), the metal transforms spontaneously by shear to martensite. Full transformation occurs below the martensite finish temperature (M_f). The formation of this hard phase introduces enormous microscopic deformation and residual stress. The strength is very much higher (about 300 ksi) but there is almost no ductility. This rapidly cooled material can spontaneously fail from "quench cracking," which results from residual stresses and the martensite acting as an internal flaw. To relieve stresses and provide some fracture toughness, martensitic steel is "tempered" at an intermediate temperature such as 500°C for about an hour to provide some ductility (about 7%) while sacrificing some strength (about 140 ksi). Tempering for shorter times or at lower temperatures can give intermediate properties. High-carbon steels are often used for cutting tools and forming dies because of their surface hardness and wear resistance. When a high-carbon steel (>0.7 ${}^{w}/_{o}$ C) requires fabrication at lower temperature, it may be held at a temperature just under the eutectoid for an extended time (e.g., for 1080 steel: 700°C, 1300°F — 100 hr) either after or without quenching to provide a soft condition (<60 ksi, 20% extension). A variety of different quenching temperatures, media, and procedures can be used to vary required combinations of the microstructures above and mechanical properties. The discussion above centered on eutectoid steel and holds for other high-carbon steels. Increasing carbon content favors the formation of martensite in steels, thereby providing increased strength, hardness, and wear resistance. However, such steels can be quite brittle.

At lower carbon content, "primary ferrite" forms (Figure 12.1.8) as the steel is quenched from above the boundary of austenitic (γ) region, the Ac_3. Subsequently, pearlite (ferrite and cementite), bainite, and/or martensite can form. Lower carbon content increases the amount of primary ferrite, a weaker/ductile phase, and decreases the tendency to form martensite, a stronger/brittle phase. The result is a more fracture tough, ductile ("safer") steel, but strength is lower. Such steels are also mechanically more forgiving if welded. Thus, a 1010 steel (0.10 ${}^{w}/_{o}$ C) might be used for applications where extreme "formability" and "weldability" are required, such as for car bodies and cans, while a 1020 steel (0.20 ${}^{w}/_{o}$ C) might be used for construction materials for which some increased strength is desired while maintaining safety. A medium-carbon steel such as a 1040 would be used when a balance of strength and toughness (and ease of welding) is needed.

In order to quench (and temper) steels continuous cooling transformation (CCT) diagrams are used such as that in Figure 12.1.9 for a 1040, medium-carbon steel. The steel is quenched from above the Ac_3. Vertical lines indicate quenching rates as shown in the lower left inset of the diagram. The cooling rate for the center of a round bar of given diameter quenched in air, oil, and water is given below the diagram. Solid lines on the diagram indicate percent transformation (start, 10%, 50%, 90%, finish of transformation), and a dotted line separates the region where primary ferrite forms from that of transformation to pearlite. The lower diagram shows the indentation hardness to be expected, as this and other mechanical behavior can be predicted from the CCT curve. As an example, the center of a 15 mm ($\sim ^1/_2$ in.) diameter bar quenched in air would be about 25% primary ferrite and 75% fine pearlite, with a Rockwell C hardness (HRC) of about 15. If quenched in oil, the bar center would be chiefly bainite with a small amount of martensite (HRC $\cong$ 25). The same bar quenched in water would be all martensite (HRC $\cong$ 55) before tempering. The transformation at other positions in the bar and for other engineering shapes (sheet, pipe, square rod, etc.) can be obtained from conversion curves.

It should be noted that layers in the steel closer to the quenched surface cool more quickly and are therefore displaced toward the left of the CCT diagram. There is a variation in structure and mechanical properties from the quenched surface to the center. One result is that the surface of the steel tends to be stronger, harder, and more wear resistant than the center. A steel beam undergoing bending has maximum strength at the near surface which undergoes the greatest stresses, while the center provides safety because of its relative fracture toughness and ductility. A thin knife edge cools quickly and can be resistant to deformation and wear, while the thick back prevents the blade from snapping in half when bent.

Many elements may be incorporated in steels to promote specific properties. Almost all common additions (other than cobalt) tend to promote strengthening by the formation of martensite (or bainite) instead of pearlite. When alloying additions tend to promote martensite throughout a thick section independent of cooling rate, the alloy is said to have *high hardenability.* Some elements such as chromium, molybdenum, and nickel also may help to provide high-temperature strength and environmental resistance. One class of alloys with relatively small alloying additions are termed *HSLA* steels (high strength, low alloy) and usually show somewhat superior mechanical properties to their plain carbon steel equivalents. As steel is alloyed, the relative cost increases substantially. A useful strategy in steel selection (and steels are usually the first engineering candidate on a cost basis) is to start by determining if a medium-carbon steel will do. If greater safety and formability are needed, a lower carbon content may be used (with slightly lower cost); alternatively, a higher-carbon steel would be chosen for greater strength and wear resistance. Heat treatment would be used to manipulate the properties. If plain carbon steels prove unsatisfactory, the HSLA steels would be the next candidate. For very demanding applications, environments, and long-term operations, specialty alloy steels would be selected insofar as they are cost-effective.

Fatigue

Fatigue is the repeated loading and unloading of metal due to direct load variation, eccentricity in a rotating shaft, or differential thermal expansion of a structure. Even substantially below the yield point (elastic limit) of a metal or alloy this repeated loading can lead to failure, usually measured in terms of the number of cycles (repeated load applications) to failure. Some studies have suggested that well over 80% of all mechanical failures of metal are attributable to fatigue.

High-stress, low-cycle fatigue usually occurs at stresses above the yield point and lifetimes are tens or hundreds of cycles (to about a thousand cycles). Failure occurs as a result of the accumulation of plastic deformation, that is, the area (energy) under the stress–strain curve (Figure 12.1.3). A simple lifetime predictive equation can be used to predict lifetime:

$$N \approx \left[\varepsilon_u / 2\varepsilon_{\text{pf}}\right]^2 \tag{12.1.3}$$

where N is the number of cycles to failure, ε_u is total strain from the stress–strain curve, and ε_{pf} is the plastic strain amplitude in each fatigue cycle.

More commonly, metals are used well below their yield point and fail after many, many cycles of repeated loading in low-stress, high-cycle fatigue. There is microscopic, local plastic deformation (cold working) and vacancy generation (recovery effects) during such cyclic loading which result in “fatigue hardening” (strengthening) of unworked metal and “fatigue softening” of unworked metal. Some have even found success relieving residual stressed with a vibratory anneal. Early in the fatigue process surface flaws or in some cases severe internal flaws begin to propagate. The fatigue crack propagates in areas of high stress a small, usually submicroscopic, distance with each tensile loading. The propagation on each cycle frequently leaves identifiable marking on the failure surface termed *fatigue striations* which mark the progress of the subcritical crack. When the crack becomes so large that the fracture toughness criterion is exceeded (Equation 12.1.2), catastrophic overload failure occurs. When the future fatigue loading can be predicted and the cyclic crack propagation rate is known, fatigue cracks can be inspected or monitored in different applications such as aircraft structures and pressure vessels to decommission or replace parts before fatigue failure. This must be done cautiously because a change to a more aggressive (corrosive, oxidative, elevated temperature) environment can increase the crack propagation rate. If a harmonic resonance occurs in the metal part, vibratory maxima can cause premature fatigue failure. Harmonics can change as fatigue cracks propagate. Harmonic vibration can be prevented with vibratory (dynamic) design concepts and/or direct monitoring.

Figure 12.1.10 shows typical metal S–N curves (stress vs. number of cycles to failure) for a high-strength aluminum and for a titanium alloy. Note that the convention is to make stress the vertical axis and to plot the number of cycles to failure on a logarithmic scale. For high-stress, low-cycle fatigue ($<10^3$ cycles) the curve is flat and linear, consistent with the model of Equation12.1.3. For high cycle fatigue the lifetime is a rapidly varying function of stress until very low stresses (long lifetimes occur). The actual fatigue life varies statistically about the mean value shown in approximate proportion to the number of cycles to failure. These curves are for testing in ambient air. Fatigue life would be longer in an inert environment and may be shortened drastically in an aggressive environment. Iron- and titanium-based alloys, such as the example shown, usually have an “endurance limit,” a stress below which lifetime is ostensibly infinite. In air, at room temperature, the endurance limit is about half the tensile strength for most iron and titanium alloys. Other metals appear to show no stress below which they last indefinitely. Therefore, a “fatigue limit” is designated — usually the stress at which the fatigue life is 10^8 cycles. This may be a long lifetime or not depending on the frequency of loading and engineering lifetime. The fatigue limit is generally about 0.3 times the tensile strength for metals with strengths below about 100 ksi (700 MPa). The factor is somewhat poorer for higher-strength metals. It is apparent that on a relative strength basis, iron- and titanium-based alloys are fatigue-resistant metals when compared with others. Dispersion-strengthened alloys have been seen to provide some lifetime advantage in fatigue.

A number of mathematical relationships have been proposed to predict fatigue life, but none works with complete success and all require experimental data. Perhaps the most successful of the so-called fatigue “laws” are the “cumulative damage” laws. The simplest is Miner’s law:

$$\sum i\left[n_i / N_i\right] = 1 \tag{12.1.4}$$

where n_i is the number of cycles applied and N_i is the number of cycles for failure at a particular stress level, σ_i. The conceptual basis is that the number of fatigue cycles at a stress level uses up its relative fraction of total fatigue lifetime and may be correlated to fatigue crack propagation (striation spacing). Modifications of this model account for the order and relative magnitude of loads. Several techniques

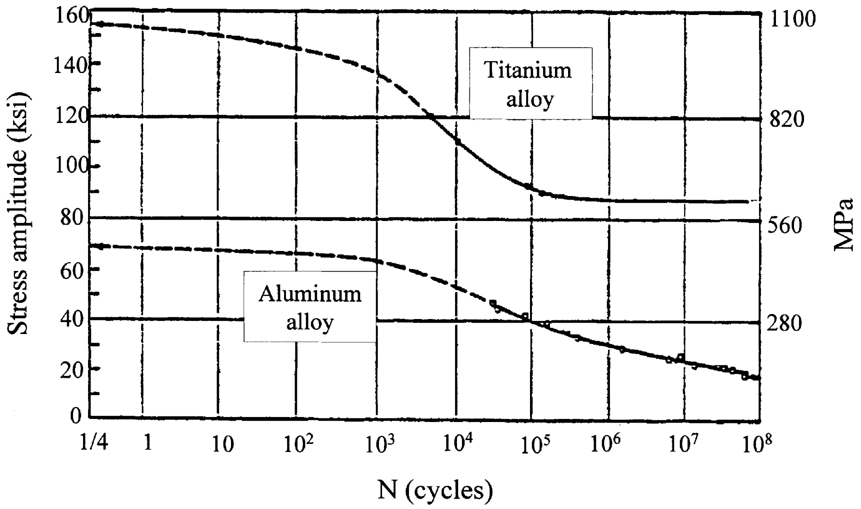

FIGURE 12.1.10 *S–N* (fatigue) curves for high-strength titanium (upper curve) and aluminum alloys. Note that titanium (and iron) alloys show an endurance limit, a stress below which the metal lasts indefinitely.

have met with partial success in increasing fatigue lifetime beyond that predicted by the cumulative damage models:

1. Coaxing — intermittent or continuous, superimposed vibration at very low stress,
2. Overstressing — intermittent or superimposed compressive loading,
3. Surface compression — intermittent shot peening or surface rolling,
4. Surface removal — chemical or mechanical surface polishing.

All but 1 are thought to close or eliminate fatigue cracks and surface damage. Coaxing has been said to introduce more of the vacancy-related recovery effects associated with fatigue.

High-Temperature Effects — Creep and Stress Rupture

Elevated temperature can cause a significant loss of strength and elastic modulus, so that a metal part may fail as a result of overheat even at loads which appear small at room temperature. High temperature is a relative matter and is usually judged as a fraction of the melting point measured on the absolute temperature scale. Thus, even moderate temperature excursions can be important for low-melting-point metals and alloys. As indicated in several sections above, many alloying and cold work strengthening methods depend upon heat treatment; an alloy can undergo metallurgical change due to overheat or to long-term holds at moderate temperatures and thereby alter properties significantly. Thus, the thermal stability of the microstructure should be determined. For example, metallographic replica techniques have been developed for determining in the field if microstructure has coarsened, making the metal weak.

Creep deformation is the continued deformation of a metal under load at elevated temperature, usually at a design stress well below the yield point. While measurable creep can occur at low temperatures over very long times or at very high (compressive) loads, creep usually becomes of engineering importance above about two thirds the melting point (absolute) of an alloy. Thus, both lead, which creeps at room temperature, and tungsten, which creeps in an incandescent light bulb at white heat, require a mechanical support or creep-resistant alloying additions. Figure 12.1.11 shows a schematic creep curve plotting creep strain* vs. time, *t*, at a particular tensile load and temperature. After the immediate elastic

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[*] If a constant extension is applied to an object, the force it generates will decline over time due to creep. This is called *stress relaxation* and can be treated in a similar way.

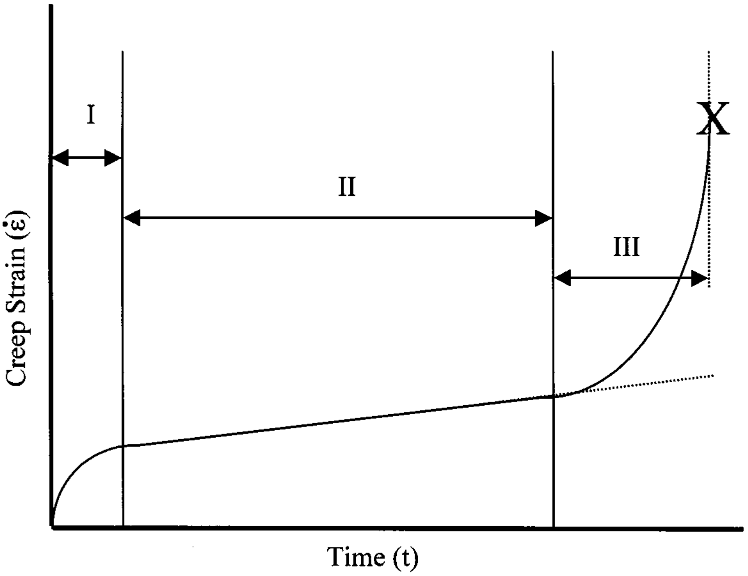

FIGURE 12.1.11 Schematic creep curve showing transient creep (I), steady-state creep (II), and tertiary creep (III). Note that the slope of the straight-line portion is the steady-state creep rate (minimum creep rate).

strain ($t = 0$), "transient creep" occurs in Region I. At elevated temperature this usually follows a $t^{1/3}$ behavior (Andrade creep). The majority of the curve has a straight-line behavior (Region II) in which the extension with time is constant. The slope of this part of the curve is termed the *steady-state strain rate* or *minimum creep rate*. It is used to calculate the creep extension which could cause functional failure when dimensional tolerances are exceeded. A simplified predictive model is

$$\varepsilon' = A\sigma^m e^{-h/kT} \tag{12.1.5}$$

where ε' is the minimum creep rate, A is a constant, σ is the applied stress, m is the stress dependence exponent (often 4 to 8), h is the activation enthalpy for creep, and T the absolute temperature.

In Region III the creep rate accelerates as the metal necks down severely in a local area, thereby increasing the local stress. The steady-state rate would continue (dotted line) if the load were adjusted to give constant load at the minimum cross section. Since loads do not readjust to compensate for necking in real applications, a final accelerated stage can be experienced. For example, a blowout can occur in late creep of a pressurized high-temperature piping system. The time to failure is termed the *stress rupture lifetime*. Predictive models are developed from Equation (12.1.5) to provide lifetime information.

Lowering use temperature or applied stress decreases susceptibility to creep deformation and increases stress rupture lifetime. Frequently, a moderate temperature decrease is most effective in this regard. Higher-melting-point metals are more creep resistant, so that the refractory metals tungsten and molybdenum can be used but require an inert atmosphere or protective coating to prevent rapid oxidation. In air or other active atmosphere, niobium-, nickel-, titanium-, and iron-based alloys may be used for creep resistance. Dispersion hardening, particularly with a high-temperature stable phase, such as an oxide, nitride, or carbide, can confer a degree of creep resistance.

Corrosion and Environmental Effects

Corrosion usually involves the slow removal of metal due to chemical and/or electrochemical reaction with an environment. Most metallic corrosion involves a galvanic, that is, electrochemical, component and localized attack in the form of pitting, attack in crevices, grain boundary attack, selective leaching of one phase, and exfoliation (attack parallel to the surface causing layers to peel away). Uniform corrosion is less common and also less of a concern as long as the rate of material removal is gradual and predictable.

Galvanic corrosion requires a medium, usually liquid (water), often containing a specific agent which promotes corrosion, a potential difference, and a complete electrical circuit, as well as an anode and a cathode. The anode will be the attacked, corroded, portion of the system. One cause for potential corrosion is dissimilar metals. For example, the galvanic series in seawater shows magnesium alloys as most anodic followed by zinc, aluminum, iron, nickel, brass, and copper alloys which are progressively more cathodic. When coupled electrically, the more-anodic metal would be corroded and the more cathodic would promote corrosion. One way of preventing corrosion is to isolate with insulator material the metal parts electrically so that a circuit is interrupted. The surfaces can be isolated from the corroding medium with paint, protective metal, conversion coatings, or a corrosion inhibitor additive to the liquid. In this situation it is more important to coat the cathode (noncorroding metal) since it impresses corrosion on the anodic metal dependent on exposed area. When in doubt, all parts should be painted repeatedly to prevent pinholes. Other possibilities include cathodic protection with an impressed electrical counterpotential or use of a sacrificial anode which is attacked instead of the metal components. Some metals such as stainless steels and aluminum alloys provide protection via an oxide coating, a *passive film*, which will form under specific, controlled electrochemical conditions providing *anodic protection*.

Another source for an anode and cathode can be the solution itself. Differences in temperature, ion concentration, oxygen content, and pH can all lead to a potential difference which results in corrosion. Often corrosion occurs far more rapidly for a specific range of solution concentration — indeed, sometimes dilution may accelerate corrosive attack. An oxygen deficiency cell under dirt or in a crevice frequently causes attack at the resulting anode. Potential differences can also exist in the metal itself: between different phases, inclusions, or grain chemistries; between grains and grain boundaries; between surface films and metal; and between different grain orientations. Selective leaching such as dezincification of high-zinc brasses (Cu–Zn) is an example for composition differences, while exfoliation corrosion of aluminum alloys and sensitized stainless steel are examples of grain boundary attack. Cold-worked metal tends to be anodic to annealed material so that a heavily formed part of a metal part may corrode preferentially.

Another important environmental cause of failure is stress corrosion cracking (SCC). A combination of applied or residual tensile stress and environmental attack results in progressive slow crack propagation over a period of time. Eventually, the crack becomes critical in size (Equation 12.1.2) and catastrophic failure occurs. There need be no evidence of corrosion for SCC to occur. When the loading is of a cyclic nature the effect is termed *corrosion fatigue*. To prevent these long-term crack propagation effects the environment and/or the source of tensile load may be removed. Considerable effort has been made to identify an ion concentration below which stress corrosion cracking will not occur (e.g., Cl for austenitic stainless steels), but there may be no level for complete immunity, merely a practical maximum permissible level.

Hydrogen embrittlement and hydrogen cracking can occur in the presence of stress and a hydrogen source. Embrittlement results when hydrogen diffuses into the metal and/or acts on the crack tip altering the fracture toughness. Hydrogen cracking may be regarded as a special case of stress corrosion cracking. Either environmental effect can lead to catastrophic failure. The source of hydrogen can be an acid solution, hydrogen evolved during corrosion, electrochemical treatment (plating, electropolishing), or hydrocarbons. Often isolation from the hydrogen source is difficult because hydrogen diffuses quickly through most materials and barrier coatings. Glass coating has met with some success.

Metal Surface Treatments

A number of treatments are employed to strengthen the surface of steels and make them more resistant to failure or wear. Some of the techniques may also be applied to selected nonferrous alloys. Flame, induction, and laser hardening provide intense heat to the outer surface of a medium- or high-carbon

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1.3 Dynamics

Stephen M. Birn and Bela I. Sandor

There are two major categories in dynamics, kinematics and kinetics. **Kinematics** involves the time- and geometry-dependent motion of a particle, rigid body, deformable body, or a fluid without considering the forces that cause the motion. It relates position, velocity, acceleration, and time. **Kinetics** combines the concepts of kinematics and the forces that cause the motion.

Kinematics of Particles

Scalar Method

The scalar method of particle kinematics is adequate for one-dimensional analysis. A particle is a body whose dimensions can be neglected (in some analyses, very large bodies are considered particles). The equations described here are easily adapted and applied to two and three dimensions.

Average and Instantaneous Velocity

The average velocity of a particle is the change in distance divided by the change in time. The instantaneous velocity is the particle's velocity at a particular instant.

$$v_{ave} = \frac{\Delta x}{\Delta t} \qquad v_{inst} = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt} = \dot{x} \tag{1.3.1}$$

Average and Instantaneous Acceleration

The average acceleration is the change in velocity divided by the change in time. The instantaneous acceleration is the particle's acceleration at a particular instant.

$$a_{ave} = \frac{\Delta v}{\Delta t} \qquad a_{inst} = \lim_{\Delta t \to 0} \frac{\Delta v}{\Delta t} = \frac{dv}{dt} = \dot{v} = \ddot{x} \tag{1.3.2}$$

Displacement, velocity, acceleration, and time are related to one another. For example, if velocity is given as a function of time, the displacement and acceleration can be determined through integration and differentiation, respectively. The following example illustrates this concept.

Example 8

A particle moves with a velocity $v(t) = 3t^2 - 8t$. Determine $x(t)$ and $a(t)$, if $x(0) = 5$.

Solution.

1. Determine $x(t)$ by integration

$$v = \frac{dx}{dt}$$

$$v\,dt = dx$$

$$\int 3t^2 - 8t\,dt = \int dx$$

$$t^3 - 4t^2 + C = x$$

$$\text{from } x(0) = 5 \qquad C = 5$$

$$x(t) = t^3 - 4t^2 + 5$$

2. Determine $a(t)$ by differentiation

$$a = \frac{dv}{dt} = \frac{d}{dt}\left(3t^2 - 8t\right)$$

$$a(t) = 6t - 8$$

There are four key points to be seen from these graphs (Figure 1.3.1).

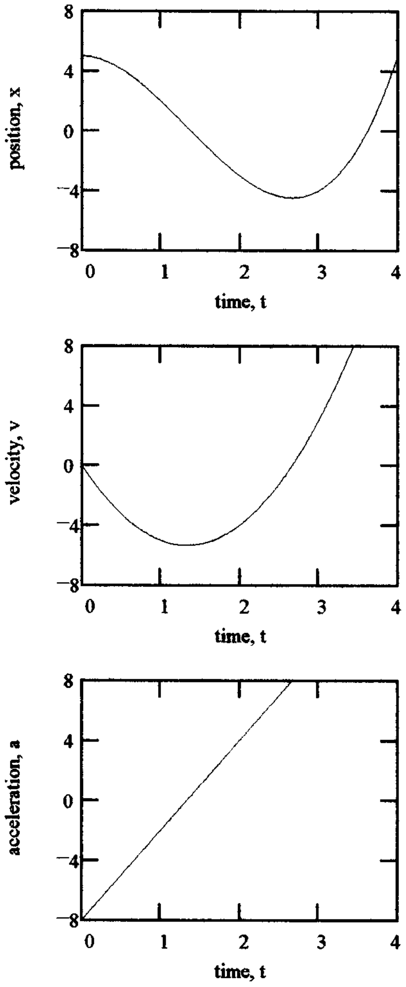


FIGURE 1.3.1 Plots of a particle's kinematics.

1. $v = 0$ at the local maximum or minimum of the x-t curve.
2. $a = 0$ at the local maximum or minimum of the v-t curve.
3. The area under the v-t curve in a specific time interval is equal to the net displacement change in that interval.
4. The area under the a-t curve in a specific time interval is equal to the net velocity change in that interval.

Useful Expressions Based on Acceleration

Equations for nonconstant acceleration:

$$a = \frac{dv}{dt} \Rightarrow \int_{v_0}^{v} dv = \int_{0}^{t} a\, dt \tag{1.3.3}$$

$$v\, dv = a\, dx \Rightarrow \int_{v_0}^{v} v\, dv = \int_{x_0}^{x} a\, dx \tag{1.3.4}$$

Equations for constant acceleration (projectile motion; free fall):

$$\begin{aligned} v &= at + v_0 \\ v^2 &= 2a\left(x - x_0\right) + v_0^2 \\ x &= \frac{1}{2}at^2 + v_0 t + x_0 \end{aligned} \tag{1.3.5}$$

These equations are only to be used when the acceleration is known to be a constant. There are other expressions available depending on how a variable acceleration is given as a function of time, velocity, or displacement.

Scalar Relative Motion Equations

The concept of relative motion can be used to determine the displacement, velocity, and acceleration between two particles that travel along the same line. Equation 1.3.6 provides the mathematical basis for this method. These equations can also be used when analyzing two points on the same body that are not attached rigidly to each other (Figure 1.3.2).

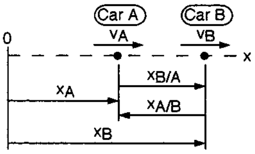


FIGURE 1.3.2 Relative motion of two particles along a straight line.

$$\begin{aligned} x_{B/A} &= x_B - x_A \\ v_{B/A} &= v_B - v_A \\ a_{B/A} &= a_B - a_A \end{aligned} \tag{1.3.6}$$

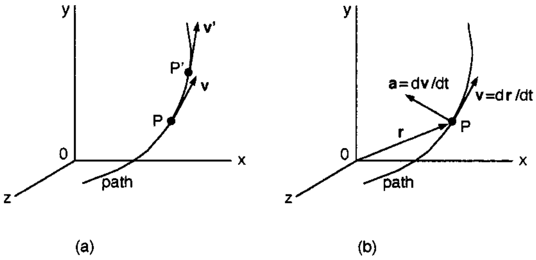
The notation B/A represents the displacement, velocity, or acceleration of particle B as seen from particle A. Relative motion can be used to analyze many different degrees-of-freedom systems. A degree of freedom of a mechanical system is the number of independent coordinate systems needed to define the position of a particle.

Vector Method

The vector method facilitates the analysis of two- and three-dimensional problems. In general, curvilinear motion occurs and is analyzed using a convenient coordinate system.

Vector Notation in Rectangular (Cartesian) Coordinates

Figure 1.3.3 illustrates the vector method.



(a) (b)

FIGURE 1.3.3 Vector method for a particle.

The mathematical method is based on determining **v** and **a** as functions of the position vector **r**. Note that the time derivatives of unit vectors are zero when the xyz coordinate system is fixed. The scalar components $(\dot{x}, \dot{y}, \ddot{x}, \ldots)$ can be determined from the appropriate scalar equations previously presented that only include the quantities relevant to the coordinate direction considered.

$$\mathbf{r} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$$

$$\mathbf{v} = \frac{d\mathbf{r}}{dt} = \frac{dx}{dt}\mathbf{i} + \frac{dy}{dt}\mathbf{j} + \frac{dz}{dt}\mathbf{k} = \dot{x}\mathbf{i} + \dot{y}\mathbf{j} + \dot{z}\mathbf{k} \tag{1.3.7}$$

$$\mathbf{a} = \frac{d\mathbf{v}}{dt} = \frac{d^2x}{dt^2}\mathbf{i} + \frac{d^2y}{dt^2}\mathbf{j} + \frac{d^2z}{dt^2}\mathbf{k} = \ddot{x}\mathbf{i} + \ddot{y}\mathbf{j} + \ddot{z}\mathbf{k}$$

There are a few key points to remember when considering curvilinear motion. First, the instantaneous velocity vector is *always* tangent to the path of the particle. Second, the speed of the particle is the magnitude of the velocity vector. Third, the acceleration vector is *not* tangent to the path of the particle and not collinear with **v** in curvilinear motion.

Tangential and Normal Components

Tangential and normal components are useful in analyzing velocity and acceleration. Figure 1.3.4 illustrates the method and Equation 1.3.8 is the governing equations for it.

$$\mathbf{v} = v\mathbf{n}_t$$

$$\mathbf{a} = a_t\mathbf{n}_t + a_n\mathbf{n}_n$$

$$a_t = \frac{dv}{dt} \qquad a_n = \frac{v^2}{\rho} \tag{1.3.8}$$

$$\rho = \frac{\left[1 + \left(dy/dx\right)^2\right]^{3/2}}{d^2y/dx^2}$$

$$\rho = r = \text{constant for a circular path}$$

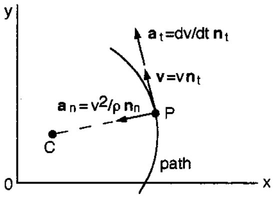


FIGURE 1.3.4 Tangential and normal components. *C* is the center of curvature.

The *osculating plane* contains the unit vectors $\mathbf{n}_t$ and $\mathbf{n}_n$, thus defining a plane. When using normal and tangential components, it is common to forget to include the component of normal acceleration, especially if the particle travels at a constant speed along a curved path.

For a particle that moves in circular motion,

$$\begin{aligned} v &= r\dot{\theta} = r\omega \\ a_t &= \frac{dv}{dt} = r\ddot{\theta} = r\alpha \\ a_n &= \frac{v^2}{r} = r\dot{\theta}^2 = r\omega^2 \end{aligned} \tag{1.3.9}$$

Motion of a Particle in Polar Coordinates

Sometimes it may be best to analyze particle motion by using polar coordinates as follows (Figure 1.3.5):

$$\begin{aligned} \mathbf{v} &= \dot{r}\mathbf{n}_r + r\dot{\theta}\mathbf{n}_\theta \qquad \text{(always tangent to the path)} \\ \frac{d\theta}{dt} &= \dot{\theta} = \omega, \ \ \text{rad/s} \\ \mathbf{a} &= \left(\ddot{r} - r\dot{\theta}^2\right)\mathbf{n}_r + \left(r\ddot{\theta} + 2\dot{r}\dot{\theta}\right)\mathbf{n}_\theta \end{aligned} \tag{1.3.10}$$

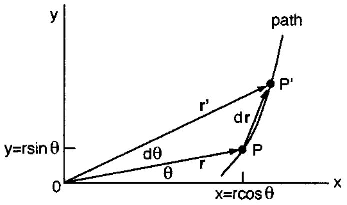


FIGURE 1.3.5 Motion of a particle in polar coordinates.

For a particle that moves in circular motion the equations simplify to

$$\begin{aligned} \frac{d\dot{\theta}}{dt} &= \ddot{\theta} = \dot{\omega} = \alpha, \ \ \text{rad/s}^2 \\ \mathbf{v} &= r\dot{\theta}\mathbf{n}_\theta \\ \mathbf{a} &= -r\dot{\theta}^2\mathbf{n}_r + r\ddot{\theta}\mathbf{n}_\theta \end{aligned} \tag{1.3.11}$$

Motion of a Particle in Cylindrical Coordinates

Cylindrical coordinates provide a means of describing three-dimensional motion as illustrated in Figure 1.3.6.

$$\begin{aligned} \mathbf{v} &= \dot{r}\mathbf{n}_r + r\dot{\theta}\mathbf{n}_\theta + \dot{z}\mathbf{k} \\ \mathbf{a} &= \left(\ddot{r} - r\dot{\theta}^2\right)\mathbf{n}_r + \left(r\ddot{\theta} + 2\dot{r}\dot{\theta}\right)\mathbf{n}_\theta + \ddot{z}\mathbf{k} \end{aligned} \tag{1.3.12}$$

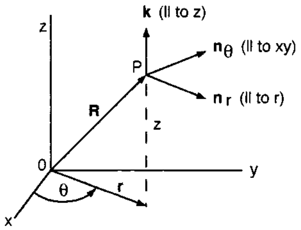


FIGURE 1.3.6 Motion of a particle in cylindrical coordinates.

Motion of a Particle in Spherical Coordinates

Spherical coordinates are useful in a few special cases but are difficult to apply to practical problems. The governing equations for them are available in many texts.

Relative Motion of Particles in Two and Three Dimensions

Figure 1.3.7 shows relative motion in two and three dimensions. This can be used in analyzing the translation of coordinate axes. Note that the unit vectors of the coordinate systems are the same. Subscripts are arbitrary but must be used consistently since $\mathbf{r}_{B/A} = -\mathbf{r}_{A/B}$ etc.

$$\begin{aligned} \mathbf{r}_B &= \mathbf{r}_A + \mathbf{r}_{B/A} \\ \mathbf{v}_B &= \mathbf{v}_A + \mathbf{v}_{B/A} \\ \mathbf{a}_B &= \mathbf{a}_A + \mathbf{a}_{B/A} \end{aligned} \tag{1.3.13}$$

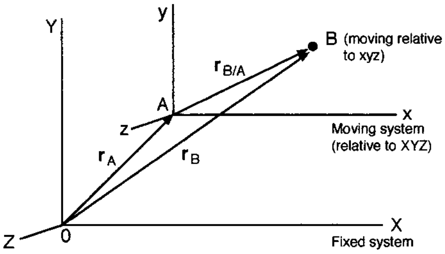


FIGURE 1.3.7 Relative motion using translating coordinates.

Kinetics of Particles

Kinetics combines the methods of kinematics and the forces that cause the motion. There are several useful methods of analysis based on Newton's second law.

Newton's Second Law

The magnitude of the acceleration of a particle is directly proportional to the magnitude of the resultant force acting on it, and inversely proportional to its mass. The direction of the acceleration is the same as the direction of the resultant force.

$$\mathbf{F} = m\mathbf{a} \tag{1.3.14}$$

where m is the particle's mass. There are three key points to remember when applying this equation.

1. **F** is the resultant force.
2. **a** is the acceleration of a single particle (use $\mathbf{a}_C$ for the center of mass for a system of particles).
3. The motion is in a nonaccelerating reference frame.

Equations of Motion

The **equations of motion** for vector and scalar notations in rectangular coordinates are

$$\sum \mathbf{F} = m\mathbf{a}$$
$$\sum F_x = ma_x \qquad \sum F_y = ma_y \qquad \sum F_z = ma_z \tag{1.3.15}$$

The equations of motion for tangential and normal components are

$$\sum F_n = ma_n = m\frac{v^2}{\rho}$$
$$\sum F_t = ma_t = m\dot{v} = mv\frac{dv}{ds} \tag{1.3.16}$$

The equations of motion in a polar coordinate system (radial and transverse components) are

$$\sum F_r = ma_r = m\left(\ddot{r} - r\dot{\theta}^2\right)$$
$$\sum F_\theta = ma_\theta = m\left(r\ddot{\theta} - 2\dot{r}\dot{\theta}\right) \tag{1.3.17}$$

Procedure for Solving Problems

1. Draw a free-body diagram of the particle showing all forces. (The free-body diagram will look unbalanced since the particle is not in static equilibrium.)
2. Choose a convenient nonaccelerating reference frame.
3. Apply the appropriate equations of motion for the reference frame chosen to calculate the forces or accelerations applied to the particle.
4. Use kinematics equations to determine velocities and/or displacements if needed.

Work and Energy Methods

Newton's second law is not always the most convenient method for solving a problem. Work and energy methods are useful in problems involving changes in displacement and velocity, if there is no need to calculate accelerations.

Work of a Force

The total work of a force **F** in displacing a particle P from position 1 to position 2 along any path is

$$U_{12} = \int_1^2 \mathbf{F} \cdot d\mathbf{r} = \int_1^2 \left(F_x\,dx + F_y\,dy + F_z\,dz\right) \tag{1.3.18}$$

Potential and Kinetic Energies

Gravitational potential energy: $U_{12} = \int_1^2 W\,dy = Wh = V_g$, where W = weight and h = vertical elevation difference.

Elastic potential energy: $U = \int_{x_1}^{x_2} kx\,dx = \frac{1}{2}k(x_2^2 - x_1^2) = V_e$, where k = spring constant.

Kinetic energy of a particle: $T = 1/2mv^2$, where m = mass and v = magnitude of velocity.

Kinetic energy can be related to work by the *principle of work and energy,*

$$U_{12} = T_2 - T_1 \tag{1.3.19}$$

where U_{12} is the work of a force on the particle moving it from position 1 to position 2, T_1 is the kinetic energy of the particle at position 1 (initial kinetic energy), and T_2 is the kinetic energy of the particle at position 2 (final kinetic energy).

Power

Power is defined as work done in a given time.

$$\text{power} = \frac{dU}{dt} = \frac{\mathbf{F}\cdot d\mathbf{r}}{dt} = \mathbf{F}\cdot\mathbf{v} \tag{1.3.20}$$

where **v** is velocity.

Important units and conversions of power are

$$1\ \text{W} = 1\ \text{J/s} = 1\ \text{N}\cdot\text{m/s}$$

$$1\ \text{hp} = 550\ \text{ft}\cdot\text{lb/s} = 33{,}000\ \text{ft}\cdot\text{lb/min} = 746\ \text{W}$$

$$1\ \text{ft}\cdot\text{lb/s} = 1.356\ \text{J/s} = 1.356\ \text{W}$$

Advantages and Disadvantages of the Energy Method

There are four advantages to using the energy method in engineering problems:

1. Accelerations do not need to be determined.
2. Modifications of problems are easy to make in the analysis.
3. Scalar quantities are summed, even if the path of motion is complex.
4. Forces that do not do work are ignored.

The main disadvantage of the energy method is that quantities of work or energy cannot be used to determine accelerations or forces that do no work. In these instances, Newton's second law has to be used.

Conservative Systems and Potential Functions

Sometimes it is useful to assume a conservative system where friction does not oppose the motion of the particle. The work in a conservative system is independent of the path of the particle, and potential energy is defined as

$$\underbrace{U_{12}}_{\substack{\text{work of }\mathbf{F}\\ \text{from 1 to 2}}} = \underbrace{-\Delta V}_{\substack{\text{difference of potential}\\ \text{energies at 1 and 2}}}$$

A special case is where the particle moves in a closed path. One trip around the path is called a *cycle*.

$$U = \oint dU = \oint \mathbf{F}\cdot d\mathbf{r} = \oint \left(F_x\ dx + F_y\ dy + F_z\ dz\right) = 0 \tag{1.3.21}$$

In advanced analysis differential changes in the potential energy function (V) are calculated by the use of partial derivatives,

$$\mathbf{F} = F_x\mathbf{i} + F_y\mathbf{j} + F_z\mathbf{k} = -\left(\frac{\partial V}{\partial x}\mathbf{i} + \frac{\partial V}{\partial y}\mathbf{j} + \frac{\partial V}{\partial z}\mathbf{k}\right)$$

1.4 Vibrations

Bela I. Sandor with assistance by Stephen M. Birn

Vibrations in machines and structures should be analyzed and controlled if they have undesirable effects such as noise, unpleasant motions, or fatigue damage with potentially catastrophic consequences. Conversely, vibrations are sometimes employed to useful purposes, such as for compacting materials.

Undamped Free and Forced Vibrations

The simplest vibrating system has motion of one degree of freedom (DOF) described by the coordinate x in Figure 1.4.1. (An analogous approach is used for torsional vibrations, with similar results.)

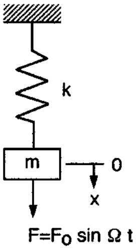


FIGURE 1.4.1 Model of a simple vibrating system.

Assuming that the spring has no mass and that there is no damping in the system, the equation of motion for **free vibration** (motion under internal forces only; $F = 0$) is

$$m\ddot{x} + kx = 0 \qquad \text{or} \qquad \ddot{x} + \omega^2 x = 0 \tag{1.4.1}$$

where $\omega = \sqrt{k/m}$ = natural circular frequency in rad/sec.

The displacement x as a function of time t is

$$x = C_1 \sin \omega t + C_2 \cos \omega t \tag{1.4.2}$$

where C_1 and C_2 are constants depending on the initial conditions of the motion. Alternatively,

$$x = A \sin(\omega t + \phi)$$

where $C_1 = A\cos\phi$, $C_2 = A\sin\phi$, and ϕ is the phase angle, another constant. A complete cycle of the motion occurs in time τ, the *period of simple harmonic motion,*

$$\tau = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{m}{k}} \; (\text{seconds per cycle})$$

The *frequency* in units of cycles per second (cps) or hertz (Hz) is $f = 1/\tau$.

The simplest case of **forced vibration** is modeled in Figure 1.4.1, with the force F included. Using typical simplifying assumptions as above, the equation of motion for a harmonic force of forcing frequency Ω,

$$m\ddot{x} + kx = F_o \sin \Omega t \tag{1.4.3}$$

Mohr's Circle for Plane Strain

As in the case of stress, there is a graphical overview by Mohr's circle of the directional dependence of the normal and shear strain components at a point in a material. This circle has a center *C* at $\varepsilon_{ave} = (\varepsilon_x + \varepsilon_y)/2$ which is always on the ε axis, but is shifting left and right in a dynamic loading situation. The radius *R* of the circle is

$$R = \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2} \tag{1.5.17}$$

Note the proper labeling (ε vs. γ/2) and preferred orientation of the strain axes as shown in Figure 1.5.13. This sets up a favorable uniformity of angular displacement between the element (+θ counterclockwise) and the circle (+2θ counterclockwise).

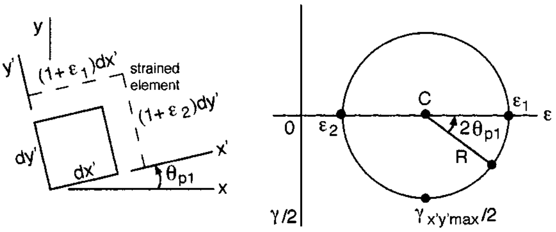


FIGURE 1.5.13 Mohr's circle for plane strain.

Mechanical Behaviors and Properties of Materials

The stress-strain response of a material depends on its chemical composition, microstructure, geometry, the magnitude and rate of change of stress or strain applied, and environmental factors. Numerous quantitative mechanical properties are used in engineering. Some of the basic properties and common variations of them are described here because they are essential in mechanics of materials analyses.

Stress-Strain Diagrams

There are several distinctive shapes of uniaxial tension or compression stress-strain plots, depending on the material, test conditions, and the quantities plotted. The chosen representative schematic diagram here is a true stress vs. true strain curve for a ductile, nonferrous metal tested in tension (Figure 1.5.14). The important mechanical properties listed in Table 1.5.1 are obtained from such a test or a similar one in pure shear (not all are shown in Figure 1.5.14).

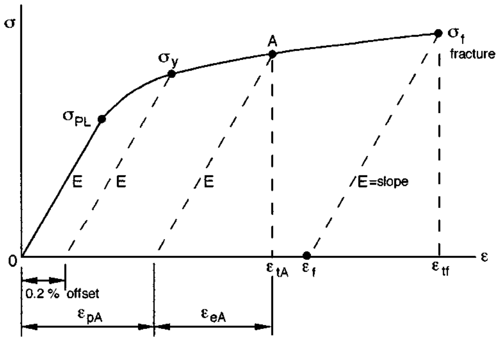


FIGURE 1.5.14 True stress vs. true strain for a ductile, nonferrous metal.

Table 1.5.1 Basic Mechanical Properties

Symbol	Definition	Remarks
E	Modulus of elasticity; Young's modulus; $E = \sigma/\varepsilon_e$	Hooke's law; T and ε_p effects small
G	Shear modulus of elasticity; $G = \dfrac{\tau}{\gamma_e} = E/2(1+v)$	T and ε_p effects small
v	Poisson's ratio; $v = \dfrac{\varepsilon_{lateral}}{\varepsilon_{longit.}}$	T and ε_p effects small
σ_{PL}	Proportional limit; at onset of noticeable yielding (or at onset of nonlinear elastic behavior)	Flow property; inaccurate; T and ε_p effects large
σ_y	0.2% offset yield strength (but yielding can occur at $\sigma < \sigma_y$ if $\sigma_{PL} < \sigma_y$)	Flow property; accurate; T and ε_p effects large
σ_f	True fracture strength; $\sigma_f = \dfrac{P_f}{A_f}$	Fracture property; T and ε_p effects medium
ε_f	True fracture ductility; $\varepsilon_f = \ln\dfrac{A_O}{A_f} = \ln\dfrac{100}{100 - \%\text{RA}}$	Max. ε_p; fracture property; T and ε_p effects medium
% RA	Percent reduction of area; $\%\text{RA} = \dfrac{A_O - A_f}{A_O} \times 100$	Fracture property; T and ε_p effects medium
n	Strain hardening exponent; $\sigma = K\varepsilon_p^n$	Flow property; T and ε_p effects small to large
Toughness	Area under σ vs. ε_p curve	True toughness or intrinsic toughness; T and ε_p effects large
σ_u	Ultimate strength; $\dfrac{P_{\max}}{A_O}$	Fracture property; T and ε_p effects medium
M_r	Modulus of resilience; $M_r = \dfrac{\sigma_{PL}^2}{2E}$	Area under original elastic portion of $\sigma - \varepsilon$ curve

Notes: T is temperature; ε_p refers to prior plastic strain, especially cyclic plastic strain (fatigue) (these are qualitative indicators here; exceptions are possible)

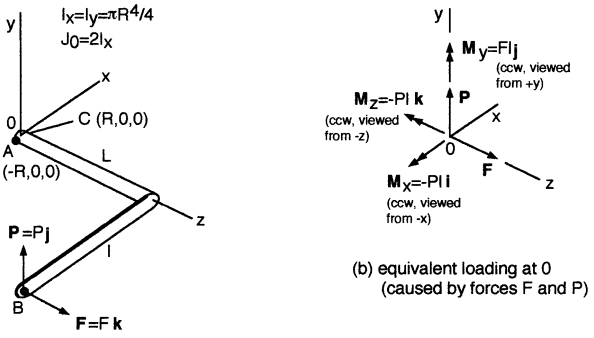
$$\underset{\text{total}}{\varepsilon_t} = \underset{\text{elastic}}{\varepsilon_e} + \underset{\text{plastic}}{\varepsilon_p} = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{1/n} = \frac{\sigma}{E} + \varepsilon_f\left(\frac{\sigma}{\sigma_f}\right)^{1/n}$$

Another useful mechanical property (not measured from the $\sigma - \varepsilon$ plot) is hardness. This is a flow property, with some qualitative correlations to the other properties.

It is important to appreciate that the mechanical properties of a material depend on its chemical composition and its history of thermal treatment and plastic deformations (cold work; cyclic plasticity). For example, consider the wide ranges of monotonic and cyclic stress-strain curves for 1045 steel (a given chemical composition) at room temperature, as functions of its hardness resulting from thermal treatment (Figure 1.5.15). See Section 1.6, "Fatigue," for more on cycle-dependent material behaviors.

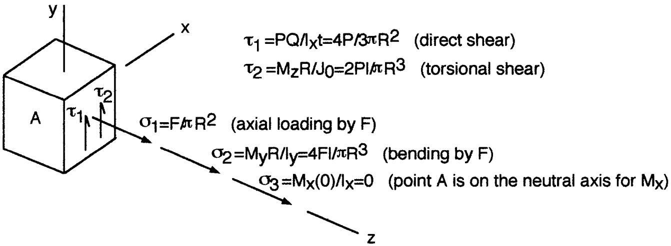
Generalized Stress-Strain Expressions. Hooke's Law

An important special case of stress-strain responses is when the material acts entirely elastically ($\varepsilon_p = 0$, $\varepsilon_t = \varepsilon_e$). In this case, for uniaxial loading, the basic **Hooke's law** $\sigma = E\varepsilon$ can be used, and similarly for unidirectional shear, $\tau = G\gamma$. For multiaxial loading (Color Plate 9), the generalized Hooke's law is applicable,



(a) problem modeling

(b) equivalent loading at 0 (caused by forces F and P)



(c) superposition of stresses at point A

FIGURE 1.5.30 Illustration of stress analysis for combined axial, shear, bending, and torsion loading.

each stress even in symbolic form has the proper units of force per area. The net normal force in this case is $\sigma_1 + \sigma_2$, and the net shear stress is $\tau_1 + \tau_2$.

The state of stress is different at other points in the member. Note that some of the stresses at a point could have different signs, reducing the resultant stress at that location. Such is the case at a point *C* diametrically opposite to point *A* in the present example (*R*, 0, 0), where the axial load **F** and $\mathbf{M}_y$ generate normal stresses of opposite signs. This shows the importance of proper modeling and setting up a problem of combined loads before doing the numerical solution.

Pressure Vessels

Maan H. Jawad and Bela I. Sandor

Pressure vessels are made in different shapes and sizes (Figure 1.5.31 and Color Plate 10) and are used in diverse applications. The applications range from air receivers in gasoline stations to nuclear reactors in submarines to heat exchangers in refineries. The required thicknesses for some commonly encountered pressure vessel components depend on the geometry as follows.

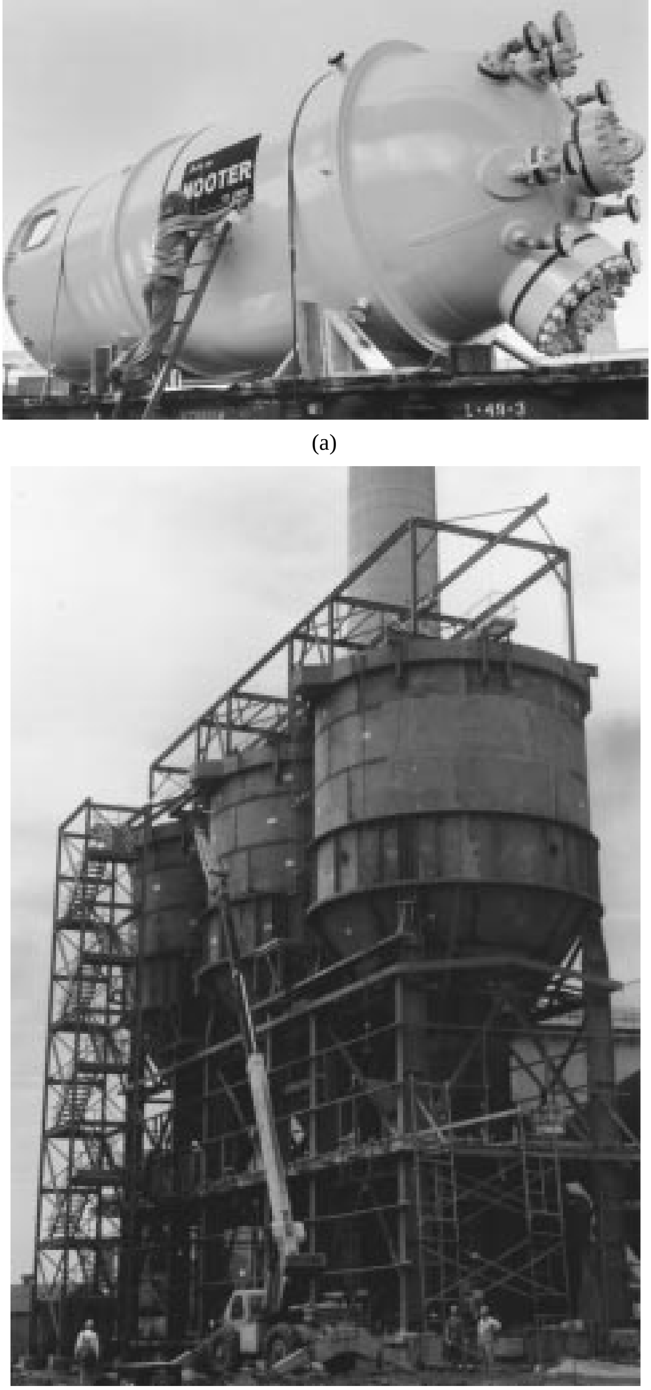
Cylindrical Shells

The force per unit length in the hoop (tangential) direction, N_t, required to contain a given pressure *p* in a cylindrical shell is obtained by taking a free-body diagram (Figure 1.5.32a) of the cross section. Assuming the thickness *t* to be much smaller than the radius *R* and summing forces in the vertical direction gives

$$2N_tL = 2RLp$$

or

$$N_t = pR \tag{1.5.52}$$



(a)

(b)

FIGURE 1.5.31 Various pressure vessels. (Photos courtesy Nooter Corp., St. Louis, MO.)

The corresponding hoop stress is $\sigma_t = pR/t$.

The longitudinal force per unit length, N_x, in the cylinder due to pressure is obtained by summing forces in the axial direction (Figure 1.5.32b),

1

Steam and Power Systems

INTRODUCTION

Basic human needs can be met only through industrial growth, which depends to a great extent on energy supply. The large increase in population during the last few decades and the spurt in industrial growth have placed tremendous burden on the electrical utility industry and process plants producing chemicals, fertilizers, petrochemicals, and other essential commodities, resulting in the need for additional capacity in the areas of power and steam generation throughout the world. Steam is used in nearly every industry, and it is well known that steam generators and heat recovery boilers are vital to power and process plants. It is no wonder that with rising fuel and energy costs engineers in these fields are working on innovative methods to generate electricity, improve energy utilization in these plants, recover energy efficiently from various waste gas sources, and simultaneously minimize the impact these processes have on environmental pollution and the emission of harmful gases to the atmosphere. This chapter briefly addresses the status of various power generation systems and the role played by steam generators and heat recovery equipment.

Several technologies are available for power generation such as gas turbine based combined cycles, nuclear power, wind energy, tidal waves, and fuel cells, to mention a few. Figure 1.1 shows the efficiency of a few types of power systems.

About 40% of the world's power is, however, generated by using boilers fired with pulverized coal and steam turbines operating on the Rankine cycle. Large pulverized coal fired and circulating fluidized bed supercritical pressure units are being considered as candidates for power plant capacity addition, though several issues such as solid particle erosion, metallurgy of pressure parts, maintenance costs, and start-up concerns remain. It may be noted that in Europe and Japan supercritical units are more widespread than in the United States.

In spite of escalation in natural gas prices, gas turbine capacity has increased by leaps and bounds during the last decade. Today's combined cycle plants are rated in thousands of megawatts, unlike similar plants decades ago when 100 MW was considered a very high rating. Steam pressure and temperature ratings for heat recovery steam generators (HRSGs) in combined cycle plants have also increased, from 1000 psig a decade or so ago to about 2400 psig. Reheaters, which improve the Rankine cycle efficiency and are generally used in utility boilers, are also finding a place in HRSGs. Complex multipressure, multimodule HRSGs are being engineered and built to maximize energy recovery.

Repowering existing steam power plants typically 30 years or older with modern gas turbines brings new useful life in addition to offering a few advantages such as improved efficiency and lower emissions. A few variations of this concept are shown in Fig. 1.2. In boiler repowering, the gas turbine exhaust is used as combustion air for the boiler. Owing to the size of such plants, solid fuel firing may be feasible and perhaps economical. Another option is to increase the power output of the steam turbine by not using the extraction steam for feedwater heating, which is performed by the turbine exhaust gases in the HRSG. The exhaust gases can also generate steam with parameters in the HRSG similar to these of the original coal-fired boiler plant, which can be taken out of service. Because gas turbines typically use premium fuels, the emissions of NOx, CO_2, and SOx are also reduced in these repowering projects. It may be noted that the various HRSG options discussed above are challenging to design and build, because numerous parameters are site-specific and cost factors vary from case to case.

Significant advances have been made in research and development of alternative methods of coal utilization such as fluidized bed combustion and gasification; integrated coal gasification and combined cycle (IGCC) plants are not research projects any longer. A few commercial plants are in operation throughout the world. Figure 1.3 shows a typical plant layout.

Research into working fluids for power generation have also led to new concepts and efficient power generation systems such as the Kalina cycle (Fig. 1.4), which uses a mixture of ammonia and water as the working fluid in Rankine cycle mode. The use of organic vapor cycles in low temperature energy recovery

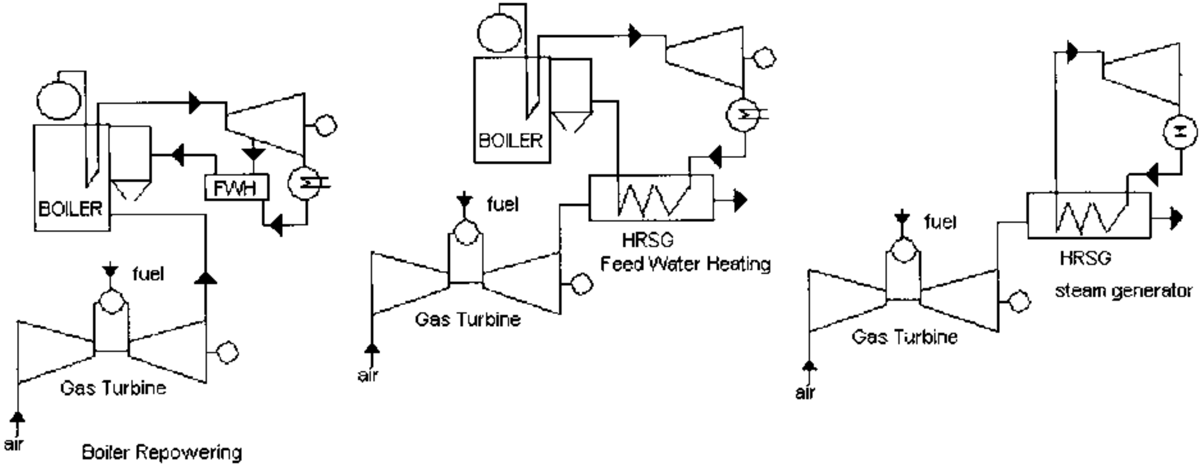


FIGURE 1.2 Repowering concepts to salvage aging power plants.

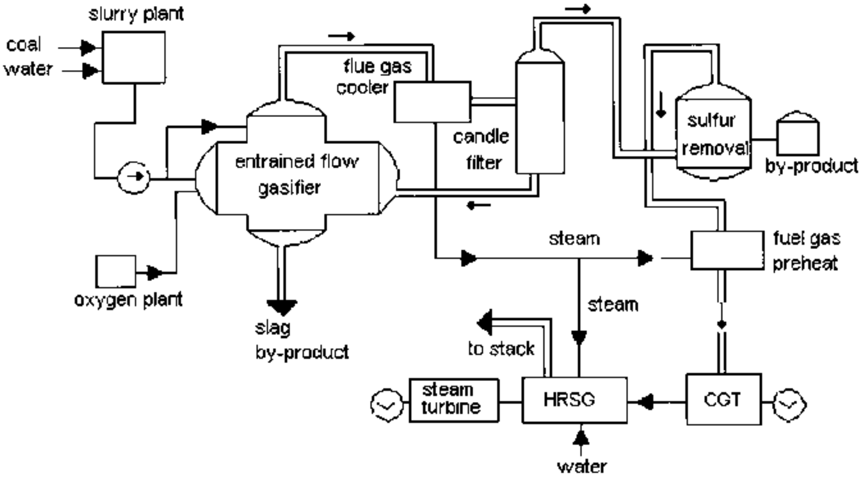


FIGURE 1.3 Wabash integrated coal gasification and combined cycle plant.

applications is also widespread. Gas turbine technology is being continuously improved to develop advanced cycles such as the intercooled aero derivative (ICAD), humid air turbine (HAT), and Cheng cycle. We have come a long way from the 35% efficiency level of the Rankine cycle to the 60% level in combined cycle plants.

Heat sources in industrial processes can be at very high temperatures, 1000–2500°F, or very low, on the order of 250–500°F, and applications have been developed to recover as much energy from these effluents as possible in order to improve the overall energy utilization. Heat recovery steam generators form an important part of these systems. (Note: The terms waste heat boiler, heat recovery boiler, and heat recovery steam generator are used synonymously). Waste gas streams sometimes heat industrial heat transfer fluids, but in nearly 90% of the applications steam is generated, that is used for either process or power generation via steam turbines.

Condensing heat exchangers are used in boilers and in HRSGs when economically viable to recover a significant amount of energy from flue gases that are often below the acid and water dew points. The condensing water removes acid vapors present in the gas stream along with particulates if any. In certain process plants, energy recovery and pollution control go hand in hand for economic and environmental reasons. Though expensive, condensing economizers, in addition to improving the efficiency of the plant, help conserve water, a precious commodity in some areas. See Chapter 3 for a discussion on condensing exchangers.

1

Engineering Thermodynamics

1.1 Fundamentals
Basic Concepts and Definitions • The First Law of Thermodynamics, Energy • The Second Law of Thermodynamics, Entropy • Entropy and Entropy Generation

1.2 Control Volume Applications
Conservation of Mass • Control Volume Energy Balance • Control Volume Entropy Balance • Control Volumes at Steady State

1.3 Property Relations and Data
Basic Relations for Pure Substances • P-v-T Relations • Evaluating Δh, Δu, and Δs • Fundamental Thermodynamic Functions • Thermodynamic Data Retrieval • Ideal Gas Model • Generalized Charts for Enthalpy, Entropy, and Fugacity • Multicomponent Systems

1.4 Combustion
Reaction Equations • Property Data for Reactive Systems • Reaction Equilibrium

1.5 Exergy Analysis
Defining Exergy • Control Volume Exergy Rate Balance • Exergetic Efficiency • Introduction to Exergy Costing

1.6 Vapor and Gas Power Cycles
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1.7 Guidelines for Improving Thermodynamic Effectiveness

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Exergy Costing • Cost Balance • Auxiliary Costing Equations • General Example • Exergoeconomic Variables and Evaluation

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An Iterative Exergoeconomic Procedure for Optimizing the Design of a Thermal System • Case Study • Additional Iterations

1.10 Economic Analysis of Thermal Systems
Estimation of Total Capital Investment • Principles of Economic Evaluation • Calculation of the Product Costs

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Although various aspects of what is now known as thermodynamics have been of interest since antiquity, formal study began only in the early 19th century through consideration of the motive power of *heat*: the capacity of hot bodies to produce *work*. Today the scope is larger, dealing generally with *energy and* *entropy*, and with relationships among the *properties* of matter. Moreover, in the past 25 years engineering thermodynamics has undergone a revolution, both in terms of the presentation of fundamentals and in the manner that it is applied. In particular, the second law of thermodynamics has emerged as an effective tool for engineering analysis and design.

1.1 Fundamentals

Classical thermodynamics is concerned primarily with the macrostructure of matter. It addresses the gross characteristics of large aggregations of molecules and not the behavior of individual molecules. The microstructure of matter is studied in kinetic theory and statistical mechanics (including quantum thermodynamics). In this chapter, the classical approach to thermodynamics is featured.

Basic Concepts and Definitions

Thermodynamics is both a branch of physics and an engineering science. The scientist is normally interested in gaining a fundamental understanding of the physical and chemical behavior of fixed, quiescent quantities of matter and uses the principles of thermodynamics to relate the *properties* of matter. Engineers are generally interested in studying *systems* and how they interact with their *surroundings.* To facilitate this, engineers have extended the subject of thermodynamics to the study of systems through which matter flows.

System

In a thermodynamic analysis, the *system is* the subject of the investigation. Normally the system is a specified quantity of matter and/or a region that can be separated from everything else by a well-defined surface. The defining surface is known as the *control surface* or *system boundary.* The control surface may be movable or fixed. Everything external to the system is the *surroundings.* A system of fixed mass is referred to as a *control mass* or as a *closed system.* When there is flow of mass through the control surface, the system is called a *control volume,* or *open, system.* An *isolated* system is a closed system that does not interact in any way with its surroundings.

State, Property

The condition of a system at any instant of time is called its *state.* The state at a given instant of time is described by the properties of the system. A *property* is any quantity whose numerical value depends on the state but not the history of the system. The value of a property is determined in principle by some type of physical operation or test.

Extensive properties depend on the size or extent of the system. Volume, mass, energy, and entropy are examples of extensive properties. An extensive property is additive in the sense that its value for the whole system equals the sum of the values for its parts. *Intensive* properties are independent of the size or extent of the system. Pressure and temperature are examples of intensive properties.

A *mole* is a quantity of substance having a mass numerically equal to its molecular weight. Designating the molecular weight by M and the number of moles by n, the mass m of the substance is $m = nM$. One kilogram mole, designated kmol, of oxygen is 32.0 kg and one pound mole (lbmol) is 32.0 lb. When an extensive property is reported on a unit mass or a unit mole basis, it is called a *specific* property. An overbar is used to distinguish an extensive property written on a per-mole basis from its value expressed per unit mass. For example, the volume per mole is $\bar{v}$, whereas the volume per unit mass is v, and the two specific volumes are related by $\bar{v} = Mv$.

Process, Cycle

Two states are identical if, and only if, the properties of the two states are identical. When any property of a system changes in value there is a change in state, and the system is said to undergo a *process.* When a system in a given initial state goes through a sequence of processes and finally returns to its initial state, it is said to have undergone a *cycle.*

Phase and Pure Substance

The term *phase* refers to a quantity of matter that is homogeneous throughout in both chemical composition and physical structure. Homogeneity in physical structure means that the matter is all *solid*, or all *liquid*, or all *vapor* (or, equivalently, all *gas). A* system can contain one or more phases. For example, a system of liquid water and water vapor (steam) contains *two* phases. A *pure substance* is one that is uniform and invariable in chemical composition. *A* pure substance can exist in more than one phase, but its chemical composition must be the same in each phase. For example, if liquid water and water vapor form a system with two phases, the system can be regarded as a pure substance because each phase has the same composition. The nature of phases that coexist in equilibrium is addressed by the *phase rule* (Section 1.3, Multicomponent Systems).

Equilibrium

Equilibrium means a condition of balance. In thermodynamics the concept includes not only a balance of forces, but also a balance of other influences. Each kind of influence refers to a particular aspect of thermodynamic (complete) equilibrium. *Thermal* equilibrium refers to an equality of temperature, *mechanical* equilibrium to an equality of pressure, and *phase* equilibrium to an equality of chemical potentials (Section 1.3, Multicomponent Systems). *Chemical* equilibrium is also established in terms of chemical potentials (Section 1.4, Reaction Equilibrium). For complete equilibrium, the several types of equilibrium must exist individually.

To determine if a system is in thermodynamic equilibrium, one may think of testing it as follows: isolate the system from its surroundings and watch for changes in its observable properties. If there are no changes, it may be concluded that the system was in equilibrium at the moment it was isolated. The system can be said to be at an *equilibrium state.* When a system is *isolated,* it cannot interact with its surroundings; however, its state can change as a consequence of spontaneous events occurring internally as its intensive properties, such as temperature and pressure, tend toward uniform values. When all such changes cease, the system is in equilibrium. At equilibrium. temperature and pressure are uniform throughout. If gravity is significant, a pressure variation with height can exist, as in a vertical column of liquid.

Temperature

A scale of temperature independent of the *thermometric substance* is called a *thermodynamic* temperature scale. The Kelvin scale, a thermodynamic scale, can be elicited from the second law of thermodynamics (Section 1.1, The Second Law of Thermodynamics, Entropy). The definition of temperature following from the second law is valid over all temperature ranges and provides an essential connection between the several *empirical* measures of temperature. In particular, temperatures evaluated using a *constant-volume gas thermometer* are identical to those of the Kelvin scale over the range of temperatures where gas thermometry can be used.

The empirical *gas scale* is based on the experimental observations that (1) at a given temperature level all gases exhibit the same value of the product $p\bar{v}$ (p is pressure and $\bar{v}$ the specific volume on a molar basis) if the pressure is low enough, and (2) the value of the product $p\bar{v}$ increases with the temperature level. On this basis the gas temperature scale is defined by

$$T = \frac{1}{\bar{R}} \lim_{p \to 0} \left(p\bar{v} \right)$$

where T is temperature and $\bar{R}$ is the *universal gas constant.* The absolute temperature at the *triple point of water* (Section 1.3, *P-v-T* Relations) is fixed by international agreement to be 273.16 K on the *Kelvin* temperature scale. $\bar{R}$ is then evaluated experimentally as $\bar{R}$ = 8.314 kJ/kmol · K (1545 ft · lbf/lbmol · °R).

The *Celsius termperature scale* (also called the centigrade scale) uses the degree Celsius (°C), which has the same magnitude as the Kelvin. Thus, temperature *differences* are identical on both scales. However, the zero point on the Celsius scale is shifted to 273.15 K, as shown by the following relationship between the Celsius temperature and the Kelvin temperature:

$$T(^\circ\mathrm{C}) = T(\mathrm{K}) - 273.15 \tag{1.1}$$

On the Celsius scale, the triple point of water is 0.01°C and 0 K corresponds to –273.15°C.

Two other temperature scales are commonly used in engineering in the U.S. By definition, the *Rankine scale*, the unit of which is the degree Rankine (°R), is proportional to the Kelvin temperature according to

$$T(^\circ\mathrm{R}) = 1.8T(\mathrm{K}) \tag{1.2}$$

The Rankine scale is also an absolute thermodynamic scale with an absolute zero that coincides with the absolute zero of the Kelvin scale. In thermodynamic relationships, temperature is always in terms of the Kelvin or Rankine scale unless specifically stated otherwise.

A degree of the same size as that on the Rankine scale is used in the *Fahrenheit scale,* but the zero point is shifted according to the relation

$$T(^\circ\mathrm{F}) = T(^\circ\mathrm{R}) - 459.67 \tag{1.3}$$

Substituting Equations 1.1 and 1.2 into Equation 1.3 gives

$$T(^\circ\mathrm{F}) = 1.8T(^\circ\mathrm{C}) + 32 \tag{1.4}$$

This equation shows that the Fahrenheit temperature of the *ice point* (0°C) is 32°F and of the *steam point* (100°C) is 212°F. The 100 Celsius or Kelvin degrees between the ice point and steam point corresponds to 180 Fahrenheit or Rankine degrees.

To provide a standard for temperature measurement taking into account both theoretical and practical considerations, the International Temperature Scale of 1990 (ITS-90) is defined in such a way that the temperature measured on it conforms with the thermodynamic temperature, the unit of which is the Kelvin, to within the limits of accuracy of measurement obtainable in 1990. Further discussion of ITS-90 is provided by Preston-Thomas (1990).

The First Law of Thermodynamics, Energy

Energy is a fundamental concept of thermodynamics and one of the most significant aspects of engineering analysis. Energy can be *stored* within systems in various macroscopic forms: kinetic energy, gravitational potential energy, and internal energy. Energy can also be *transformed* from one form to another and *transferred* between systems. For closed systems, energy can be transferred by *work* and *heat transfer.* The total amount of energy is *conserved* in all transformations and transfers.

Work

In thermodynamics, the term *work* denotes a means for transferring energy. Work is an effect of one system on another that is identified and measured as follows: work is done by a system on its surroundings if the *sole effect* on everything external to the system *could have been* the raising of a weight. The test of whether a work interaction has taken place is not that the elevation of a weight is actually changed, nor that a force actually acted through a distance, but that the sole effect *could be* the change in elevation of a weight. The magnitude of the work is measured by the number of standard weights that could have been raised. Since the raising of a weight is in effect a force acting through a distance, the work concept of mechanics is preserved. This definition includes work effects such as is associated with rotating shafts, displacement of the boundary, and the flow of electricity.

Work done *by* a system is considered positive: $W > 0$. Work done *on* a system is considered negative: $W < 0$. The time rate of doing work, or *power,* is symbolized by $\dot{W}$ and adheres to the same sign convention.

Energy

A closed system undergoing a process that involves only work interactions with its surroundings experiences an *adiabatic* process. On the basis of experimental evidence, it can be postulated that *when a closed system is altered adiabatically, the amount of work is fixed by the end states of the system and is independent of the details of the process.* This postulate, which is one way the *first law of thermodynamics* can be stated, can be made regardless of the type of work interaction involved, the type of process, or the nature of the system.

As the work in an adiabatic process of a closed system is fixed by the end states, an extensive property called *energy* can be defined for the system such that its change between two states is the work in an adiabatic process that has these as the end states. In engineering thermodynamics the change in the energy of a system is considered to be made up of three macroscopic contributions: the change in *kinetic energy, KE,* associated with the motion of the system *as a whole* relative to an external coordinate frame, the change in gravitational *potential energy, PE,* associated with the position of the system *as a whole* in the Earth's gravitational field, and the change in *internal energy, U,* which accounts for all other energy associated with the system. Like kinetic energy and gravitational potential energy, internal energy is an extensive property.

In summary, the change in energy between two states of a closed system in terms of the work W_{ad} of an adiabatic process between these states is

$$\left(KE_2 - KE_1\right) + \left(PE_2 - PE_1\right) + \left(U_2 - U_1\right) = -W_{ad} \tag{1.5}$$

where 1 and 2 denote the initial and final states, respectively, and the minus sign before the work term is in accordance with the previously stated sign convention for work. Since any arbitrary value can be assigned to the energy of a system at a given state 1, no particular significance can be attached to the value of the energy at state 1 or at *any* other state. Only *changes* in the energy of a system have significance.

The specific energy (energy per unit mass) is the sum of the specific internal energy, u, the specific kinetic energy, $\mathrm{v}^2/2$, and the specific gravitational potential energy, gz, such that

$$\text{specific energy} = u + \frac{\mathrm{v}^2}{2} + \mathrm{gz} \tag{1.6}$$

where the velocity v and the elevation z are each relative to specified datums (often the Earth's surface) and g is the acceleration of gravity.

A property related to internal energy u, pressure p, and specific volume v is *enthalpy,* defined by

$$h = u + pv \tag{1.7a}$$

or on an extensive basis

$$H = U + pV \tag{1.7b}$$

Heat

Closed systems can also interact with their surroundings in a way that cannot be categorized as work, as, for example, a gas (or liquid) contained in a closed vessel undergoing a process while in contact with a flame. This type of interaction is called a *heat interaction,* and the process is referred to as *nonadiabatic.*

A fundamental aspect of the energy concept is that energy is conserved. Thus, since a closed system experiences precisely the same energy change during a nonadiabatic process as during an adiabatic process between the same end states, it can be concluded that the *net* energy transfer to the system in each of these processes must be the same. It follows that heat interactions also involve energy transfer. Denoting the amount of energy transferred *to* a closed system in heat interactions by Q, these considerations can be summarized by the *closed system energy balance:*

$$\left(U_2 - U_1\right) + \left(KE_2 - KE_1\right) + \left(PE_2 - PE_1\right) = Q - W \tag{1.8}$$

The closed system energy balance expresses the conservation of energy principle for closed systems of all kinds.

The quantity denoted by Q in Equation 1.8 accounts for the amount of energy transferred to a closed system during a process by means other than work. On the basis of an experiment, it is known that such an energy transfer is induced only as a result of a temperature difference between the system and its surroundings and occurs only in the direction of decreasing temperature. This means of energy transfer is called an *energy transfer by heat.* The following sign convention applies:

$Q > 0$: heat transfer *to* the system

$Q < 0$: heat transfer *from* the system

The time rate of heat transfer, denoted by $\dot{Q}$, adheres to the same sign convention.

Methods based on experiment are available for evaluating energy transfer by heat. These methods recognize two basic transfer mechanisms: *conduction* and *thermal radiation.* In addition, theoretical and empirical relationships are available for evaluating energy transfer involving *combined* modes such as *convection.* Further discussion of heat transfer fundamentals is provided in Chapter 3.

The quantities symbolized by W and Q account for *transfers* of energy. The terms *work* and *heat* denote different *means* whereby energy is transferred and not *what* is transferred. Work and heat are not properties, and it is improper to speak of work or heat "contained" in a system. However, to achieve economy of expression in subsequent discussions, W and Q are often referred to simply as work and heat transfer, respectively. This less formal approach is commonly used in engineering practice.

Power Cycles

Since energy is a property, over each cycle there is no net change in energy. Thus, Equation 1.8 reads for *any* cycle

$$Q_{cycle} = W_{cycle}$$

That is, for *any* cycle the net amount of energy received through heat interactions is equal to the net energy transferred out in work interactions. A *power cycle,* or *heat* engine, is one for which a net amount of energy is transferred out by work: $W_{cycle} > 0$. This equals the net amount of energy transferred in by heat.

Power cycles are characterized both by addition of energy by heat transfer, Q_A, and inevitable rejections of energy by heat transfer, Q_R:

$$Q_{cycle} = Q_A - Q_R$$

Combining the last two equations,

$$W_{cycle} = Q_A - Q_R$$

The *thermal efficiency* of a heat engine is defined as the ratio of the net work developed to the total energy added by heat transfer:

$$\eta = \frac{W_{cycle}}{Q_A} = 1 - \frac{Q_R}{Q_A} \tag{1.9}$$

The thermal efficiency is strictly less than 100%. That is, some portion of the energy Q_A supplied is invariably rejected $Q_R \neq 0$.

The Second Law of Thermodynamics, Entropy

Many statements of the second law of thermodynamics have been proposed. Each of these can be called a statement of the second law *or* a corollary of the second law since, if one is invalid, all are invalid. In every instance where a consequence of the second law has been tested directly or indirectly by experiment it has been verified. Accordingly, the basis of the second law, like every other physical law, is experimental evidence.

Kelvin-Planck Statement

The Kelvin-Plank statement of the second law of thermodynamics refers to a *thermal reservoir.* A thermal reservoir is a system that remains at a constant temperature even though energy is added or removed by heat transfer. A reservoir is an idealization, of course, but such a system can be approximated in a number of ways — by the Earth's atmosphere, large bodies of water (lakes, oceans), and so on. Extensive properties of thermal reservoirs, such as internal energy, can change in interactions with other systems even though the reservoir temperature remains constant, however.

The Kelvin-Planck statement of the second law can be given as follows: *It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of energy by work to its surroundings while receiving energy by heat transfer from a single thermal reservoir.* In other words, a *perpetual-motion machine of the second kind* is impossible. Expressed analytically, the Kelvin-Planck statement is

$$W_{cycle} \leq 0 \qquad (\text{single reservoir})$$

where the words *single reservoir* emphasize that the system communicates thermally only with a single reservoir as it executes the cycle. The "less than" sign applies when *internal irreversibilities* are present as the system of interest undergoes a cycle and the "equal to" sign applies only when no irreversibilities are present.

Irreversibilities

A process is said to be *reversible* if it is possible for its effects to be eradicated in the sense that there is some way by which *both* the system and its surroundings can be *exactly restored* to their respective initial states. A process is *irreversible* if there is no way to undo it. That is, there is no means by which the system and its surroundings can be exactly restored to their respective initial states. A system that has undergone an irreversible process is not necessarily precluded from being restored to its initial state. However, were the system restored to its initial state, it would not also be possible to return the surroundings to their initial state.

There are many effects whose presence during a process renders it irreversible. These include, but are not limited to, the following: heat transfer through a finite temperature difference; unrestrained expansion of a gas or liquid to a lower pressure; spontaneous chemical reaction; mixing of matter at different compositions or states; friction (sliding friction as well as friction in the flow of fluids); electric current flow through a resistance; magnetization or polarization with hysteresis; and inelastic deformation. The term *irreversibility* is used to identify effects such as these.

Irreversibilities can be divided into two classes, *internal* and *external.* Internal irreversibilities are those that occur within the system, while external irreversibilities are those that occur within the surroundings, normally the immediate surroundings. As this division depends on the location of the boundary there is some arbitrariness in the classification (by locating the boundary to take in the immediate surroundings, all irreversibilities are internal). Nonetheless, valuable insights can result when this distinction between irreversibilities is made. When internal irreversibilities are absent during a process, the process is said to be *internally reversible.* At every intermediate state of an internally reversible process of a closed system, all intensive properties are uniform throughout each phase present: the temperature, pressure, specific volume, and other intensive properties do not vary with position. The discussions to follow compare the actual and internally reversible process concepts for two cases of special interest.

For a gas as the system, the work of expansion arises from the force exerted by the system to move the boundary against the resistance offered by the surroundings:

$$W = \int_1^2 F dx = \int_1^2 pA dx$$

where the force is the product of the moving area and the pressure exerted by the system there. Noting that *Adx* is the change in total volume of the system,

$$W = \int_1^2 p dV$$

This expression for work applies to both actual and internally reversible expansion processes. However, for an internally reversible process p is not only the pressure at the moving boundary but also the pressure of the entire system. Furthermore, for an internally reversible process the volume equals mv, where the specific volume v has a single value throughout the system at a given instant. Accordingly, the work of an internally reversible expansion (or compression) process is

$$W = m\int_1^2 p dv \tag{1.10}$$

When such a process of a closed system is represented by a continuous curve on a plot of pressure vs. specific volume, the area *under* the curve is the magnitude of the work per unit of system mass (area a-b-c′-d′ of Figure 1.3, for example).

Although improved thermodynamic performance can accompany the reduction of irreversibilities, steps in this direction are normally constrained by a number of practical factors often related to costs. For example, consider two bodies able to communicate thermally. With a *finite* temperature difference between them, a spontaneous heat transfer would take place and, as noted previously, this would be a source of irreversibility. The importance of the heat transfer irreversibility diminishes as the temperature difference narrows; and as the temperature difference between the bodies vanishes, the heat transfer approaches *ideality.* From the study of heat transfer it is known, however, that the transfer of a finite amount of energy by heat between bodies whose temperatures differ only slightly requires a considerable amount of time, a large heat transfer surface area, or both. To approach *ideality,* therefore, a heat transfer would require an exceptionally long time and/or an exceptionally large area, each of which has cost implications constraining what can be achieved practically.

Carnot Corollaries

The two corollaries of the second law known as *Carnot* corollaries state: (1) the thermal efficiency of an irreversible power cycle is always less than the thermal efficiency of a reversible power cycle when each operates between the same two thermal reservoirs; (2) all reversible power cycles operating between the same two thermal reservoirs have the same thermal efficiency. A cycle is considered *reversible* when there are no irreversibilities within the system as it undergoes the cycle, and heat transfers between the system and reservoirs occur ideally (that is, with a vanishingly small temperature difference).

Kelvin Temperature Scale

Carnot corollary 2 suggests that the thermal efficiency of a reversible power cycle operating between two thermal reservoirs depends only on the temperatures of the reservoirs and not on the nature of the substance making up the system executing the cycle or the series of processes. With Equation 1.9 it can be concluded that the ratio of the heat transfers is also related only to the temperatures, and is independent of the substance and processes:

$$\left(\frac{Q_C}{Q_H}\right)_{\substack{rev\\cycle}} = \psi\left(T_C, T_H\right)$$

where Q_H *is* the energy transferred to the system by heat transfer from a *hot* reservoir at temperature T_H, and Q_C is the energy rejected from the system to a *cold* reservoir at temperature T_C. The words *rev cycle* emphasize that this expression applies only to systems undergoing reversible cycles while operating between the two reservoirs. Alternative temperature scales correspond to alternative specifications for the function ψ in this relation.

The *Kelvin temperature scale is* based on $\psi(T_C, T_H) = T_C/T_H$. Then

$$\left(\frac{Q_C}{Q_H}\right)_{\substack{rev\\cycle}} = \frac{T_C}{T_H} \tag{1.11}$$

This equation defines only a ratio of temperatures. The specification of the Kelvin scale is completed by assigning a numerical value to one standard reference state. The state selected is the same used to define the *gas scale:* at the triple point of water the temperature is specified to be 273.16 K. If a reversible cycle is operated between a reservoir at the reference-state temperature and another reservoir at an unknown temperature T, then the latter temperature is related to the value at the reference state by

$$T = 273.16\left(\frac{Q}{Q'}\right)_{\substack{rev\\cycle}}$$

where Q is the energy received by heat transfer from the reservoir at temperature T, and Q' is the energy rejected to the reservoir at the reference temperature. Accordingly, a temperature scale is defined that is valid over all ranges of temperature and that is independent of the thermometric substance.

Carnot Efficiency

For the special case of a reversible power cycle operating between thermal reservoirs at temperatures T_H and T_C on the Kelvin scale, combination of Equations 1.9 and 1.11 results in

$$\eta_{\max} = 1 - \frac{T_C}{T_H} \tag{1.12}$$

called the *Carnot efficiency.* This is the efficiency of *all* reversible power cycles operating between thermal reservoirs at T_H and T_C. Moreover, it is the *maximum theoretical* efficiency that any power cycle, real or ideal, could have while operating between the same two reservoirs. As temperatures on the Rankine scale differ from Kelvin temperatures only by the factor 1.8, the above equation may be applied with either scale of temperature.

Chapter 11
Turbomachinery

Motivation. The most common practical engineering application for fluid mechanics is the design of fluid machinery. The most numerous types are machines which *add* energy to the fluid (the pump family), but also important are those which *extract* energy (turbines). Both types are usually connected to a rotating shaft, hence the name *turbomachinery*.

The purpose of this chapter is to make elementary engineering estimates of the performance of fluid machines. The emphasis will be upon nearly incompressible flow, i.e., liquids or low-velocity gases. Basic flow principles are discussed, but not the detailed construction of the machine.

11.1 Introduction and Classification

Turbomachines divide naturally into those which add energy (pumps) and those which extract energy (turbines). The prefix *turbo-* is a Latin word meaning “spin’’ or “whirl,’’ appropriate for rotating devices.

The pump is the oldest fluid-energy-transfer device known. At least two designs date before Christ: (1) the undershot-bucket waterwheels, or *norias*, used in Asia and Africa (1000 B.C.) and (2) Archimedes’ screw pump (250 B.C.), still being manufactured today to handle solid-liquid mixtures. Paddlewheel turbines were used by the Romans in 70 B.C., and Babylonian windmills date back to 700 B.C. [1].

Machines which deliver liquids are simply called *pumps*, but if gases are involved, three different terms are in use, depending upon the pressure rise achieved. If the pressure rise is very small (a few inches of water), a gas pump is called a *fan*; up to 1 atm, it is usually called a *blower*; and above 1 atm it is commonly termed a *compressor*.

Classification of Pumps

There are two basic types of pumps: positive-displacement and dynamic or momentum-change pumps. There are several billion of each type in use in the world today.

Positive-displacement pumps (PDPs) force the fluid along by volume changes. A cavity opens, and the fluid is admitted through an inlet. The cavity then closes, and the fluid is squeezed through an outlet. The mammalian heart is a good example, and many mechanical designs are in wide use. The text by Warring [14] gives an excellent summary of PDPs. A brief classification of PDP designs is as follows:

- A. Reciprocating
  - 1. Piston or plunger
  - 2. Diaphragm
- B. Rotary
  - 1. Single rotor
    - *a.* Sliding vane
    - *b.* Flexible tube or lining
    - *c.* Screw
    - *d.* Peristaltic (wave contraction)
  - 2. Multiple rotors
    - *a.* Gear
    - *b.* Lobe
    - *c.* Screw
    - *d.* Circumferential piston

All PDPs deliver a pulsating or periodic flow as the cavity volume opens, traps, and squeezes the fluid. Their great advantage is the delivery of any fluid regardless of its viscosity.

Figure 11.1 shows schematics of the operating principles of seven of these PDPs. It is rare for such devices to be run backward, so to speak, as turbines or energy extractors, the steam engine (reciprocating piston) being a classic exception.

Since PDPs compress mechanically against a cavity filled with liquid, a common feature is that they develop immense pressures if the outlet is shut down for any reason. Sturdy construction is required, and complete shutoff would cause damage if pressure-relief valves were not used.

Dynamic pumps simply add momentum to the fluid by means of fast-moving blades or vanes or certain special designs. There is no closed volume: The fluid increases momentum while moving through open passages and then converts its high velocity to a pressure increase by exiting into a diffuser section. Dynamic pumps can be classified as follows:

- A. Rotary
  - 1. Centrifugal or radial exit flow
  - 2. Axial flow
  - 3. Mixed flow (between radial and axial)
- B. Special designs
  - 1. Jet pump or ejector (see Fig. P3.36)
  - 2. Electromagnetic pumps for liquid metals
  - 3. Fluid-actuated: gas-lift or hydraulic-ram

We shall concentrate in this chapter on the rotary designs, sometimes called *rotodynamic pumps*. Other designs of both PDP and dynamic pumps are discussed in specialized texts [for example, 11, 14, 31].

Dynamic pumps generally provide a higher flow rate than PDPs and a much steadier discharge but are ineffective in handling high-viscosity liquids. Dynamic pumps also generally need *priming*; i.e., if they are filled with gas, they cannot suck up a liquid from below into their inlet. The PDP, on the other hand, is self-priming for most

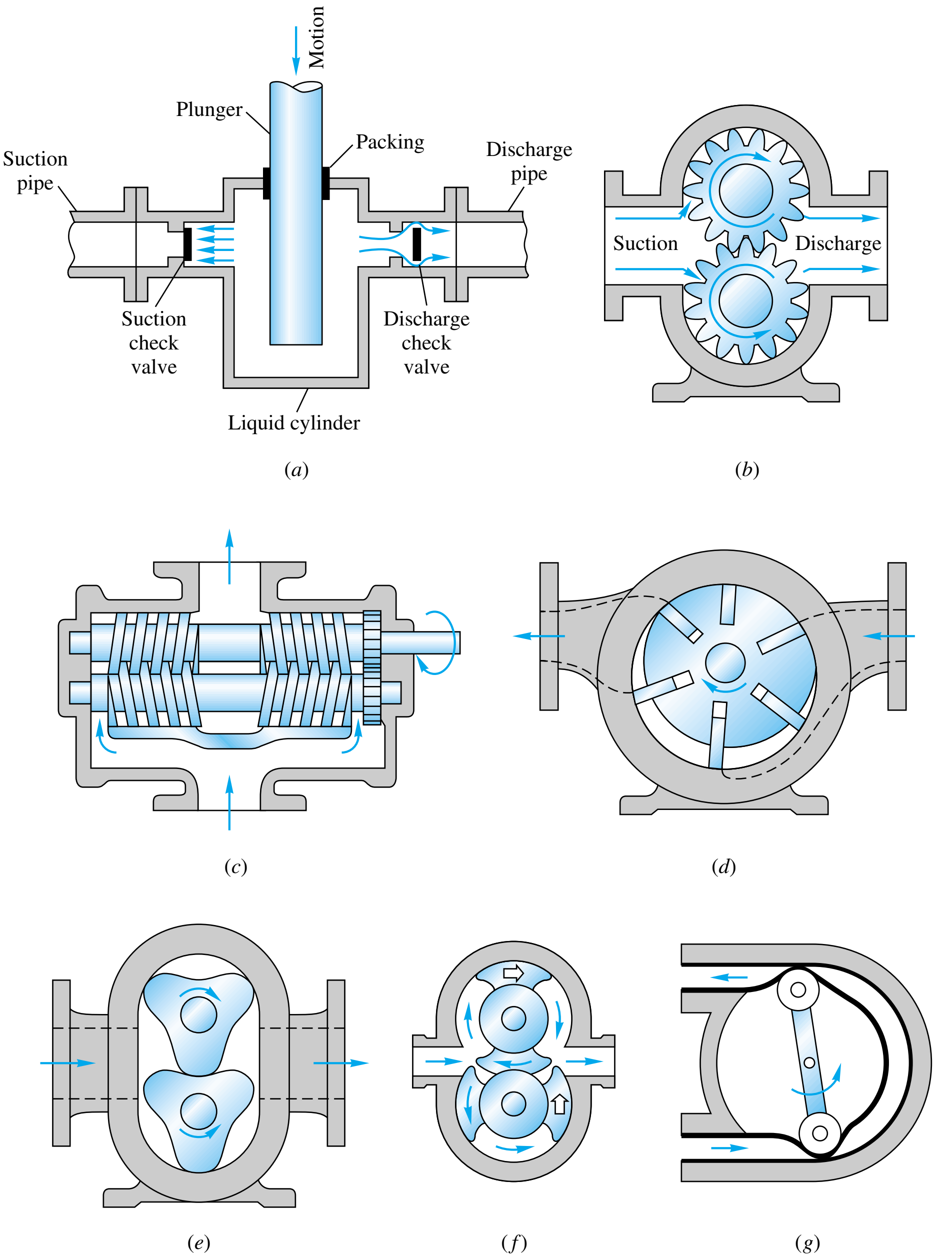

Fig. 11.1 Schematic design of positive-displacement pumps: (*a*) reciprocating piston or plunger, (*b*) external gear pump, (*c*) double-screw pump, (*d*) sliding vane, (*e*) three-lobe pump, (*f*) double circumferential piston, (*g*) flexible-tube squeegee.

applications. A dynamic pump can provide very high flow rates (up to 300,000 gal/min) but usually with moderate pressure rises (a few atmospheres). In contrast, a PDP can operate up to very high pressures (300 atm) but typically produces low flow rates (100 gal/min).

The relative *performance* (Δp versus Q) is quite different for the two types of pump, as shown in Fig. 11.2. At constant shaft rotation speed, the PDP produces nearly con-

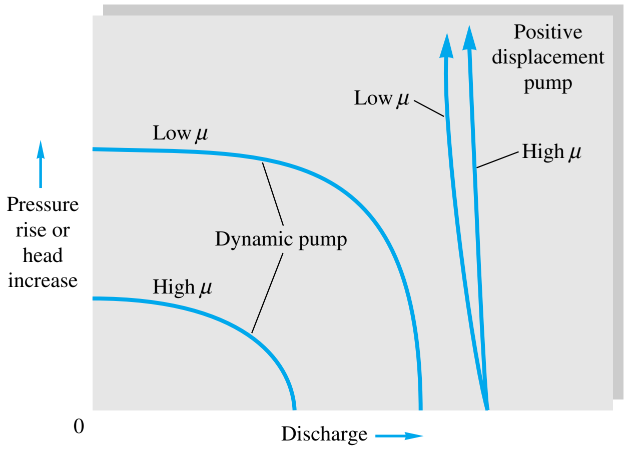

Fig. 11.2 Comparison of performance curves of typical dynamic and positive-displacement pumps at constant speed.

stant flow rate and virtually unlimited pressure rise, with little effect of viscosity. The flow rate of a PDP cannot be varied except by changing the displacement or the speed. The reliable constant-speed discharge from PDPs has led to their wide use in metering flows [35].

The dynamic pump, by contrast in Fig. 11.2, provides a continuous constant-speed variation of performance, from near-maximum Δp at zero flow (shutoff conditions) to zero Δp at maximum flow rate. High-viscosity fluids sharply degrade the performance of a dynamic pump.

As usual—and for the last time in this text—we remind the reader that this is merely an introductory chapter. Many books are devoted solely to turbomachines: generalized treatments [2 to 7], texts specializing in pumps [8 to 16], fans [17 to 20], compressors [21 to 23], turbines [24 to 28], and PDPs [35 to 38]. There are several useful handbooks [29 to 32], and at least two elementary textbooks [33, 34] have a comprehensive discussion of turbomachines. The reader is referred to these sources for further details.

11.2 The Centrifugal Pump

Let us begin our brief look at rotodynamic machines by examining the characteristics of the centrifugal pump. As sketched in Fig. 11.3, this pump consists of an impeller rotating within a casing. Fluid enters axially through the *eye* of the casing, is caught

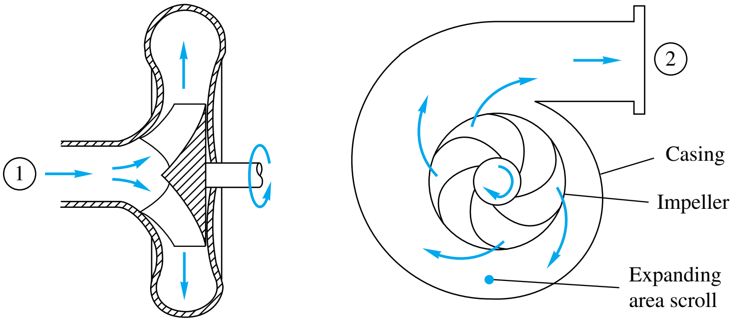

Fig. 11.3 Cutaway schematic of a typical centrifugal pump.

up in the impeller blades, and is whirled tangentially and radially outward until it leaves through all circumferential parts of the impeller into the diffuser part of the casing. The fluid gains both velocity and pressure while passing through the impeller. The doughnut-shaped diffuser, or *scroll*, section of the casing decelerates the flow and further increases the pressure.

The impeller blades are usually *backward-curved*, as in Fig. 11.3, but there are also radial and forward-curved blade designs, which slightly change the output pressure. The blades may be *open*, i.e., separated from the front casing only by a narrow clearance, or *closed*, i.e., shrouded from the casing on both sides by an impeller wall. The diffuser may be *vaneless*, as in Fig. 11.3, or fitted with fixed vanes to help guide the flow toward the exit.

Basic Output Parameters

Assuming steady flow, the pump basically increases the Bernoulli head of the flow between point 1, the eye, and point 2, the exit. From Eq. (3.67), neglecting viscous work and heat transfer, this change is denoted by H:

$$H = \left(\frac{p}{\rho g} + \frac{V^2}{2g} + z\right)_2 - \left(\frac{p}{\rho g} + \frac{V^2}{2g} + z\right)_1 = h_s - h_f \tag{11.1}$$

where h_s is the pump head supplied and h_f the losses. The net head H is a primary output parameter for any turbomachine. Since Eq. (11.1) is for incompressible flow, it must be modified for gas compressors with large density changes.

Usually V_2 and V_1 are about the same, $z_2 - z_1$ is no more than a meter or so, and the net pump head is essentially equal to the change in pressure head

$$H \approx \frac{p_2 - p_1}{\rho g} = \frac{\Delta p}{\rho g} \tag{11.2}$$

The power delivered to the fluid simply equals the specific weight times the discharge times the net head change

$$P_w = \rho g Q H \tag{11.3}$$

This is traditionally called the *water horsepower*. The power required to drive the pump is the *brake horsepower*[1]

$$\text{bhp} = \omega T \tag{11.4}$$

where ω is the shaft angular velocity and T the shaft torque. If there were no losses, P_w and brake horsepower would be equal, but of course P_w is actually less, and the *efficiency* η of the pump is defined as

$$\eta = \frac{P_w}{\text{bhp}} = \frac{\rho g Q H}{\omega T} \tag{11.5}$$

The chief aim of the pump designer is to make η as high as possible over as broad a range of discharge Q as possible.

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[1] Conversion factors may be needed: 1 hp = 550 ft · lbf/s = 746 W.

The efficiency is basically composed of three parts: volumetric, hydraulic, and mechanical. The *volumetric efficiency* is

$$\eta_v = \frac{Q}{Q + Q_L} \tag{11.6}$$

where Q_L is the loss of fluid due to leakage in the impeller-casing clearances. The *hydraulic efficiency* is

$$\eta_h = 1 - \frac{h_f}{h_s} \tag{11.7}$$

where h_f has three parts: (1) *shock* loss at the eye due to imperfect match between inlet flow and the blade entrances, (2) *friction* losses in the blade passages, and (3) *circulation* loss due to imperfect match at the exit side of the blades.

Finally, the *mechanical efficiency* is

$$\eta_m = 1 - \frac{P_f}{\text{bhp}} \tag{11.8}$$

where P_f is the power loss due to mechanical friction in the bearings, packing glands, and other contact points in the machine.

By definition, the total efficiency is simply the product of its three parts

$$\eta \equiv \eta_v \eta_h \eta_m \tag{11.9}$$

The designer has to work in all three areas to improve the pump.

Elementary Pump Theory

You may have thought that Eqs. (11.1) to (11.9) were formulas from pump *theory*. Not so; they are merely definitions of performance parameters and cannot be used in any predictive mode. To actually *predict* the head, power, efficiency, and flow rate of a pump, two theoretical approaches are possible: (1) simple one-dimensional-flow formulas and (2) complex digital-computer models which account for viscosity and three-dimensionality. Many of the best design improvements still come from testing and experience, and pump research remains a very active field [39]. The last 10 years have seen considerable advances in *computational fluid-dynamics* (CFD) modeling of flow in turbomachines [42], and at least eight commercial turbulent-flow three-dimensional CFD codes are now available.

To construct an elementary theory of pump performance, we assume one-dimensional flow and combine idealized fluid-velocity vectors through the impeller with the angular-momentum theorem for a control volume, Eq. (3.55).

The idealized velocity diagrams are shown in Fig. 11.4. The fluid is assumed to enter the impeller at $r = r_1$ with velocity component w_1 tangent to the blade angle β_1 plus circumferential speed $u_1 = \omega r_1$ matching the tip speed of the impeller. Its absolute entrance velocity is thus the vector sum of w_1 and u_1, shown as V_1. Similarly, the flow exits at $r = r_2$ with component w_2 parallel to the blade angle β_2 plus tip speed $u_2 = \omega r_2$, with resultant velocity V_2.

We applied the angular-momentum theorem to a turbomachine in Example 3.14 (Fig. 3.13) and arrived at a result for the applied torque T

$$T = \rho Q(r_2 V_{t2} - r_1 V_{t1}) \tag{11.10}$$

The measured shutoff head of centrifugal pumps is only about 60 percent of the theoretical value $H_0 = \omega^2 r_2^2 / g$. With the advent of the laser-doppler anemometer, researchers can now make detailed three-dimensional flow measurements inside pumps and can even animate the data into a movie [40].

The positive-slope condition in Fig. 11.5 can be unstable and can cause pump *surge*, an oscillatory condition where the pump "hunts" for the proper operating point. Surge may cause only rough operation in a liquid pump, but it can be a major problem in gas-compressor operation. For this reason a backward-curved or radial blade design is generally preferred. A survey of the problem of pump stability is given by Greitzer [41].

11.3 Pump Performance Curves and Similarity Rules

Since the theory of the previous section is rather qualitative, the only solid indicator of a pump's performance lies in extensive testing. For the moment let us discuss the centrifugal pump in particular. The general principles and the presentation of data are exactly the same for mixed-flow and axial-flow pumps and compressors.

Performance charts are almost always plotted for constant shaft-rotation speed n (in r/min usually). The basic independent variable is taken to be discharge Q (in gal/min usually for liquids and ft^3/min for gases). The dependent variables, or "output," are taken to be head H (pressure rise Δp for gases), brake horsepower (bhp), and efficiency η.

Figure 11.6 shows typical performance curves for a centrifugal pump. The head is approximately constant at low discharge and then drops to zero at $Q = Q_{\max}$. At this speed and impeller size, the pump cannot deliver any more fluid than $Q_{\max}$. The positive-slope part of the head is shown dashed; as mentioned earlier, this region can be unstable and can cause hunting for the operating point.

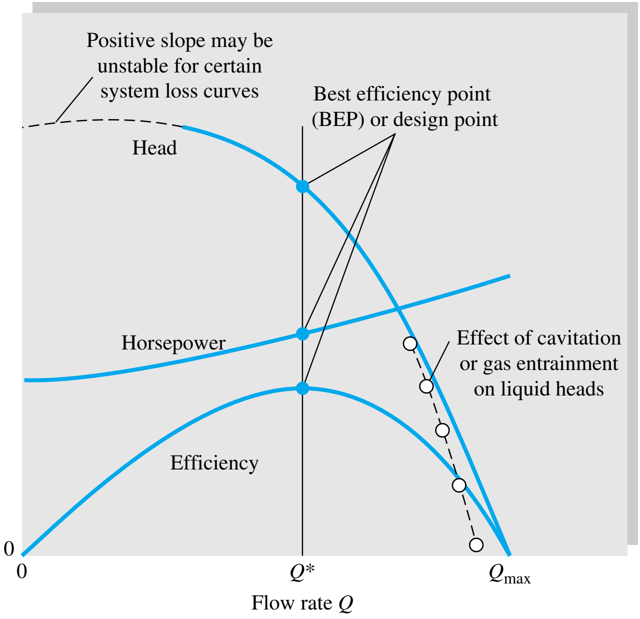


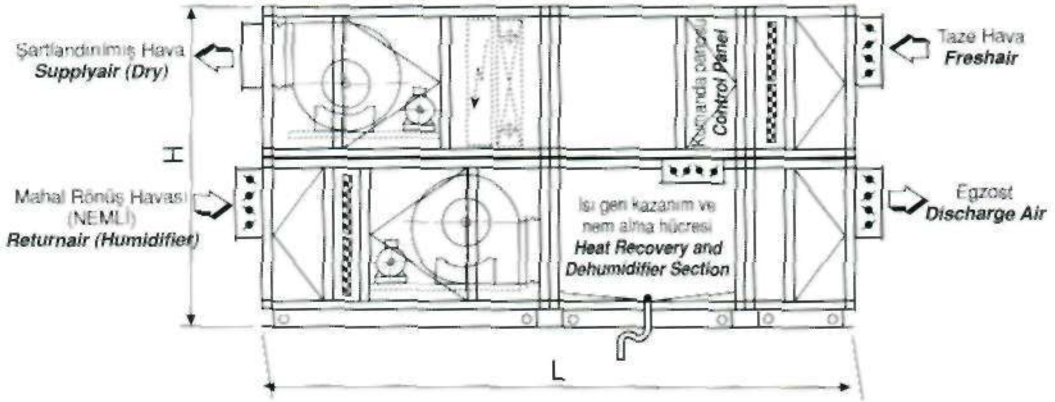
Fig. 11.6 Typical centrifugal pump performance curves at constant impeller-rotation speed. The units are arbitrary.

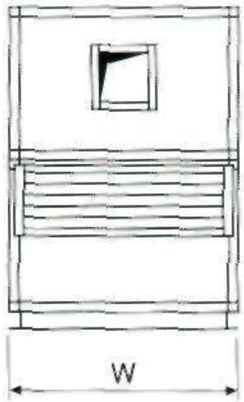
Havuz Tipi Nem Alıcı Klima Santralları ALP Pool Type Dehumidifier Air Handling Units

Kapalı yüzme havuzları, kurutma prosesleri ve nem alma ihtiyacı duyulan özel yerlerin rutubetinin alınması ile iklimlendirilmesi için geliştirilmiş özel klima santrallarıdır. Aspiratör, vantilatör, ısı geri kazanım bataryası, direkt expension, soğutucu ve ısıtıcı, sıcak sulu son ısıtıcı ve elektrikli rezistans tipi ısıtıcı bölümlerinden oluşmaktadır.
Nem alma ve soğutma çevriminin kademeli olarak sağlanması için sessiz olan hermetik kompresörlere haizdir.
Cihaz; nem alma çevrimi için özel olarak hazırlanmış kontrol programını içeren elektronik panel ve seri koruma kilitlemeleri ile techiz edilmiş, elektrik kumanda sistemi cihaz bünyesine yerleştirilmiş ve elektrik bağlantıları yapılmış vaziyette teslim edilmektedir.
Otomatik kontrol sistemi sayesinde yaz, kış gece ve kış gündüz seçenekleri ile havuz mahallini istenilen sıcaklık derecesi ve nem mertebesinde şartlandırmak, taze hava ve egzost ihtiyacını karşılamak mümkün olmaktadır.
Kapalı havuz yüzeyleri gözönünde bulundurularak 6 ayrı tip ve kapasitede seri ve modüler olarak paket halde üretilmektedir.

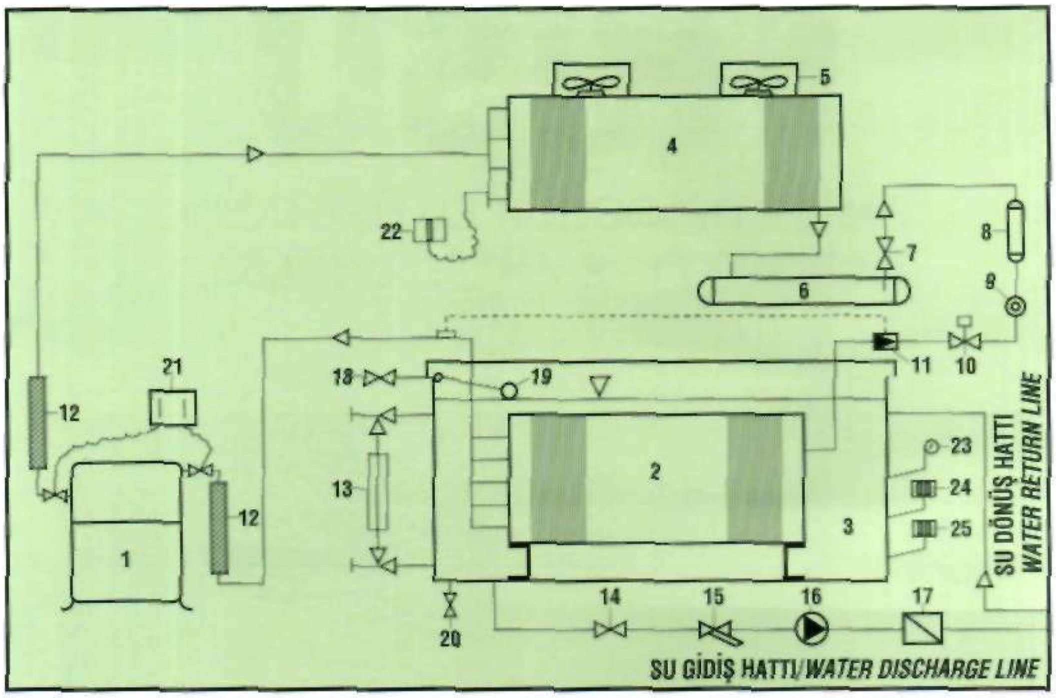
***These are specially designed air handling units specially to climate and dehumidify indoors swimming pools, drying processes and special places where exists dehumidifing need. Return fan, supply fan, heat recovery coil, direct expansion cooling and heating coil, secondary hot water heating coil and electrical heater sections are the major sections of the unit.
In order to maintain the step control of the cooling and dehumidifying processes, silent hermetic compressors are used.
The unit is equipped and delivered with a special electronic control panel which is used to control the dehumidifying process, in addition to this panel the electrical control box with the necessary electrical series protection locks made on it is also delivered on the unit. The automatic control system used on the unit provides to maintain the specified temperature and humidity values, fresh air and exhaust air amount of the pool area according to summer winter nighttime and winter daytime setpoint alternatives. According to the indoors pool surface areas, there exists six different model and capacity alternatives which are series and modular packaged type manufactured.***

TİP/ *TYPE*		**ALP-05**	**ALP-10**	**ALP-15**	**ALP-20**	**ALP-30**	**ALP-40**
Kapalı Havuz Yüzeyi/*Indoors Pool Surface* m²		50	100	150	200	250	300
Nem Alma Kapasitesi/Dehumidifying *Capacity* kg/h		11	20	32	43	53	65
Isıtma Kapasitesi/*Heater Capacity* kcal/h (90/70 °C Sıcak Su ile/90/70 °C*Hot Water*)		19500	39000	54600	66300	85800	109200
Elektrikli Rezistans Isıtıcısı/*Electrical Heating* Kw		15-2	30-2	45-3	45-3	60-3	60-3
Hava Debisi/*Air Flow* Rate m³/h		2500	5000	7000	8500	1100	14000
Çekilen Toplam Güç/*Total Power Resignation* Kw		9	15	24	30	41	53
(Rezistans Dahil/*Included Resistance*)		24	45	69	75	101	113
Boyutlar / *Sizes* (mm)	**L**	3840	38400	4490	4790	5120	5420
	W	1280	1580	1930	1930	2230	2230
	H	1480	2080	2080	2680	2680	3280
Ağırlık / *Weight* Kg		1680	2030	2180	2700	3150	3275





PRENSİP ŞEMASI / *PIRINCIPAL DRAWING*



- 1 - KOMPRESÖR
- 2 - EVAPORATÖR
- 3 - SU TANKI
- 4 - KONDENSER
- 5 - AKSİYAL FAN - MOTOR
- 6 - RESİVER
- 7 - LİKİT VANASI
- 8 - KURUTUCU FİLTRE
- 9 - GÖZETLEME CAMI
- 10 - SOLENOID VALF
- 11 - EXPANSION VALF
- 12 - ABSORBER
- 13 - SEVİYE GÖSTERGESİ
- 14 - SU VANASI
- 15 - PİSLİK TUTUCU
- 16 - POMPA
- 17 - ÇEK VALF
- 18 - SU BESLEME
- 19 - ŞAMANDIRA
- 20 - SU BOŞALTMA
- 21 - ALÇAK-YÜKSEK BASINÇ PRESOSTADI
- 22 - YÜKSEK BASINÇ PRESOSTADI
- 23 - TERMOMETRE
- 24 - DONMA TERMOSTADI
- 25 - İŞLETME TERMOSTADI (Dijital programlanabilir)

- *1 - COMPRESSOR*
- *2 - EVAPORATOR*
- *3 - WATER TANK*
- *4 - CONDENSER*
- *5 - AXIAL FAN-MOTOR*
- *6 - RESIVER*
- *7 - LIQUID LINE CUT-OFF VALVE*
- *8 - DRYER FILTER*
- *9 - SIGHT GLASS*
- *10 - SOLENOID VALVE*
- *11 - EXPANSION VALVE*
- *12 - ABSORBER*
- *13 - LEVEL INDICATOR*
- *14 - WATER VALVE*
- *15 - DIRT HOLDER*
- *16 - PUMP*
- *17 - CHECK VALVE*
- *18 - WATER SUPPLY*
- *19 - FLOAT VALVE*
- *20 - WATER DISCHARGE*
- *21 - LOW-HIGH PRESSURE PRESOSTAT*
- *22 - HIGH PRESSURE PRESOSTAT*
- *23 - THERMOMETER*
- *24 - FREEZING THERMOSTAT*
- *25 - OPERATING THERMOSTAT (Digital programmable)*

"Daldırma" tip soğutuculu / ***"Immarsed"*** *type of chiller*

"Shell and tube" tip soğutuculu/***"Shell and tube"*** *type of chiller*

AHRV

ISI GERİ KAZANIM ÜNİTELERİ
HEAT RECOVERY UNITS

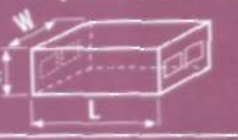
AHRV; ALDAĞ *Isı geri kazanım* üniteleri taze hava gereksinimi duyulan mahallerde enerji tasarrufu sağlamak amacı ile üretilen cihazlar olup, 500 m³/h ÷ 2000 m³/h hava debisi aralığında üretilmektedir. Isıtma - Soğutma - Klima yapılan ve taze hava gereksinimi duyulan iş merkezleri, ofisler, konutlar vb. *yerlerde kullanılırlar. Asma tavan arasına* konulabilecek yükseklikte, kolaylıkla montaj ve bakım yapılabilecek şekilde dizayn edilmişlerdir. Sessiz çalışan direkt akuple motora sahip radyal fanları, yüksek verimli recuperatörü, maximum ses yutumu ve ısı izolasyonu yapılmış tam sızdırmaz *hücresi ile kompakt bir cihazdır. Isıtma ve Soğutma yapılan mahallerde* hava kalitesinin iyileştirilmesi amacı ile temiz ve taze havaya ihtiyaç vardır. Genellikle egzost edilen hava yerine direkt dış ortamdan taze hava alınır ve ortam havasının sıcaklığını sabit tutabilmek için (Örneğin dışarıdan -3 °C'de *alınan havanın +24 ÷ +26 °C'ye yükseltilmesi) ek ısıtma yapılması gerekir.*

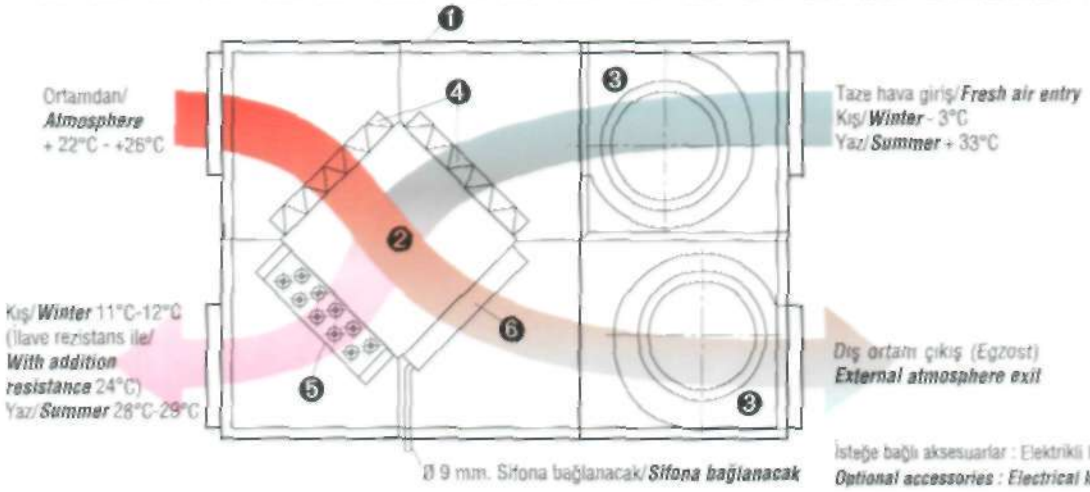
AHRV; üniteleri içinde bulunan ısı geri kazanım recuperatörü dışarı atılan hava ile, içeri alınan havanın birbirine teması sağlanmadan zıt hava akımı ile *havadan havaya ısı transferi yaparak dışarıdan içeri alınan havanın sıcaklığını ortam hava sıcaklığına yaklaştırır.* Gerekenden daha az kapasitede yardımcı bir ısı veya soğuk kaynağı ile istenilen ortam sıcaklığı sağlanmış olur. %70 verimlilikteki ısı recuperatörü ile %30 enerji tasarrufu gerçekleşir.

AHRV; ALDAĞ Heat recovery units is produced for saving energy of buildings large offices, residence, hospitals etc. where large amount of fresh air required. Product range between 500 m³/h - 2000 m³/h air volume. It is easy to mounting suspended ceiling and giving service with its specially designed. Compact unit with radyal fans runing silencely, high performance heat recovery, heat and accustic insulating completely leakness box.

For improving air quaality of heated and cooled places fresh and clean air are required. Generally instead of exhausted air fresh air taking directly and to obtain fixes temperature (for example; if -3°C supply air must be rised +24 -26°C) it is necessary to additional heating. AHRV units crossflow plate heat exchanger make heat transfer air to air to approximate supply air temperature to exhausted air temperature withcomplete seperation of supply and exhaust air flows. With using less heating or cooling capacity units optimum temperatures can be optained. % 30 energy saving achivable with % 70 efficiency heat exchanger.

TEKNİK ÖZELLİKLER / *TECHNICAL SPECIFICATIONS*

TİP/*TYPE*		5	7.5	10	15	20
Kapasite/Capacity (Debi/*Flow* m³/h)		500	750	1000	1500	2000
Motor Gücü/Motor Power (Watt) 220V 50Hz		2 x 147	2 x 147	2 x 300	2 x 550	2 x 550
Cihaz Dışı Basınç *External Pressure* (Pa)		120	100	150	200	180
Gürültü Seviyesi/*Sound Level* (dBA)		42	43	45	47	48
Boyutlar / *Dimensions* 	L	850	850	1000	1300	1300
	W	760	760	860	970	970
	H	360	360	400	400	400
Ağırlık/*Weight* (Kg)		40	44	55	68	70
Elektrikli Isıtma Serpantini *Electrical Heating Coil* (Kw)		3	3	5	7	10



1 - Ses ve ısı izolasyonu yapılmış hücre
2 - Recuperatör
3 - Direkt akuple radyal fanlar
4 - Filtre (Yıkanabilir)
5 - Isıtıcı rezistans (İsteğe bağlı)
6 - Damlama tavası

1 - Heat and accustic insulating
2 - Recuperator
3 - Radial fan
4 - Cleanable filter
5 - Heat resitance (Optional)
6 - Drain pan

İsteğe bağlı aksesuarlar : Elektrikli Isıtıcı Serpantin, Kontrol anahtarı (Hız ayar)
Optional accessories : Electrical heating, velocity control switch

2JALDAG ISITMA SOĞUTMA KLİMA SAN. ve TİC. A.Ş.

FACTORY & İSTANBUL REGION OFFICE
Yakacık (E5 Karayolu Üzeri)
Cumhuriyet Mah. Abdi ipekçi Cad. No: 3
Kartal 34876 İSTANBUL - TÜRKİYE
Phone : (90-216) 451 62 04 PBX
Fax : (90-216) 451 62 05

ANKARA REGION OFFICE
Sancak Man. 12,Cad. Sema Yazar Sok.
No: 10/5 - A Yıldız
Çankaya 06550 ANKARA - TÜRKİYE
Phone : (90-312) 441 41 82 PBX
Fax : (90-312) 441 92 76

İZMİR REGION OFFICE
1203 / 5 Sok. No: 10 / 318 Yener
iş Merkezi - Gıda Çarşısı
Yenişehir 35220 İZMİR - TÜRKİYE
Phone : (90-232) 449 00 88 PBX
Fax : (90-232) 449 87 88

BURSA REGION OFFICE
Yeni Yalova Yolu 4. Km. Buttim iş
Merkezi C Blok 5,Kat No:1475
16200 BURSA - TÜRKİYE
Phone : (90-224) 211 15 36 PBX
Fax : (90-224) 21115 38

ADANA REGION OFFICE
Kurtuluş Man. 9.Sok. No:4/A
01130 ADANA - TÜRKİYE
Phone : (90-322) 457 75 85
: (90-322) 457 51 45
Fax : (90-322) 458 69 95

www.aldag.com.tr E.Mail: aldag@aldag.com.tr

>KHfc

KOD NO: 12

ESG-ESG/V

HORIZONTAL AND VERTICAL STEAM OR PRESSURIZED WATER GENERATORS

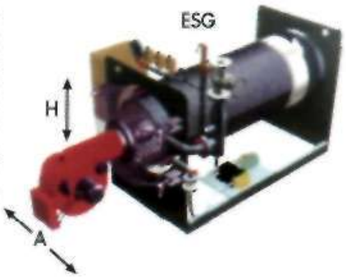
YATAY VE DİKEY BUHAR VEYA BASINÇLI SU JENERATÖRLERİ

www.erensan.com.tr

horizontal and vertical steam or pressurized water generators

Over 3000 units installed in every field of industry, from laundries to large chemical pharmaceutical, textile and mechanical factories have brillantly solved the problem of steam production at low costs. In the range of the model for producing steam power from 120 up to 8000 Kg/h, you can find the most suitable for your needs or realize high power plant with several units working simultaneously. **ESG** e **ESG/V** generators are forced circulation steam boilers based on the La Mont principle, according to which water, forced by one or several pumps, circulates through pipes forming the heated surface. This surface is devided into three sections. The first one forms the economizer which takes care of the water preheating until it reaches the evaporation temperature. The second one is the vaporizer where the water is transformed into steam. The third is the steam dryer, which dryes the water drops still floating. The reverse current heat exchange between water, steam and products of combustion, the deriving turbolent motions, the velocity of the fluids kept as constant as possible with the variation of the opening sections, allow to obtain a particulary efficient thermic transfer. The size of the furnace is designed on the average of all commercial burner. This grants both an extremely high efficiency (same or more than 90%) without preheaters or economizers, and longer life to the generators, even under the toughest working conditions. The utilization of conventional combustion systems grants a quick and cheaper service to the customer, anywhere in the world. **ESG** e **ESG/V** are steam generators designed for modern industry, to produce steam with the highers performance and the cheapest operating costs. **ESG** e **ESG/V** generators are delivered after the fire inspection performed by the manufacturer. Two steps burner and progressive modulated regulation burners with automatic range varying from 30 up to 100 % can be installed. The generators can be supplied with inspection by: R.I.N.A., Lloyd Register, A.PA.VE., T.U.V., A.I.B. VINCOTTE, DET NORSKE VERITAS, S.V.D.B. STOOMWEZEN, ISCIR.

ESG

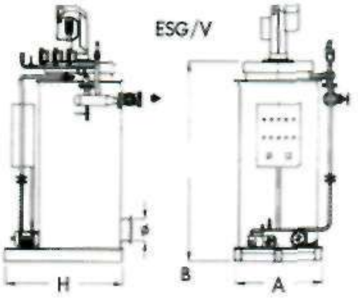


yatay ve dikey buhar veya basınçlı su jeneratörleri

Çamaşırhanelerden büyük kimyasal ürün, tıbbi ürün, tekstil ve makine fabrikalarına kadar sanayinin her alanında kurulu 3000 adet jeneratör, buhar üretimi sorununu akıllıca çözmüştür. Modelin 120 kg/h'ten 8000 kg/h'e uzanan buhar kapasitesi aralığında, ihtiyacınıza en uygun olanını bulabilir veya bir çok ünitenin aynı anda çalışmasıyla daha yüksek bir güç tesisi kurabilirsiniz. **ESG** ve **ESG/V** jeneratörleri bir veya daha fazla pompa tarafından beslenen suyun ısıtma yüzeyini oluşturan boruların içinde dolaşması anlamına gelen La Mant prensibine göre çalışan zorlanmış sirkülasyonlu buhar kazanlarıdır.

Yüzey 3 parçaya ayrılır. İlk parça buharlaşma sıcaklığına ulaşana kadar suyun ön ısıtmasını sağlayan ekonomizörü oluşturur. İkincisi suyun buhara dönüştüğü buharlaştırıcıdır. Üçüncüsü halen akmakta olan su damlalarını kurutan buhar kurutucusudur. Su, buhar ve yanma sonucu oluşan maddeler arasındaki ters akımlı ısı transferi, ortaya çıkan türbülans hareketleri, ve boşluk kısımlarındaki varyasyonla mümkün olduğunca sabit tutulan sıvı hızı özellikle verimli ısı transferi sağlar. Yanma odası boyutları piyasadaki tüm brülörlerin ortalama değerlerine uygun olarak dizayn edilmiştir. Bu en zor çalışma koşullarında dahi ön ısıtıcılar veya ekonomizörler olmadan çok yüksek verim sağladığı gibi (%90 veya daha fazla), jeneratörün ömrünü de uzatır. Geleneksel yanma sistemlerinin kullanılması dünyanın her yerindeki müşteriye hızlı ve aynı zamanda daha ekonomik servis olanağı sunar. **ESG** ve **ESG/V** modern sanayi için en yüksek performans ve en düşük işletim masraflarıyla buhar üretmek tasarlanmış buhar jeneratörleridir. **ESG** ve **ESG/V** jeneratörleri üretici tarafından yanma denetlemesi yapıldıktan sonra sevk edilir. Otomatik çalışma aralığı %30'dan %100'e kadar değişen iki kademeli ve progresif/oransal brülörler ile kullanılabilir. Jeneratörler aşağıdaki kurumlar tarafından yapılan denetlemelerle müşteriye sağlanabilir: R.I.N.A., Lloyd Register, A.PA.VE., T.U.V., A.I.B., VINCOTTE, DET NORSKE VERITAS, S.V.D.B., STOOMWEZEN, ISCIR.

ESG/V



Type/Tip	ESG-ESG/V	12	20	30	40	50	60	80	100	120	150
Steam prod./ Buhar Üretimi	Kg/h	120	200	300	400	500	600	800	1.000	1.200	1.500
Capacity/ Kapasite	kcal/h	72.000	120.000	180.000	240.000	300.000	360.000	480.000	600.000	720.000	900.000
Width / En	A	1.450	1.450	1.450	1.450	1.450	1.450	1.450	1.450	1.450	1.700
Lenght / Boy	B	1.600	1.600	1.600	1.600	1.600	2.250	2.250	2.250	2.250	3.250
Height / Yükseklik	H	1.550	1.550	1.550	1.550	1.550	1.650	1.650	1.750	1.750	1.880
Chimney/ Baca	Ø	180	180	180	180	180	250	250	250	250	350
Weight / Ağırlık	Kg	750	750	750	850	850	1.250	1.250	1.350	1.350	2.000

Type/Tip	ESG-ESG/V	180	200	250	300	400	500	600	700	800
Steam prod./ Buhar Üretimi	Kg/h	1.800	2.000	2.500	3.000	4.000	5.000	6.000	7.000	8.000
Capacity/ Kapasite	kcal/h	1080.000	1200.000	1500.000	1800.000	2400.000	3000.000	3600.000	4200.000	4500.000
Width / En	A	1.700	1.700	1.700	1.700	2.000	2.400	2.400	2.400	2.650
Lenght / Boy	B	3.250	3.250	3.450	3.900	4.100	4.200	5.000	5.400	5.700
Height / Yükseklik	H	1.920	1.920	2.040	2.040	2.150	2.350	2.350	2.350	2.600
Chimney/ Baca	Ø	350	350	450	450	550	550	600	650	700
Weight / Ağırlık ESG	Kg	2.250	2.250	3.300	3.700	4.600	6.200	7.000	7.700	9.000

erensan

"The Heating Engineer"

High Pressure Steam Boiler
"Three pass, fire-tube type"

Design Standards: Computer Aided Design in compliance with latest CE pressure equipment directives and EN
Large Water and Steam Volume : Ready for peak steam draws - suitable for fluctuating steam demands
Large Heating Surface : Drier steam, higher heat absorption
Wet – Back Design : Maximum benefit from heating surface.
Low Counter - Pressure : Easier combustion. Less burner power consumption
Welded Construction : Robust construction, safe operation and easy tube replacement
Design with Minimum Refractor : Low thermal inertia, reduced service cost and better heat transfer
Optimum Combustion Chamber Sizes : Well - distributed thermal loading More effective use of Radiation Heat Transfer Surfaces
Full combustion with low NOx
Three Pass / Three Draught : Suitable to operate with Rotary - cup Type or Pressure - jet Burners
High Efficiency : 90 % efficiency on LHV, without economizer... Savings on fuel
Wide Capacity Range : 1 ton/h - 25 ton/h steam

Plants

Erensan boilers are manufactured in two modern plants build over a total area of 45.000 m². Plants are located in Istanbul and in Yozgat. Istanbul plant and head office is near Atatürk International Airport and at the very heart of International Exhibition Centers. 10 minutes driving from the airport, Erensan can be reached from any country over the world. Istanbul being one of the main ports of world trade, transportation can easily be arranged to every destination through alternative choices.

Options:

Economizer (air or water type), Superheater

Yüksek Basınçlı Buhar Kazanı
"Üç Geçişli, Alev – Duman Borulu"

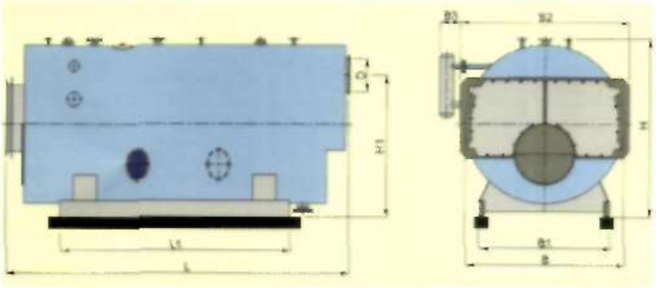
Tasarım Standartları : CE basınçlı kaplar direktifine, Avrupa normlarına (EN) uygun bilgisayar destekli dizayn
Büyük Su ve Buhar Hacmi : Ağır çalışma şartları ve ani buhar çekişlerine uygun
Yüksek Isıtma Yüzeyi : Daha kuru buhar
Wet - Back Tasarım : Isı transfer yüzeyinden maximum fayda sağlar
Düşük Karşı Basınç : Daha rahat yanma, daha az Brülör elektrik sarfiyatı
Aynaya Kaynaklı Borular : Emniyetli çalışma ve kolay boru değişimi
Minimum Refrakterli Dizayn : Düşük ısıl atalet, düşük servis maliyeti, külhanda daha iyi ısı transferi
Optimum Yanma Odası Boyutları : Düşük külhan ısıl yüklemesi, Radyasyon Isı Transfer Yüzeyleri'nin daha verimli kullanımı. Yanma Odası içinde tam yanma.
Düşük NOx
Üç Çekişli : Dönel tip ve basınçlı Brülör'le çalışabilme imkanı
Yüksek Verim : Ekonomizörsüz % 90' a varan verim, yakıttan tasarruf
Geniş Kapasite Aralığı : 1 ton/h - 25 ton/h

Üretim

Endüstriyel proses buharı ve ısı enerjisi üretiminde 40 yıllık bir deneyime sahip olan Erensan, İstanbul'daki tesislerinde, modern teknoloji ile üretim yapmaktadır.

Opsiyonlar:

Ekonomizör (su veya hava), Kızdırıcı



HPS BOILER DIMENSIONS
HPS KAZAN ÖLÇÜLERİ

Type/Tip	HPS	1210	1512	2016	2520	3025	4030	5040	7055	8570	10085	120100	150120	160150	200180	T-200180	T-250200
Steam Output / **Buhar Kapasitesi**	kg/h	1,200	1,500	2,000	2,500	3,000	4,000	5,000	7,000	8,500	10,000	12,000	15,000	16,000	20,000	20,000	25,000
Heat Output / **Isı Kapasitesi**	kW	815	1,019	1,358	1,698	2,038	2,717	3,396	4,754	5,773	6,792	8,150	10,188	10,867	13,584	13,584	15,980
Water Volume (Plain Combustion Chamber) / **Su Hacmi (Düz Külhan)**	lt	3,735	4,440	5,085	6,080	6,780	7,985	10,815	12,510	16,315	16,410	17,880	22,300	25,895	31,025	30,805	34,140
Water Volume (Corrugated Combustion Chamber) / **Su Hacmi (Ondüle Külhan)**	lt	3,850	4,580	5,250	6,275	7,000	8,240	10,930	12,890	16,770	16,905	18,435	22,935	26,630	31,870	31,875	35,335
Steam Volume / **Buhar Hacmi**	lt	905	1,045	1,180	1,360	1,530	1,855	2,340	2,660	3,810	3,810	4,070	5,085	5,920	7,320	7,790	10,420
L	mm	4,010	4,295	4,510	4,890	5,010	5,290	5,930	6,150	6,740	6,895	7,225	7,600	8,205	8,705	7,980	8,600
L1	mm	2,450	2,740	2,740	3,110	3,140	3,350	3,850	3,840	4,450	4,585	4,860	5,335	5,840	6,190	4,215	4,790
B	mm	1,852	1,912	1,995	2,080	2,180	2,300	2,470	2,670	2,880	2,975	3,100	3,230	3,400	3,580	4,030	4,075
B1	mm	1,530	1,550	1,600	1,670	1,770	1,870	2,040	2,050	2,350	2,360	2,400	2,560	2,700	2,860	3,325	3,500
B2	mm	1,980	2,090	2,170	2,215	2,350	2,475	2,690	2,835	3,080	3,215	3,340	3,370	3,535	3,780	4,295	4,340
B3	mm	295	250	260	290	255	235	275	275	335	315	270	380	456	435	250	250
H	mm	2,127	2,225	2,305	2,390	2,490	2,620	2,775	2,975	3,230	3,350	3,470	3,580	3,745	3,970	4,526	4,575
H1	mm	1,700	1,810	1,865	1,950	2,040	2,135	2,250	2,410	2,635	2,685	2,785	2,850	2,990	3,225	*	*
D	mm	300	300	350	400	450	500	600	700	750	800	850	950	950	1100	1100	1200
Air Went Nozzle / **Havalandırma Nozulu**	DN	20	20	20	25	25	25	25	25	25	25	25	32	32	32	32	32
Surface Blow-Off Nozzle / **Yüzey Blöf Nozulu**	DN	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Bottom Blow-Down Nozzle / **Dip Blöf Nozulu**	DN	32	32	32	40	40	40	40	40	40	40	40	40	40	40	40	40
Counter Pressure / **Karşı Basınç**	mbar	5	6	7	8	8	8	9	8	8	9	9	10	10	10	10	11
Approx Empty Weight / **Yaklaşık Boş Ağırlık****	ton	4.7	5.3	6.2	7.2	8.1	9.6	12.2	15	18.8	21.5	23.9	27.8	34.6	42	42.7	47.7

(*) Upper flue - gas connection / Baca Çıkışı Üstten
(**) Approx empty weight is given for 10 bar operation pressure / Yaklaşık ağırlık, işletme basıncı 10 bar olan kazanlar için verilmiştir.

KT52101 - 1

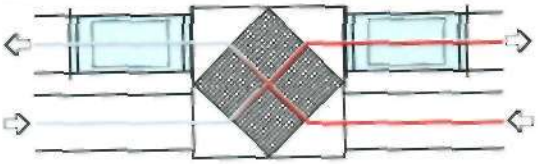
erensan
"Isı Mühendisi"

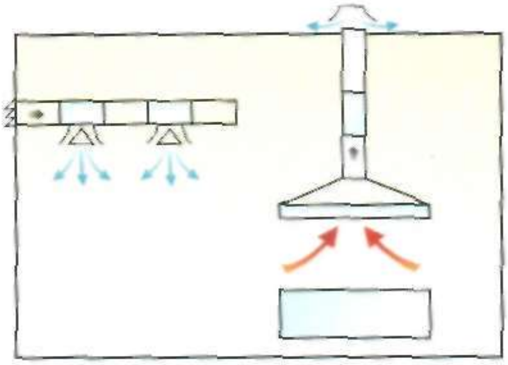
AKA KANAL TİPİ FANLAR / *IN - LINE FANS*

AKA Kanal fanları; ekonomik havalandırma aplikasyonları için ideal olarak tasarlanmıştır. Kolayca kanala bağlanabilir; aspirasyon, vantilasyon için kullanılırlar. Kabul edilebilir hava hızlarına göre seçilen cihazlar sessiz çalışarak çevreyi rahatsız etmezler.

The "AKA" unit represents a modern and economic solution for the use of centrifugal fans on ducted applications. They are supplied with duct section calculated to give normally accepted air velocities.

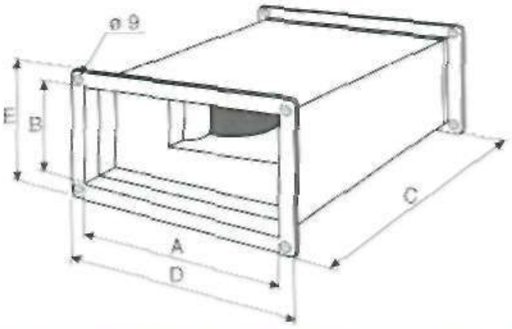
TEKNİK BİLGİLER / *TECHNICAL DATA*





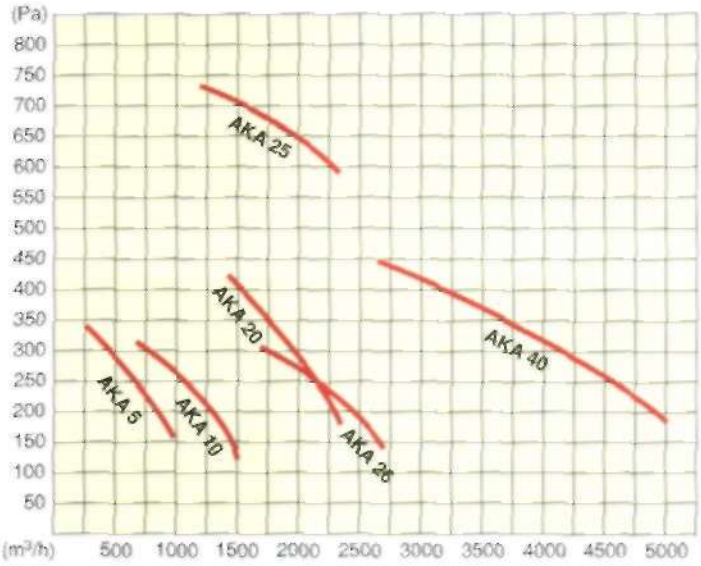
TİP / *TYPE*	Hava Debisi *Air Flow* m³/h	Total Basınç *Pressure* Pa	Voltaj *Voltage* V 50 Hz	Güç *Power* Watt	Kutup Sayısı *Poles Number* n	Amper *Ampere* I	Ses Seviyesi *Sound Level* dB (A)
AKA 5	500 750	290 220	230	147	4	1.2	60 65
AKA 10	1000 1300	260 200	220/240	300	4	2.4	65 67
AKA 20	2000 2200	300 190	230	550	4	4.3	65 67
AKA 25	1500 2600	710 550	220/240	550	4	5.4	66 68
AKA 26	1500 2600	300 160	220/240	515	6	4.3	63 66
AKA 40	4000 5000	300 180	220/380	1300	6	5.5/3.1	70 73

ÖLÇÜLER / *DIMENSIONS*



TİP / *TYPE*	A	B	C	D	E	Ağırlık *Weight* Kg
AKA 5	400	300	500	450	350	18
AKA 10	500	350	600	550	400	25
AKA 20	600	350	700	650	400	28
AKA 25	600	350	700	650	400	37
AKA 26	600	350	700	650	400	37
AKA 40	700	450	800	750	500	49

PERFORMANS EĞRİLERİ *PERFORMANCE CURVES*



SELNİKEL, yeniden tevsi ve modern makinalarla takviye ve teçhiz olunan fabrikasında, Dünya çapında şöhrete ve 100 yılı aşkın bir geçmişe sahip BABCOCK-BSH (Büttner-Schilde-Haas) firmasından sağladığı teknik yardımla, en ileri teknolojinin ve modern tekniğin imkanlarından faydalanarak, 30 yıldan beri imalât programına dahil bulunan Endüstri Vantilatörü imalâtını daha da geliştirmiş ve mükemmelleştirmiştir.

Bugün Firmamız, uluslararası norm ve standartlara uygun imâlatı ile, Çimento, Cam, Demir Çelik, Boya, Kimya, Ağaç, İlaç, Kağıt, Tütün, Tekstil gibi genellikle bütün endüstri tesislerinin ihtiyaç ve taleplerine cevap verecek bir seviye ve kapasiteye erişmiştir.

With the technical cooperation of the world-famous century old Firm of "BABCOCK-BSH" (Büttner-Schilde, Haas) and by utilizing the means and facilities that the most advanced technology and modern techniques can offer, SELNİKEL, at its new factory supplemented by the latest machinery, has even further developed and perfected the manufacturing of industrial fans, which have been a part of SELNİKEL's production programme for the past 30 years.

Today our Company, manufacturing according to international standards and norms, has attained a wide-range level and capacity which enables it to meet the needs and demands of almost all types of industrial plants, such as those engaged in the production of Cement, Glass, Steel, Paint, Chemicals, Wood, Pharmaceuticals, Paper, Tobacco, Textiles etc.

- **İçerisinde serbest halde kuru toz bulunan gaz veya normal hava vantilatörleri**
- **Tozlu akışkanlar ve küçük materyal parçalarının sevki için uygun fan tipleri**
- **Kanatlara yapışmaya müsait toz veya materyal sevki için uygun fan tipleri**
- **Baca gazı aspiratörleri**
- **% 87 Değerine ulaşan yüksek verim**
- **Exproof vantilatörler**
- **Malzeme:**
  - **Karbon çeliği,**
  - **Isıya mukavim çelik,**
  - **Aşınmaya dayanıklı çelik,**
  - **Paslanmaz çelik,**
  - **Zırhlanmış çelik.**

- *Fans for clean air and for gases containing free dry dust*
- *Fans for dusty fluids and for transport of small material pieces*
- *Fans for transport of dust or materials which adhere to the blades*
- *Flue gas exhaust fans*
- *High efficiency up to 87%*
- *Exproof fans*
- *Materials:*
  - *Structural steel,*
  - *Heat resistant steel,*
  - *Wear resistant steel,*
  - *Stainless steel,*
  - *Armored steel.*

KAT KLİMASI: normal katların, villaların, yazlık evlerin, büroların, banka hollerinin, restaurantların vb. yerlerin soğutulması ve ısıtılmasını sağlayan cihazlardır. Bir veya birkaç iç ünite (Fancoil) ve bir dış üniteden oluşmaktadır.
Split klima cihazlarının alternatifi olan cihazlar soğutma veya ısıtma işlemini su ile yapmaktadır. Böylece mahal içlerinden bakır R22 gaz *borularının geçmesi önlenmiştir. Cihazlarda Heat Pumps sistemi ile ısıtma yapılarak enerji tasarrufu sağlanmıştır. Sadece soğutmalı tiplerin* montajında mevcut kat kaloriferi veya doğalgazlı kombi kazanları ile kombinasyon yapmak mümkün olmakta ve ısıtma - soğutma ihtiyacı karşılanabilmektedir.
ALDAĞ Kat Kliması *montaj, bakım ve işletme kolaylığı nedeniyle tercih edilen cihazlardır.* Klimatizasyon suyu dış ünitede istenilen şartlara getirilmekte (Yazın 6 - 10 °C, Kışın 45 - 55 °C), mahal içindeki Fancoil Unit'lere alışılagelmiş boru tesisatı ile (Siyah veya galvaniz dişli boru, mavi veya yeşil boru vs.) şartlandırılmış su iletilmektedir.
Dış ünite binaların balkon ve terasına konulabildiği gibi, binanın alt kısmına bahçe, park vb. yerlere de konulabilmektedir.

Home type chiller is used in flats, villas, holiday resorts, offices, banks, restaurants, etc. for cooling or heating purposes. It consists of one or more fan coils and an external unit. Designed as an alternative to split air-conditioners, these air-conditioners uses water for the cooling or heating process so that it is not necessary to install copper R22 gas pipe inside the space to be conditioned. Air-conditioners designed for cooling only can be combined with an existing individual combi heating system or natural gas central heating system, so that both cooling and heating functions can be provided.
ALDAĞ independent air-conditioners are preferred because they are easy to maintain and oparate.
Conditioning water is delivered to the external unit at any temparature (generally 6-10°C in the summer, 45-55°C in the winter), and is fed to the fancoils inside the space by means of a conventional piping system (black or galvanized steel pipe, blue or green PVC pipe, etc.). The external unit can be mounted to a balcony, terrace, garden, park, etc.

TEKNİK ÖZELLİKLER / *TECHNICAL SPECIFICATIONS*

1 - DIŞ ÜNİTE : Soğutma kompresörü, plakalı eşanjör, sessiz çalışan fanları ve kondenser bataryası ile su sirkülasyon pompasından oluşmaktadır ve bir sac kabin içine yerleştirilmiştir. Ortam dışına, balkon, dış duvar, teras vb. yerlere monte edilirler.

1 - EXTERNAL UNIT : It consists of a cooling compressor, a plate exchanger, silent fans, a condenser coil, and a water circulation pump, which are placed in a cabin made of steelplate. It is mounted to a balcony, external wall, terrace, etc.

2 - İÇ ÜNİTE : Sessiz çalışan fanları ve dekoratif kabini ile iç ortama yerleştirilirler. Bir termostat ile kumanda edilen ünite ortamın istenilen sıcaklıkta kalmasını sağlar.

2 - INTERNAL UNIT : It consists of silent fans and a decorative cabin, installed within the space to be conditioned.
A thermostat controls the unit to keep the space at the preset temparature.

3 - BORU DONANIMI : İç ünite ile dış ünite arasında normal kalorifer tesisatında kullanılan dikişli çelik ve galvaniz borular kullanılır. Monte edilecek yerde müstakil bir kalorifer tesisatı var ise ondan da yararlanılabilmektedir.

3 - PIPING : Seam steel and galvanized pipes are used for connecting the internal unit to the external unit, as in conventional central heating systems. If an independent heating system is available in the space to be conditioned, this unit can be connected to that system.

TİP / *TYPE*	AKK-7	AKK-10	AKK-12	AKK-16
Soğutma Kapasitesi / *Cooling Capacity* (Kcal / h - Kw)	7500/8.72	10000/11.63	12000/13.9	16000/18.6
Isıtma Kapasitesi / *Heating Capacity* (Kcal / h - Kw)	8450/9.82	11300/13.14	13550/15.75	18050/20.98
Kompresör / *Compressor* Hermetic (Ad.)	1	1	1	1
Hava Debisi / *Air Flow Rate* (m^3/h - Kw)	7000	7000	8000	11000
Su Debisi / *Water Flow Rate* (Lt / h)	1875	2500	3000	4000
Basınç Düşümü / *Pressure Drop* (Su Tarafı / *Water Side*) (mSS)	2.5	2.7	2.8	2.9
Toplam Güç / *Total Power* (Kw) 380 Volt / 3 Faz / 50 Hz	4	5	5.8	7.9
Uzunluk / *Length* (mm)	900	1100	1100	1100
Derinlik / *Depth* (mm)	500	500	500	500
Yükseklik / *Height* (mm)	1050	1050	1050	1050
Ağırlık / *Weight* (Kg)	110	125	145	165
Giriş Çıkış Bağlantıları / *Input-Output Connections*	1"	1"	1"	1"

Her hakkı mahfuzdur. Kapasite ve ölçüler haber verilmeksizin değiştirilebilir. / ***The data in this brochures are not binding. With a view to continuous product improvement, ALDAĞ reserves the right to make changes without prior notice.***

ALDAĞ ISITMA SOĞUTMA KLİMA SAN. ve TİC. A.Ş.

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Sancak Mah. 12.Cad. Sema Yazar Sok.
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Çankaya 06550 ANKARA - TÜRKİYE
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Yeni Yalova Yolu 4. Km. Buttim İş
Merkezi C Blok 5.Kat No:1475
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AE Serisi / *Serie* — *Fan Coil Units*

ALDAĞ AE serisi fan coil cihazları 8 ölçüde, 6 değişik özellikte monte edilebilecek şekilde imal edilmektedirler.

- Döşeme tipi, kasetli veya ayaklı, önden ve alttan emiş havalı,
- Tavan tipi kabinli, arkadan ve önden emişli, tavana monte edilebilir,
- Kabinsiz gizli döşeme ve tavan tipi.

İsteğe bağlı olarak standart fan coil cihazları aşağıdaki şekilde sipariş verilebilir :

- Tek sıralı ilave ısıtma bataryalı 4 borulu sisteme uygun
- 3 yollu vanalı ve çok fonksiyonlu termostatlı
- Manuel veya motorlu taze hava damperli
- Plenum hücresi 90°
- Gizli tiplerde boyalı dekoratif panelli

İÇ ÜNİTE

0,8 - 1 mm galvanizli sacdan konstrüksiyona sahiptir.
Bütün iç üniteler duvara ve tavana monte edilebilecek şekilde montaj delikleri açılmış olarak imal edilmişlerdir.
Sadece ısıtmaya çalışan fan coiller hariç tüm fan coillerde ana yoğuşma tavası bulunur ve damlamayı önlemek için 3 mm. thermal izolasyon uygulanmıştır.
Su giriş çıkış boruları üzerine bağlanan elemanlardan gelen yoğuşma, ilave damlama tavası konularak önlenmiştir.
İç gövde, ses ve titreşimin önlenmesi için özel takviyeli büküm ve pres işçiliği ile şekillendirilmiştir.

BATARYA

Standart ölçülerde alüminyum kanatlar bakır boru üzerine mekanik genleşme metodu ile fikse edilmiştir. Böylece en yüksek ısıl verim sağlanır. Su giriş - çıkış bağlantıları prinç dişli 1/2" ve 3/4" 'tir. Ve önden bakıldığında sol veya sağ bağlantılı imal edilebilir.

FAN

Dinamik ve statik balansı alınmış kendinden motorlu çift emişli santrifüj fan kullanılmaktadır. Tiplere göre; 4 veya 5 hızlı, 1,2 veya 3 adet fan bağlanmıştır. Standart olarak 3 hız seçilir.
Avrupa standartları ve özelliklerinde olan fan; son derece sessiz çalışır.

KABİN

Modern, dekoratif bir görünüme sahiptir.
Standart beyaz (RAL 9002) renktedir. 0.8 - 1 mm. galvaniz sac üzerine epoksi toz boyadır. ABS plastik panjurlara ve kontrol paneline kolayca ulaşılacak hareketli yan panjurlara sahiptir.
Hava, panjurlar vasıtası ile 60° açıda ortama üflenir.

KONTROL PANELİ

Fan colli çalıştıracak hız anahtarı ve şalterin bulunduğu paneldir. İsteğe bağlı olarak 3 hızlı, yaz - kış konumlu, on - off termostat bağlanacak şekilde dizayn edilmiştir.

HAVA FİLTRESİ

Özel olarak tasarlanmış kızaklı ve kolayca çıkarılabilen filtre, EUI sınıfında ve yıkanabilir. Polypropylene materyaldendir.

ALDAĞ AE type fan coil units available in 8 sizes and 6 different versions to suite any kind of installation.

- *Vertical with cabinet or feet, with bottom and frontal air supply,*
- *With cabinet from ceiling installation, with back or frontal air return,*
- *Conceled vertical or ceiling installation (Without cabinet).*

To match any request standart unit can be supplied with a wide variety of optionals :

- *Auxiliary heating coil for a 4 pipe system*
- *3 - way valves and multi - function thermostat*
- *Manuel or motorized fresh air louver*
- *90° plenums*
- *Painted wooden with decorative panel for recessed units.*

BEARING STRUCTURE

Made of 0.8 - 1 mm. galvanized steel. All of this units provided with holes for wall and ceiling installation. All units are equipped with a main drain pan (Except heating fan coil units). Drain pan covered by 3 mm. thickness thermal insulation. Auxiliary drain pan for valve condensate collecting is available as option.
This unit shaped with rain forcement torsion and press work for prevent to sound and vibration.

COIL

Standard coil is made byaluminium fins fixed on mechanically expanded copper pipes. In this way provided maximum thermal production. Water inlet and outlet connections made of brass pipe with 1/2" and 3/4". Standard units are supplied with left hand coil connections. Optionally, right hand connection side is supplied.

FAN SECTION

Built with 1, 2 or 3 aluminium fans, double inlet centrifugal type, dynamically and statically balanced, fan has 4 or 5 speeds; 3 of these are connected in the factory. Particularly efficient with very low noise levels.

CABINET

Modern and elegant design. White standard colour; optionally RAL 9002 colour is available. The casing is made of baked - on epoxy coated galvanized steel 0.8 - 1 mm. ABS discharge grilles, part of the grille is hinged for easy access to the control panel. Air is blown by air shutter with 60° angle.

CONTROL PANEL

Panel with circuit breaker and speed switch working the fan coil. Designed optional on request as 3 speeds switch, summer / winter switch or on / off switch.

AIR FILTER

Specially designed sliding and easy extract filter. Regenerable by washing; filtration class EU1. Made of polypropylene.

IMAS

CLIMAVENETA

TC/SRAT 0401-1402

Air cooled liquid chillers

WITH AXIAL FANS

ICIM CISQ CE

HCFC R-22

HFC R-407C

Screw Compressors

IQNet

CERTIFICATE

Air cooler liquid chillers

Unit description

This series finds a wide range of applications in modern air-conditioning systems in civil and industrial contexts calling for medium capacity systems. They incorporate all the features required for ourdoor location. In particular the semi-hermetic screw compressors are housed in a purpose built soundproofed closed compartment. The control panel is protected by a double enclosure designed specifically for outdoor locations.

Standard Unit Composition

- Base of galvanized hot-painted sheet steel.
- *Outer casing made of paraluman and frame of aluminium* structural sections.
- 2 semi-hermetic screw compressors.
- Axial fans with six-pole motors and die-cast aluminium blades, with IP54 protection ratio.
- Thermally insulated evaporator, with asymmetric refrigerant paths.
- Thermostatic heating element for evaporator anti-frost protection.
- Condensing coil with cooper tubes and aluminium fins, complete with subcooling circuit.
- Thermostatic expansion valves. Dryer filters. Sight glasses. Solenoid valves on the liquid line.
- Electrical power and control panel complying with EN 60204-1/IEC 204-1 standards.
- Microprocessor control system.
- *Freeze-proff oil charge and refrigerant charge.*
- Interlock door mains isolator.
- General testing and operational test carried out in the factory.

Hava soğutmalı chiller grubu

Cihaz tanıtımı

Bu "Chiller" serisi, sivil ve endüstriyel çevrelerde orta kapasiteli sistemler olarak tanınan, modern havalandırma uygulamalarının geniş kapsamlı olarak yapılanmasını içermektedir. Dış tesisatlar için gerekli olan tüm özellikleri bünyesinde içermektedir. Özellikle, yarı hermetik vidalı kompresörler sese dayanıklı kapalı bölme içine yerleştirilmişlerdir. Kontrol panelleri özellikle dış tesisatlar için çift kapaklı olarak korunmaktadır.

Standart Cihaz Özellikleri

- Temeli galvanizli sıcak-boyalı çelik levhadan yapılmıştır.
- *Dış kasası cihaza uygun alüminyum bölmelerden oluşan* çerçeve ve paralumandan yapılmıştır.
- Üzerinde 1 veya 2 yarı hermetik vidalı kompresör vardır.
- Üzerinde IP54 koruma oranı ile basılmış alüminyum kanat ve 6 kutuplu elektrik motorları ile aksiyal fanlar bulunmaktadır.
- Asimetrik soğutucu hatları ile termik izoleli evaporatör kullanılmıştır.
- Anti-frost (donmàya karşı) korumalı evaporatör için ısıtıcı *elemanı vardır.*
- Bakır borular ve alüminyum eletli kondens eşanjörü subkuling ile devre tamamlanmıştır.
- Üzerinde termostatik ekspenşın vanaları, drayer filtreler, gözetleme camı ve likit hattı üzerinde solenoid vanası vardır.
- Elektrik güç ve kontrol panoları EN 60204-1/EC 204-1 standartlarına uygundur.
- Mikropressör kontrol sistemi vardır.
- *Donmaya dayanıklı yağ ve soğutucu şarjları vardır.*
- Ara kilit kapıları ana izolatörleri kapatır.
- Genel ve çalışma testleri fabrikamızda yapılmaktadır.

TERMOSİFON

THERMOSIPHON (ELECTRIC WATER HEATER)

Isıtıcı akışkan temininin zor olduğu yerler veya elektrik enerjisinin kullanımının tercih edildiği yerlerde hijyenik sıcak su temini için en pratik ve kolay çözüm yolu KODSAN termosifonlar:

- İç yüzey toz emaye kaplama
- Katodik koruma için Magnezyum anot
- Poliüretan izolasyonlu
- Elektrostatik toz boyalı dış kılıf
- Kolay montaj yapılabilir
- *5 litreden 100 litreye kadar farklı kapasitelerde*
- Serpantinli-serpantinsiz
- Yatık veya dik

özellikleri ile estetik, dayanıklı, hijyenik bir sıcak su kaynağıdır.

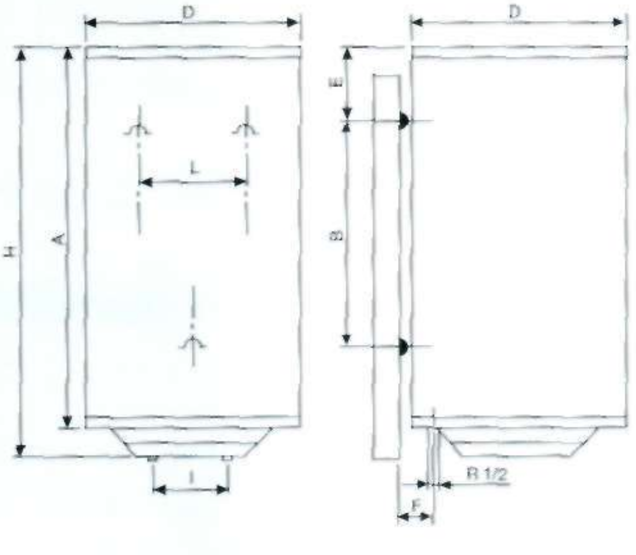
The difficult to find heating liquid or prefer to use electric energy for hot water, the best way to use KODSAN thermosiphons:

- *Inside powder enameled*
- *Magnesium anode for chaotic protection*
- *PU insulation*
- *Powder paint outside cover*
- *Easy to montage*
- *Different capacity from 5 liters to 100 liters*
- *With serpantines or not*
- *Vertical or horizontal*

With all these specialties, aesthetic, durable, hygienic water heaters.

BOYUT TABLOSU / DIMENSIONS

MODEL *Type*	LİTRE *Litres*	BOYUT / *Dimensions (mm)*								İŞLETME BASINCI *Working Pressure*	ISITICI *Heater (kw)*
		D	H	A	B	F	L	I	E		
KT 5	5	250x210	400	-	220	80	150	90	80	8 atü	1.5
KT 10	10	250x235	450	-	260	80	160	90	80	8 atü	1.5
KT 30	30	Ø430	410	375	-	110	260	100	180	8 atü	2
KT 40	40	Ø430	479	444	110	110	260	100	180	8 atü	2
KT 50	50	Ø430	556	521	-	110	260	100	180	8 atü	2
KT 60	60	Ø430	637	602	268	110	260	100	180	8 atü	2
KT 80	80	Ø430	802	767	433	110	260	100	180	8 atü	2
KT 100	100	Ø430	929	894	560	110	260	100	180	8 atü	3



FABRİKA / FACTORY

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e-mail: info@kodsan.com.tr

Yetkili Satıcı / Distributor

Banyo ve mutfaklarda ısıtma ve havlu kurutma amaçlı üretilen BAYKAN Havlu Radyatörleri 6 farklı genişlik, 6 farklı yükseklik , farklı renk ve tipleriyle sizlere geniş bir ürün yelpazesi sunmaktadır. Oval modellerin estetik görünümü ve banyonuz renklerine uygun değişik renk alternatifleri ile ısınma ve havlu kurutmayı şıklıkla birleştirebilirsiniz. Banyonuza en uygun renkteki havlu radyatörlerin yanı sıra, ortamdaki musluk ve armatürlerle mükemmel uyum sağlayacak olan krom kapmalı havlu radyatör seçenekleriyle de şıklık sınırlarını zorlayabilirsiniz.

Tüm üretimin TS-EN 442 normlarına uygun olarak otomasyonla yapıldığı tesislerde, titiz bir imalat ve kalite kontrol aşamalarından sonra, RAL standartlarındaki epoksi polyester elektrostatik toz boya kullanılır. Tüm mamül 13 barda test edilerek naylon ve karton kutu ile ambalajlanır. BAYKAN Havlu Radyatörleri 5 yıl süreyle garanti kapsamında satışa sunulur.

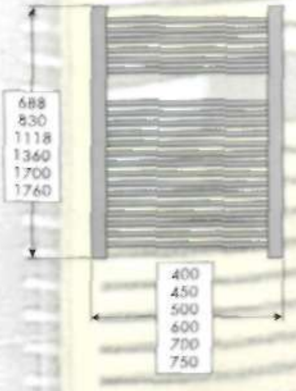
Şıklığın ön planda olduğu banyo ve mutfaklarınızda en az yer kaplayarak ortamı ısıtmanın yanı sıra havlu kurutma amaçlı olarak da dizayn edilen havlu radyatörler yüksek kaliteli ve montajı çok kolay olan montaj aksesuarlarıyla birlikte teslim edilir.

BAYKAN towel warmers which are produced for heating and towel warming for bathroom and kitchens are presenting a wide range of products to you with 6 different width, 6 different heights, different color and types. You can unify the heating and towel warming and the aesthetic outlook of oval shape models together with various color alternatives suitable to colors of your bathroom with Elegance. Besides the most suitable colored towel warmers for your bathroom, you can push the limits of Elegance with chromium- plated towel warmer variations which will enable a perfect harmony with the tap and armatures at place. After meticulous production and control phases, in factories where all the production is made according to TS-EN 442 standards with automation, electrostatical epoxy powder in RAL standards is applied. All the products are tested under the pressure of 13 bar and packaged by nylon and carton. Baykan Towel Warmers are presented with 5 year guarantee.

Baykan Towel Warmers which are designed with the purpose of heating the places along with warming towels with a minimum place occupancy in your bathrooms and kitchens where the Elegance is emphasized, are delivered with installation accessories that are of high quality and easy to install.

Estetik görünümü ve banyonuz renklerine uygun çeşitli renk alternatifleriyle ısıtma ve havlu kurutmayı şıklıkla birleştirebilirsiniz.

With aesthetic outlook and suitable color variations for your bathroom, you can unify the heating and towel warming together with elegance.



20°C banyo ortamında,
90-70°C su giriş çıkış sıcaklığında ısı verimleri.
Heating Efficiency in a bathroom temperature of 20°C , water in-out temperature 90-70°C.

ÖLÇÜ Size (mm)		BAĞLANTI EKSENİ Connection Axis (mm)	SU HACMİ Water Volume (lt)	ELEKTROSTATİK EPOKSİ POLYESTER Electrostatical Epoxy Polyester		KROM KAPLAMA Chromium Plate	
EN Width	BOY Height			WATT	Kcall	WATT	Kcall
400	688	355	3.17	496	427	397	341
	830		3.84	575	495	460	396
	1118		5.12	826	710	661	568
	1360		6.25	917	789	734	631
	1700		7.84	1197	1030	-	-
	1760		7.91	1230	1058	-	-
450	688	405	3.45	540	464	432	372
	830		4.12	631	543	505	434
	1118		5.58	868	746	694	597
	1360		6.71	1024	881	819	704
	1700		8.30	1243	1069	-	-
	1760		8.60	1271	1093	-	-
500	688	455	3.73	583	501	466	401
	830		4.40	692	596	554	476
	1118		6.03	909	782	727	625
	1360		7.16	1101	947	881	758
	1700		8.75	1437	1136	-	-
	1760		9.29	1476	1269	-	-
600	688	555	4.30	684	588	547	470
	830		4.97	810	697	648	557
	1118		6.95	1004	863	803	691
	1360		8.08	1290	1110	1032	888
	1700		9.67	1686	1450	-	-
	1760		10.67	1707	1468	-	-
700	688	655	4.86	788	678	630	542
	830		5.53	905	779	724	623
	1118		7.85	1161	998	929	799
	1360		8.98	1470	1222	1176	1011
	1700		10.57	1926	1657	-	-
	1760		12.05	2022	1739	-	-
750	688	705	5.15	834	717	667	574
	830		5.82	925	796	740	636
	1118		8.32	1230	1058	984	846
	1360		9.45	1586	1364	1269	1091
	1700		11.04	2062	1773	-	-
	1760		12.88	2142	1842	-	-

Baykan®

DOĞALGAZ MALZEMELERİ PAZARLAMA SAN. TİC. A.Ş.

Merkez *Central Office* & **Merkez Servis** *Central Service:*
İkitelli Organize San. Böl. Haseyad Kooperatifi, Turgut Özal Cad.
1. Kısım No:147/1 Küçükçekmece 34670 İSTANBUL/TURKEY
Tel:+90.212.671 20 55 pbx Fax:+90.212.671 20 60
www.baykangrup.com e-mail: baykanas@baykangrup.com

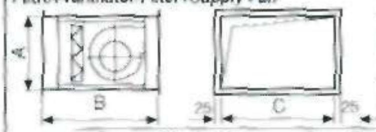
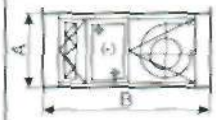
ALO Baykan
0800 219 6817

Kat Klima Santralları **ALKK** *For Ceiling Void Mounting Air Handling Units*

TEKNİK ÖZELLİKLER / *TECHNICAL DATA*		ALKK 100	ALKK 115	ALKK 120	ALKK 130	ALKK 140
HAVA DEBİSİ / *AIR FLOW* m3/h		1000	1500	2000	3000	4000
SOGUTMA KAPASİTESİ *COOLING CAPACITY*	Toplam/*Total* kcal/h	6000	8150	9940	16240	19860
	Duyulur/*Sencible* kcal/h	4000	5580	6940	11130	13855
ISITMA KAPASİTESİ *HEATING CAPACITY*	90 / 70 °C Kcal / h	12690	16925	20575	33200	40350
	80 / 60 °C Kcal / h	10575	14100	17100	27500	33350
FAN TİPİ / *FAN TYPE* Alternative 1 / 2		0991	0991	0991	0992	0992
TOPLAM BASINÇ / *TOTAL PRESSURE* (Pascal)		380	380	370	380	370
FAN MOTOR GÜCÜ / *FAN MOTOR POWER* 230 V / 50 HZ		373/2.4	373/2.6	373/3.0	750/5.2	750/6.0
SES SEVİYESİ / *SOUND LEVEL* dB (A)		53	61	60	62	63

Soğutma / **Cooling** - Oda Sıcaklığı / **Room Temperature** : 27 °C % 50 RH Su Giriş - Çıkış Sıcaklığı / **Water Inlet - Outlet Temperature** : 7 / 12 °C Hava Giriş Sıcaklığı / **Air Inlet Temperature** T_G : 18 °C

BOYUTLAR / SIZES

TİP / *TYPE*		ALKK 100	ALKK 115	ALKK 120	ALKK 130	ALKK 140
Filtre+Vantilatör / *Filter+Supply Fan* 	A	425	425	425	425	425
	B	650	650	650	650	650
	C	600	600	600	1100	1100
Basınç Kaybı / *Pressure Drop* Pascal		65	80	90	65	90
Ağırlık / *Weight* Kg		25	25	25	40	45
 Filtre+Isıtıcı+ Vantilatör *Filter+Heater+ Supply Fan*	A	425	425	425	425	425
	B	850	850	850	850	850
	C	600	600	600	1100	1100
Basınç Kaybı / *Pressure Drop* Pascal		85	100	110	85	110
Ağırlık / *Weight* Kg		35	35	40	50	55
 Filtre+Soğutucu+ Damla Tutucu+ Vantilatör *Filter+Cooler+ Seperator+ Supply Fan*	A	425	425	425	425	425
	B	1000	1000	1000	1000	1000
	C	600	600	600	1100	1100
Basınç Kaybı / *Pressure Drop* Pascal		105	120	130	105	130
Ağırlık / *Weight* Kg		50	50	50	65	70
 Filtre+Isıtıcı+ Soğutucu+ Damla Tutucu+ Vantilatör / *Filter+ Heater+Cooler+ Seperator+ Supply Fan*	A	425	425	425	425	425
	B	1100	1100	1100	1100	1100
	C	600	600	600	1100	1100
Basınç Kaybı / *Pressure Drop* Pascal		130	150	160	130	160
Ağırlık / *Weight* Kg		55	55	55	85	90
 Karışım+Damper *Mixture+Damper*	A	425	425	425	425	425
	B	850	850	850	850	850
	C	600	600	600	1100	1100
Basınç Kaybı / *Pressure Drop* Pascal		60	65	70	75	85
Ağırlık / *Weight* Kg		20	20	20	30	30
 Susturucu / *Silencer*	A	425	425	425	425	425
	B	650	650	650	650	650
	C	600	600	600	1100	1100
Ses Yutumu / *Sound Absorber* dB (A)		20	20	20	20	20
Basınç Kaybı / *Pressure Drop* Pascal		65	75	80	85	95
Ağırlık / *Weight* Kg		30	30	30	40	40

Kat klima santralları, ofisler, işmerkezleri, oteller ve restaurantlarda aynı hacim içersindeki farklı mahallerin ayrı ayrı klimatizasyonu amacına yönelik olarak dizayn edilmiştir. Bu tip santrallar mahal içersindeki asma tavan arasına yerleştirilebildiği için yer kaplamazlar, makina dairesi gerektirmezler. Montaj kolaylığının yanısıra havanın taşınması için uzunca büyük boyutlu kanallar kullanılmamasıda yatırım maliyetlerini düşürür.

GÖVDE : Özel şekillendirilmiş galvaniz sac üzeri elektrostatik toz boyalıdır. Ses ve ısıya karşı izole edilmiştir. Bakım ve montaj kolaylığı özel kapaklar vasıtasıyla kolayca yapılır.

VANTİLATÖR : Direkt akuple kendinden motorlu çift emişli radyal fan kullanılmaktadır.

Air handling units for ceiling void mounting for central heating, aeration, ventilation and air conditioning in offices, commercial buildings, hotels, living accommodation, restaurants etc.

***HOUSING :** Casing is build as a insulated and electrostatic painted galvanized steel.*

***VENTILATOR :** Double inlet direct driven radyal fan is used.*

DİPAZ

Evaporative Cooler

Evaporative cooling and humidifying

Summer heat can cause indoor conditions to become much hotter than desired. Evaporative cooling and humidifying is the economical method to reduce temperatures inside buildings by natural way. The system contains cooling pads, fan, water pump and sump all together. The pump supplies water from the sump to the pads. The pads will be kept wet. When hot and dry air induced trough wetted pad surface by fan, it will be humidified and cooled. The relative humidity of entired hot and dry air will increase, intake air temperature will decrease. Needed ideal ambient moisture level will be also reached. The dryer the air the faster the water evaporates and the higher the temperature reduction by evaporative cooling system.


Dipaz Cooling Pad


Easy Changeable Pads

Ideal cooling solution in big premises

- *Big advantages in investment. Your investment pays off quickly.*
- Offers effective, high quality cooling at an extremely low operational cost.
- Increases worker productivity by making the environment more comfortable.
- Easy and quick installation, wherever the cooled air is required.
- Back-up or assistant when the conventional cooling system is inoperable.
- Easy maintenance by take off and take on of casette-pads without bolt and nut.
- High cooling efficiency even in high relative humidity conditions.
- Allowed % 100 fresh air handling and air filtration.
- Elimination of warm, fumes, smoke, unpleasant smells from inside of building.
- Ducting can uniform distribution of cooler air.
- With high capacity cetrifugal fans lowest pressure drop.
- Maximum durability.
- Environment friendly. No refrigeration gases and no compressor are needed.
- Large products range 4.860 m³/h ÷ 32.400 m³/h, with top or side air outlet.

Application areas

- Factories
- Workshops
- Stores, Warehouse
- Offices
- Supermarkets, shopping malls
- Sporthalls
- Mosques, churches
- Restaurant, cafes, bars
- Discos, night clubs
- Dining halls
- *Hotels, holiday villages*
- Banks
- Foundries
- Industrial ovens
- Hangars
- Barracks
- Tents
- Farms

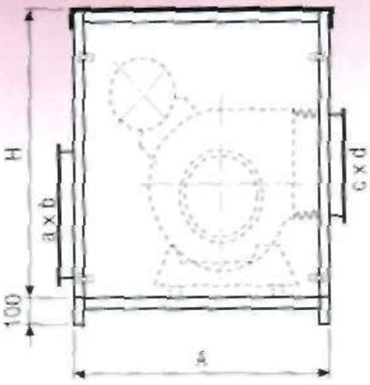
ECOVANT

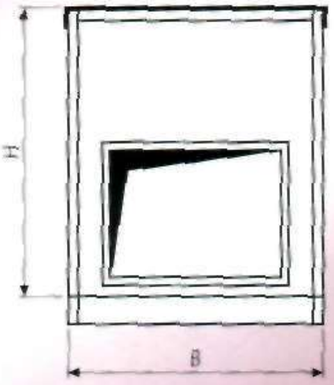
- Fan üfleme yönü basitçe değiştirilebilir
- Kolay montaj - demontaj
- Her mekana uygunluk sağlar
- Optimum boyutları ile mekanda yer tasarrufu sağlar
- İsteğe bağlı hava filtre sistemi

- ***Discharge side can be change basicly***
- ***Easy to attach and remove***
- ***Compact unit***
- ***Saving space with optimum size***
- ***Optinal air filter system***

Kullanılan Yerler

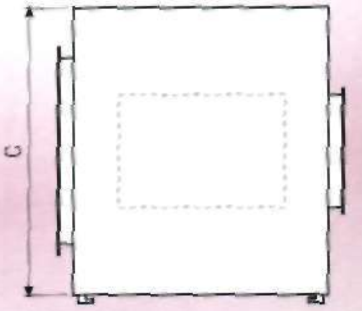
- İşyerleri
- Ofisler
- Kafeteryalar
- Marketler
- Restaurantlar
- Toplantı Salonları





Suitable For

- ***Buildings***
- ***Offices***
- ***Cafeterias***
- ***Supermarkets***
- ***Restaurants***
- ***Meeting Rooms***



TİPİ / *TYPE*		Hava Debisi *Air Flow* m^3/h	Basınç Pressure mmSS	Motor Gücü *Motor Power* HP - d/d	Ana Ölçüler / *Dimensions*						Ağırlık *Weight* Kg
					A	B	C	H	a x b	c x d	
MINI	I	1500 ÷ 2500	30 / 38	0.75 / 1 - 1500	600	600	600	600	300x350	210x230	48
	II	2500 ÷ 3500	40 / 60	1 / 1.5 - 1500	600	600	600	600	350x400	262x298	55
MIDI		3500 ÷ 4500	37 / 52	1.5 / 2 - 1500	700	700	700	700	400x475	290x330	65
MAXI	I	4500 ÷ 6500	40 / 56	2 / 3 - 1500	800	800	800	800	475x500	330x390	84
	II	6500 ÷ 10000	40 / 55	3 / 4 - 1500	900	900	900	900	500x750	405x470	101

Her hakkı mahfuzdur. Kapasite ve ölçüler haber verilmeksizin değiştirilebilir. / *The datas in this brochures are not binding. With a view to continuous product improvement, ALDAĞ reserves the right to make changes without prior notice.*

NA R SERIES HOT WATER BOILERS
Advanced Technology, Small Size, High Efficiency

- Combination of high technology and superior workmanship.
- Long life, compact design, high capacity to size ratio
- Suitable for use of Natural Gas, LPG, Light Oil and Heavy Oil as fuel
- Special design to minimize the effects of sediments and scaling on waterside
- Well-distributed expansion pattern due to balanced heat absorption within the boiler
- *Also transportable in modular configuration for site assembly, for boiler rooms with narrow passages*

Basic Principles of Reversed Flame Technology

- Burner flame is reversed in the same chamber due to counter pressurized combustion.
- Returning hot gases are forced to meet with the burner flame once again to ensure full combustion and cleaner flue gases.
- The intensive heat generated by the reversing flame is effectively transferred to water mainly by means of radiation heat transfer. A full transfer of heat is achieved during the consecutive passages of boiler with a combination of radiation and convection heat transfer.
- Gas turbulators increase the velocity of combustion gases in flame tubes to keep the convection heat transfer in tube surfaces at the maximum level.

Plants

Erensan boilers are manufactured in two modern plants build over a total area of 45.000 m². Plants are located in İstanbul and in Yozgat. İstanbul plant and head office is near Atatürk International Airport and at the very heart of International Exhibition Centers. 10 minutes driving from the airport, Erensan can be reached from any country over the world. İstanbul being one of the main ports of world trade, transportation can easily be arranged to every destination through alternative choices.

NA R Serisi Sıcak Su Kazanları
İleri Teknoloji, Küçük Boyut, Yüksek Verim...

- ERENSAN NA R kazanlar doğalgaz, LPG ve sıvı yakıt kullanımına uygun, yüksek verimli ve uzun ömürlüdür. Düşük yakıt tüketimi ile tasarruf sağlar.
- Tasarımı itibari ile su içindeki tortu ve kireçlerden en az düzeyde etkilenir.
- *Kazan içindeki ısı farklarını dengeleyen dizaynı ile rahat genleşme yeteneğine sahiptir.*
- NA R kazan, gelişmiş "reverse flame" teknolojisi ile Türkiye'de, tamamen yerli malzeme ve işçilikle üretilmektedir.
- Dar girişli kazan dairelerine parçalı olarak da nakledilebilen NA R, kısa sürede yerine monte edilebilme özelliğine sahiptir.

NA R Tipi Kazan Teknolojisi'nin Temel Prensipleri

- Basınçlı yanma sayesinde alev aynı hücre içerisinde geri döndürülür.
- Brülör alevi ile ikinci kez karşılaşan gazlar ve yarı yanmış yakıt partiküllerini tekrar yakarak ısıya dönüştürür ve zararlı atıklar tamamen yok edilir.
- Çift geçişli yoğun yanmanın meydana geldiği alev görnleği odasında oluşan parlak alev, "radyasyon ısı transferi" yolu ile yanma hücresinden suya taşınır.
- *Gaz oyalayıcı türbülatörler, alev boruları içindeki duman ve gazların hızını* arttırarak bu bölgedeki taşınım (konveksiyon) ısı iletiminin optimal seviyede tutulması sağlanır.

Üretim

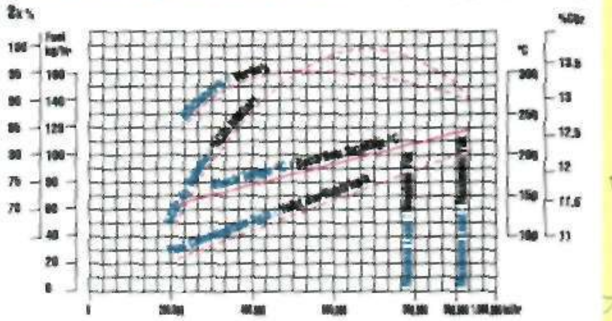
Endüstriyel proses buharı ve ısı enerjisi üretiminde 40 yıllık bir deneyime sahip olan Erensan, İstanbul ve Yozgat'taki tesislerinde, modern teknoloji ile *üretim yapmaktadır.*

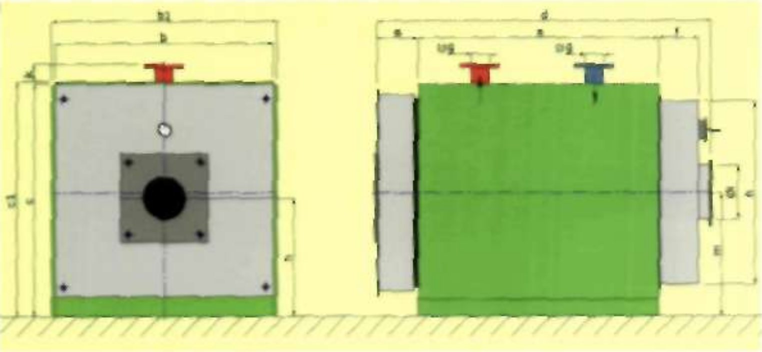
DIMENSIONS OF NAR BOILERS / *NA R KAZAN ÖLÇÜLERİ*

Type / Tip	NAR	60	80	100	130	160	200	250	320	400	500	640	800	1.000	1.250	1.600	2.000	2.500
Capacity/ Kapasite	kcal/h	60.000	80.000	100.000	130.000	160.000	200.000	250.000	320.000	400.000	500.000	640.000	800.000	1.000.000	1.250.000	1.600.000	2.000.000	2.500.000
	kW	70	93	116	151	186	233	291	372	465	581	744	930	1,163	1,453	1,860	2,326	2,907
a	(mm)	735	735	970	980	985	985	1,235	1,380	1,573	1,787	1,980	2,380	2,370	2,625	2,910	2,920	3,255
b1	(mm)	900	900	900	920	1,050	1,050	1,060	1,090	1,150	1,150	1,370	1,370	1,520	1,505	1,730	1,865	2,020
b	(mm)	780	780	780	800	930	930	940	970	1,030	1,030	1,250	1,250	1,400	1,485	1,610	1,745	1,900
c 1	(mm)	960	960	960	980	970	970	970	1,030	1,130	1,130	1,280	1,380	1,490	1,545	1,780	1,815	1,980
c	(mm)	840	840	840	860	950	950	950	1,010	1,110	1,110	1,260	1,360	1,470	1,525	1,760	1,795	1,960
d	(mm)	1,070	1,070	1,305	1,370	1,385	1,385	1,565	1,810	2,036	2,247	2,497	2,910	2,945	3,206	3,525	3,545	3,915
e	(mm)	130	130	130	170	170	170	185	185	185	185	190	210	246	246	266	266	271
f	(mm)	155	155	155	170	180	180	195	195	218	215	267	260	270	250	290	300	320
Øg	DN	50	50	50	50	65	65	65	65	80	80	100	100	125	125	150	150	200
h	(mm)	610	610	640	660	750	750	770	810	870	870	1,070	1,090	1,240	1,295	1,460	1,550	1,680
Øi	(mm)	150	150	150	150	150	150	150	150	200	200	250	300	300	300	350	400	450
k	(mm)	67	67	67	67	67	67	67	67	67	67	67	67	67	67	67	67	67
m	(mm)	465	465	458	460	505	505	490	530	600	600	650	740	770	797	950	938	1,035
n	(mm)	445	445	438	440	485	485	470	510	580	580	631	720	750	777	930	918	1,015
Water content lt / Su hacmi	(lt)	122	120	175	179	234	233	282	305	381	447	641	942	1,361	1,572	2,403	2,828	3,221
Counter pressure / Karşı basınç	(mbar)	0,2	0,6	1	1,1	1,2	1,6	1,8	2	2,5	3,2	4,4	5,4	6,2	6,7	7	9	10,5
*Approx empty weight/Yaklaşık boş ağırlık	(kg)	335	340	415	440	530	560	655	855	1,075	1,210	1,710	2,085	2,510	2,930	3,840	4,605	5,535

* Approximate empty weight is given for 4 bar operation pressure / Boş ağırlıklar, işletme basıncı 4 bar olan kazanlar için verilmiştir.

Parametric combustion diagram for an oil fired NA R 800 / NA R 800 tip kazan için geometrik verim diagram





KT52301 - 1

erensan
"Isı Mühendisi"

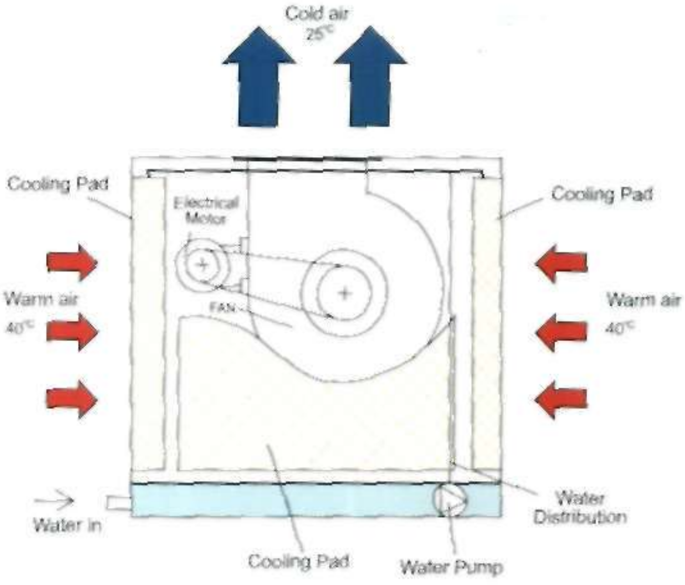
Technical specifications

Model SK 100 - 2 - 4
Height of pad (cm)
Quantity of pad on each surface
Quantity of surface with pad

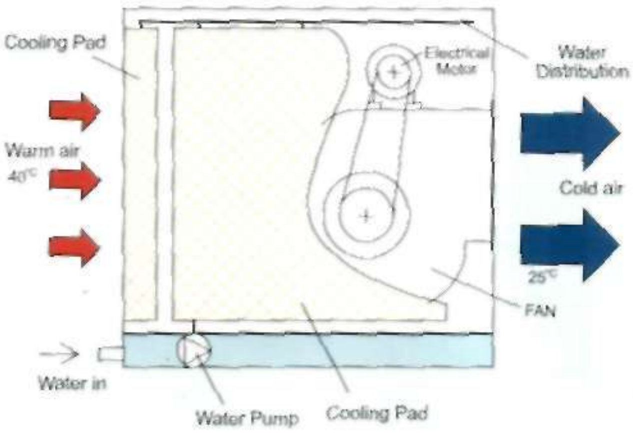
Model	Air Displacement m³/h	Motor Power kW	E-Supply V , Hz	Dimension W x L x H (mm)
SK 75-2-3	4.860	0,75	220/380 ~50	790 x 790 x 960
SK 75-2-4	6.480	1,1	220/380 ~50	790 x 790 x 960
SK 100-2-3	9.720	1,5	220/380 ~50	790 x 790 x 1210
SK 100-2-4	12.960	1,5	220/380 ~50	790 x 790 x 1210
SK 150-3-3	14.580	2,2	220/380 ~50	1090 x 1090 x 1710
SK 150-3-4	19.440	3	220/380 ~50	1090 x 1090 x 1710
SK 150-4-3	24.300	4	220/380 ~50	1390 x 1390 x 1710
SK 150-4-4	32.400	5,5	220/380 ~50	1390 x 1390 x 1710

Specifications subjects to change without notice

Dipaz evaporative cooler

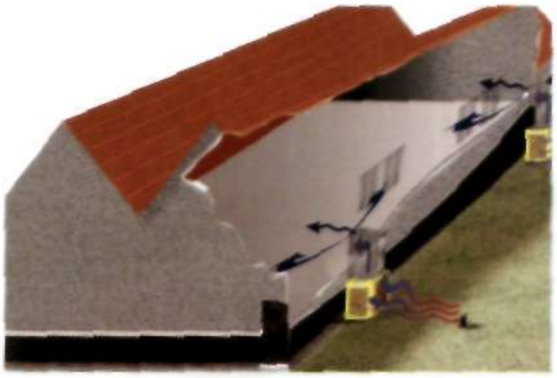


Model with air outlet at the top



Model with air outlet at the side wall

Typically installation examples



DİPAZ
Makine Tic. ve San. A.Ş.

Akçaburgaz Mevkii, Sanbir Bulvarı 5. Bölge 12. Cad.
No:64/A 34909 Büyükçekmece-İSTANBUL-TURKEY
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E-mail: dipaz@dipaz.com.tr
www.dipaz.com.tr

Boxford

PC Controlled CNC Turning Centre

T220

A floor standing CNC Lathe designed for educational and training installations

The PC controlled Boxford T220 lathe is ideally suited to a classroom environment and offers the perfect solution for high tech. education and training requirement's. The rigid construction allows steel to be cut to close tolerances. Operating on IBM/100% compatible computers, the inclusive user-friendly software has routines for Computer Aided Design [CAD] at both simple and sophisticated levels and will process the drawings through to a full machining routine.

CNC features

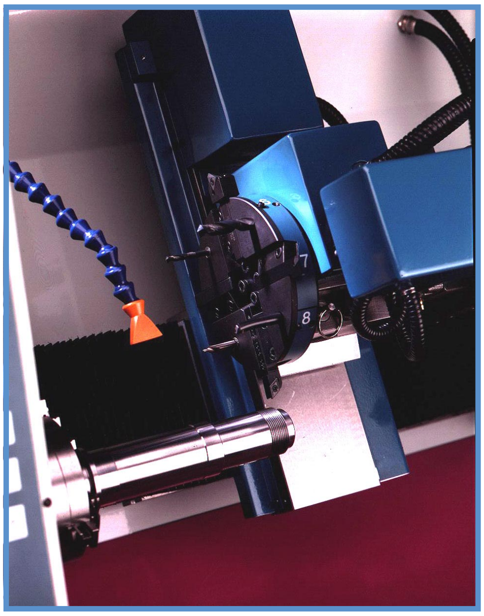
- The Boxford software is an integrated suite of powerful CAD/CAM tools.
- The CAD allows ONLY components suitable for lathe machining to be designed and provides automatic and dynamic dimensioning. A 3D solid model view is also available.
- Drawings from other CAD applications can also be imported and processed.
- A full 3D simulation of the manufacturing process, including a cycle time, can be shown enabling work to be proven without the need for trial cutting.
- Manual Data Input, utilising Industrial Standard Codes, allows programs to be entered using either line by line or conversational programming.
- The generous swing over bed capacity and long Z axis allows a large variety of components to be machined.
- Touch sensitive control panel incorporating illuminated push buttons allows the machines to be operated without a computer.
- Active and accurate tool path graphics continuously displayed line by line during program write, test run and manufacture.

Safety equipment and features

- Full perimeter guarding with interlocking switches on access doors arranged in the positive (safety) mode for spindle stop and feed hold.
- Overload cut-out on spindle drive.
- Positive end stops on all axes.
- Mandatory graphics run required for new programs before machining cycle can be commenced and step by step graphics in advance of cut in machining cycle.
- Integrated electrical panel with no volt supply protection.
- Feed rate override.
- Feed hold.
- Single block operation.
- Latching emergency stop button.
- Power on indicator lamp.
- Low voltage control circuitry.

PC Controlled CNC Turning Centre
T220

Machine specification

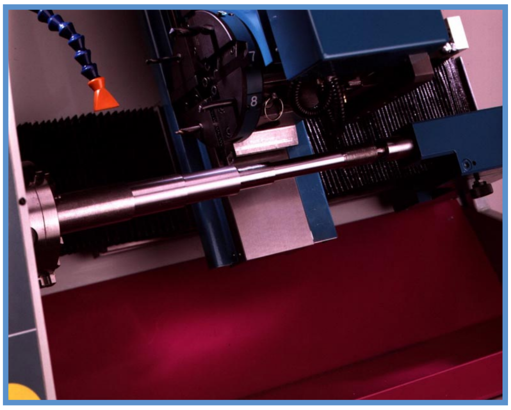


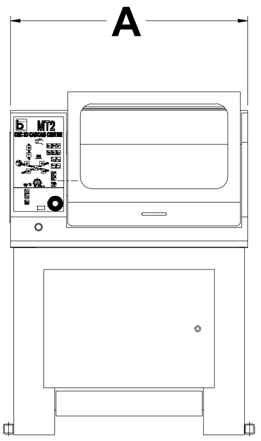
- Slant-bed configuration.
- Precision linear ways.
- Linear ball bearings on all axes.
- Three axis simultaneous operation.
- Fully enclosed see through guarding for safety and improved student viewing.
- Integrated electrical panel.
- 100mm diameter 3 jaw chuck.
- Automatic 8 station lathe turret.
- Spindle speeds in RPM, M/min or in/min.
- Feedrates in mm/min, in/min, mm/rev or in/rev.
- Steel, Brass, Aluminium and Brass cutting capability.
- Generous swing over bed
- Long Z axis travel for 'between centres' work

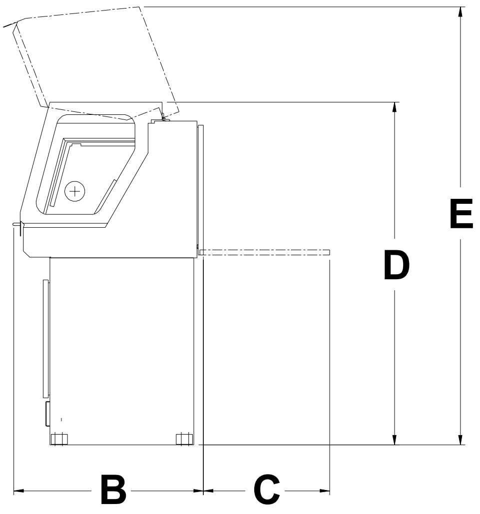
Swing Over bed	210mm
X Axis travel	150mm
Z Axis travel	350mm
Distance between centres	400mm
Spindle bored to pass	20mm
Spindle motor	490 watts
Infinitely variable spindle speeds	200 - 4000 rpm
Electrics	110/220/240v 1 PHASE
Programmable feed (linear and circular interpolation modes)	0 - 1000mm/min
Rapid feed rate at 100%	1200mm/min

Accessories

Accessories are available, including:-
- Tailstock Steady
- Spindle Centre and carrier
- Flood Coolant System
- Comprehensive set of tooling







Machine Dimensions	
A	1000mm
B	790mm
C	530mm
D	1380mm
E	1770mm

Machine Weight
265kg (580lbs)

Boxford

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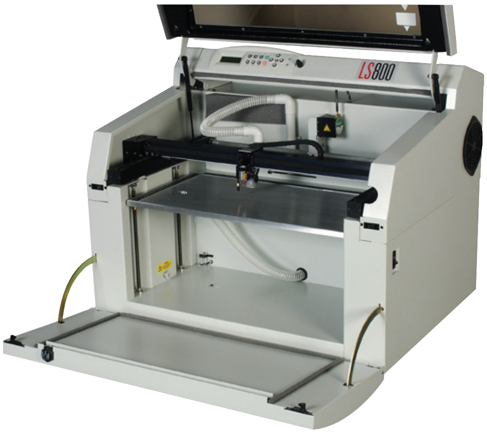
LASER

CO_2 Laser Engraving, Marking & Cutting

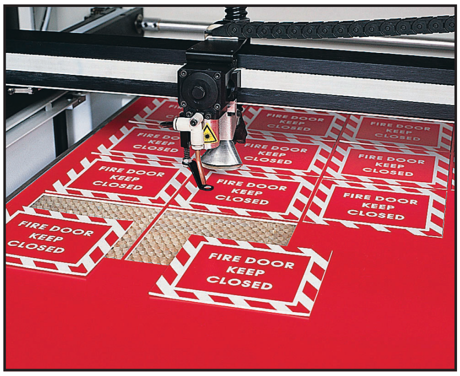
CO_2 Laser Engraving, Marking & Cutting systems for educational and training installations

The PC controlled LS800 & LS900 CO_2 laser systems are ideally suited to all training needs.

System features



- The unique design incorporates F-load (Front loading concept) which allows complete access and effortless loading and adjusting of materials, jigs, cutting tables and rotary attachments etc. With its extra large opening, bulky objects can be easily positioned without awkward manoeuvring.
- A rigid motion system incorporating high quality linear guide rails allows speeds up to 2000mm per second to be achieved.
- The A-sens function (Auto sensor concept) automatically adjusts the focal length depending on the position of the material surface.
- The unique D-fit function (Depth fitting concept) calculates and automatically adjusts the position of the laser head when cutting thick materials in several passes.
- The beam expander allows the same power level and dot size to be maintained across the entire working area.
- The integrated red dot beam pointer allows easy positioning of the laser prior to running a job.
- Available with a variety of laser tube powers from 30 to 80 watt to suit all types of work.



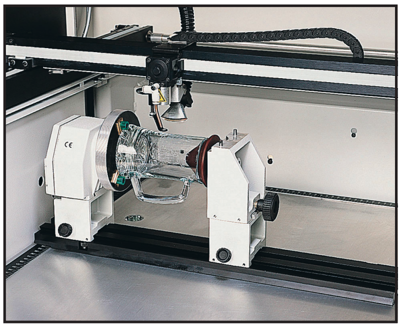
What materials can be laser processed?

- Acrylic
- Anodised Aluminium
- Cardboard
- Coated Metals
- Cork
- Fabrics
- Foam
- Glass
- Laminated Plastics
- Leather
- Marble
- MDF
- Nylon
- Paper
- Plastics
- Polycarbonate
- Rubber
- Stone
- Veneer
- Wood

System specifications

	LS800	LS900
Engraving Area	610 x 305 mm	610 x 610 mm
	(24 x 12 in)	(24 x 24 in)
Max. Part Size	690 x 350x 250 mm	690 x 690 x 250 mm
Max Part Weight	25 kg	25 kg
Laser source power	30, 40, 60 or 80 watts	30, 40, 60 or 80 watts
	air cooled	air cooled
Max. Engraving Speed	2000 mm/sec	2000 mm/sec
Machine Weight	185kg	215kg
Dimensions (W x D x H)	945 x 780 x 1210 mm	945 x 1080 x 1300 mm
Mounting	Floor	Floor
Rotary Attachment	3mm to 200mm Ø	3mm to 200mm Ø
Safety	Class 1 closed configuration	
Operating Modes	Raster mode for engraving, Vector mode for engraving and cutting	
	or Raster / Vector combination mode	
Resolution	50 - 1200 DPI	
Optics	50.8mm (2.0") focal lens as standard	

Included Accessories



The Laser systems are packaged with the following accessories:-

- Honeycomb material cut-out table eliminating cut marks on the bottom side of the component by keeping the laser away from the machine table during vector cutting.
- Automated rotary device for engraving cylindrical objects.
- Air assist including compressor. This prevents combustion of flammable materials.
- Windows Software drivers.
- Warranty - 3 Years parts and labour (excludes consumable items - lenses, mirrors, honeycomb table and fume extraction filters)

Optional Accessories

- Integrated fume extraction/air filtration system*. The laser system’s internal ventilation system is engineered with air exhaust paths that virtually eliminate mirror contamination. For rubber processing, a hose at the point of cutting is included to help remove the smoke at the source.

- Set of replacement filters for extraction / air filtration system.
- 38.1 (1.5”) 63.5 (2.5”), 89 (3.5”) and 102mm (4”) focal lenses.

* *Laser systems can produce noxious fumes of varying levels depending on the material been processed. If exhausting internally, extraction must be to HEPA standards. Uses may wish to consider exhausting externally, eliminating the need for continual filter replacement. Please ask for further details.*

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Sherline Lathe and Mill Specifications

Lathe Specifications

FEATURE	4000(4100)	4400(4410)
Swing over bed	3.50" (90 mm)	3.50" (90 mm)
Swing over carriage	1.75" (45 mm)	1.75" (45 mm)
Distance between centers	8.00" (200 mm)	17.00" (430 mm)
Hole through spindle	.405" (10 mm)	.405" (10 mm)
Spindle nose thread	3/4"-16 T.P.I.	3/4"-16 T.P.I .
Spindle nose taper	#1 Morse	#1 Morse
Travel of crosslide	4.25" (110 mm)	4.25" (110 mm)
Taper of tailstock spindle	#0 Morse	#0 Morse.
Protractor graduations	0° to 45° by 5°	0° to 45° by 5°
Handwheel graduations	.001" (.01 mm)	.001" (.01 mm)
Length overall	24" (610 mm)	32.25" (820 mm)
Width overall	7.5" (190 mm)	8.75" (220 mm)
Height overall	6" (150 mm)	8" (200 mm)
Shipping weight	24 lb. (10.9 kg)	30 lb. (13.6 kg)
Motor	1/3 HP DC (90 Volts) with electronic speed control that accepts any incoming current from 100VAC to 240 VAC, 50 Hz or 60 Hz. Click here for motor specifications.	
Spindle speed range	70-2800 RPM continuously variable by electronic speed control	

Mill Specifications

FEATURE	5000(5100)	5400(5410)	2000 (2010)
Max clearance, table to spindle	8.00" (203 mm)	8.00" (203 mm)	9.00" (229 mm)
Throat (without headstock spacer)	2.25" (50 mm)	2.25" (50 mm)	Adjustable
Throat (with headstock spacer block)	(Not included)	Included, 3.50" (89 mm)	Not Required
Travel, "X" Axis	8.68" (228 mm) (9" w/ stop screw removed)	8.68" (228 mm) (9" w/ stop screw removed)	8.68" (229 mm) (9" w/ stop screw removed)
Travel, "Y" Axis	3.00" (76 mm)	5.00" (127 mm)	7.00" (178 mm)
Travel, "Z" Axis	6.25" (159 mm)	6.25" (159 mm).	5.38" (137 mm)
Hole through spindle	.405" (10 mm)	.405" (10 mm)	.405 (10 mm)
Spindle nose thread	3/4-16 T.P.I.	3/4-16 T.P.I.	3/4-16 T.P.I.
Spindle taper	#1 Morse	#1 Morse.	#1 Morse
Handwheel graduations	.001" (.01 mm)	.001" (.01 mm)	.001" (.01 mm)
Width overall*	14.75" (375 mm)	15.00" (381 mm)	15.00 (381 mm)
Depth overall*	11.75" (298 mm)	14.00" (356 mm)	22.25" (565 mm)
Height overall*	20.75" (527 mm)	20.75" (527 mm)	23.38" (568 mm)
Table size	2.75" x 13.00" (70 x 330 mm)	2.75" x 13.00" (70 x 330 mm)	2.75" x 13.00" (70 x 330 mm)
Hold down provision	2 "T" Slots	2 "T" Slots	2 "T" Slots
Shipping weight	33 lb. (15.0 kg)	36 lb. (16.3 kg)	38 lb. (17.2 kg)
Movements in addition to X-, Y- and Z-axes	Headstock rotation 90° left/right	Headstock rotation 90° left/right	Headstock rotation 90° left/right, column rotation (90° L/R), column pivot (front/back), column swing (90° L/R) and 5.5" column travel (in/out)
Motor	1/3 HP DC (90 volts) electronic speed control automatically converts any input from 100 VAC to 240 VAC, 50 or 60 Hz. (See motor specifications)		
Spindle speed range	70-2800 RPM continuously variable by electronic speed control		

*Overall dimensions include motor and speed control

Milling Machine

Model No.:XA5032

Product Origin:	China
Brand Name:	DLCHEM
Certification(s):	ISO9002

Detailed Product Description

Main specifications:
Working table:
1) Working surface (width x length): 320 x 1250mm
2) Loading weight: 500kg
3) No. of T-slots of table: 3
4) Width of T-slot of table: 13mm
5) Distance between T-slots: 70mm

Travels:
1) Longitudinal (manual / auto): 700 / 680mm
2) Cross (manual / auto): 255 / 240mm
3) Vertical (manual / auto): 370 / 350mm

Spindle:
1) Max. swivel angle: +/- 45 degrees
2) Speed: 30-1500rpm
3) Taper: ISO7:24No.50
4) Axial motion: 35mm
5) Distance from spindle nose to table surface Min/Max: 45/415mm
6) Distance from centre line of spindle to vertical guideway surface of column: 350mm

Feedrates:
1) Cutting feed rate: X.Y: 23.5-1180mm/min. Z: 8-394mm/min.
2) Rapid feed rate: X.Y: 2300mm/min. Z: 770mm/min.
3) No. of feeds: 8 steps

Motor:
Power of spindle motor: 7.5kW
Power of feed motor: 1.5kW

Net weight: 2800kg
Overall dimensions of machine: 2,272 x 1,770 x 2,094mm

We export it to many countries and it is very popular with clients by its high quality and competitive price.

Milling & Drilling Machine

Model No.:	ZX7045
Product Origin:	China
Brand Name:	QILONG
Price Terms:	FOB Shanghai
Payment Terms:	L/C, T/T
Supply Ability:	2,500pcs/month
Minimum Order:	20pcs
Delivery Lead Time:	20 days

See the most recent posting for this Milling & Drilling Machine (Oct 25, 2006)

Detailed Product Description

Features:
1) Model: ZX7045
2) Max. boring diameter: 45mm
3) Max. width of face milling: 80mm
4) Max. diameter of vertical spindle milling: 28mm
5) Max. distance from spindle end to bench surface: 475mm
6) Bench stroke: 500 x 200mm
7) Taper of spindle: MT 4
8) Max. stroke of spindle: 120mm
9) Distance from spindle central line to upright post surface: 260mm
10) Range of spindle speed: 65 - 1,380rpm
11) Motor power: 1.1kW (6 grades)
12) Total height: 1,050mm
13) Total weight: 370kg
14) Size of bench working surface: 820 x 240mm

CNC Lathe

CNC Lathe

Model No.:	CJK6132, CK6132
Product Origin:	China
Brand Name:	QILONG
Price Terms:	FOB Shanghai
Payment Terms:	L/C, T/T
Supply Ability:	500pcs/month
Minimum Order:	5pcs
Delivery Lead Time:	20 days

See the most recent posting for this CNC Lathe (Sep 15, 2006)

Detailed Product Description

Function:
This machine can automatically finish the turning of workpieces, including processing inner and outer circles, terminal surfaces, grooving, random pyramidal faces, curved faces, metric and British system cylinders, and conical threading.

Performance:
This machine tool can send and receive different signals to control the automatic processing because using such numerical coefficients as FANUC OTD, GSK 980TA and WA-21SN. The machine's bed guide is manufactured using supersonic quenching, and has strong resistance to abrasion.

With good returning accuracy and high resistance to shock, good cutting performance is guaranteed. With the balled screws in both the longitudinal and cross-directions driven by a step motor or servo-actor, good dynamic response and low operation noise are produced.

This type of machine tool has better adaptive abilities for continuous processing of workpieces in various sizes, models and specifications.

Radial Drilling Machine

Radial Drilling Machine

Model No.:	Z3032x10
Product Origin:	China
Brand Name:	QILONG
Price Terms:	FOB Shanghai
Payment Terms:	L/C, T/T
Supply Ability:	2,500pcs/month
Minimum Order:	20pcs
Delivery Lead Time:	20 days

See the most recent posting for this Radial Drilling Machine (Sep 25, 2006)

Detailed Product Description

Features:
1) Model: Z3032x10
2) Max. boring diameter: 32mm
3) Taper of spindle: MT 4
4) Max. stroke of spindle: 250mm
5) Max. distance from spindle end to bench surface: 1,064mm
6) Distance from spindle central line to upright post surface: 1,000mm
7) Range of spindle speed: 71 - 1,800rpm
8) Motor power: 2.2kW
9) Total height: 2,360mm
10) Total weight: 1,700 / 1,400kg

Light Type Bench Drilling Machine

Light Type Bench Drilling Machine

Model No.:	ZQ4113, ZQ4116, ZQ4119
Product Origin:	China
Brand Name:	QILONG
Price Terms:	FOB Shanghai
Payment Terms:	L/C, T/T
Supply Ability:	2,500pcs/month
Minimum Order:	20pcs
Delivery Lead Time:	20 days

See the most recent posting for this Light Type Bench Drilling Machine (Oct 14, 2006)

Detailed Product Description

Features:
1) Model: ZQ4113, ZQ4116, ZQ4119
2) Max. boring diameter: 13 / 16 / 19mm
3) Taper of spindle: B16 / B18 / B18
4) Max. stroke of spindle: 85mm
5) Distance from spindle central line to upright post surface:
165 / 180 / 180mm
6) Max. distance from spindle end to bench surface: 318 / 432 / 432mm
7) Range of spindle speed: 420 - 280rpm / 270 - 2880rpm /
270 - 2880rpm
8) Size of bench working surface: 230 x 230mm
9) Motor power: 0.37 / 0.55 / 0.55kW
10) Total height: 825 / 950 / 950mm
11) Total weight: 60 / 65 / 65kg

Grizzly Industrial, Inc.®

MODEL H7832
ARBOR PRESS STAND
INSTRUCTION SHEET

Inventory (Figure 1)

A.	Rear Panel	1
B.	Front Panel	1
C.	Cup	1
D.	Base	1
E.	Top Panel	1
F.	Tray	1

Tools and Hardware:

Cap Screws M12-1.75 x 25	16
Cap Screws M12-1.75 x 35	8
Flat Washers 12mm	24
Lock Washers 12mm	24
Phillips Head Screws M6-1 x 20	2
Hex Nuts M6-1	2
Hex Nuts M12-1.75	16
Mounting Pins M10-1.5 x 40	2

Assembly (Figure 2)

1. Align the lower holes of the front and rear panels with the holes in the base. Secure with M12-1.75 x 25 cap screws flat washers, and lock washers.

3. Secure the tray to the front and rear panels with M12-1.75 x 25 cap screws, flat washers, lock washers, and hex nuts.

4. Align the large bolt holes in the top panel with the bolt holes in the front and rear panels.

5. Secure the top panel with M12-1.75 x 35 cap screws, flat washers, lock washers, and hex nuts.

6. Attach the cup to the front panel with the Phillips head screws and hex nuts.

7. Secure the stand to the floor with appropriate fasteners for the floor type (not included).

8. Mount the arbor press with hex bolts, flat washers, lock washers and hex nuts, using the mounting pins as a guide, as shown in **Figure 3**. These fastener sizes will vary depending on your arbor press.

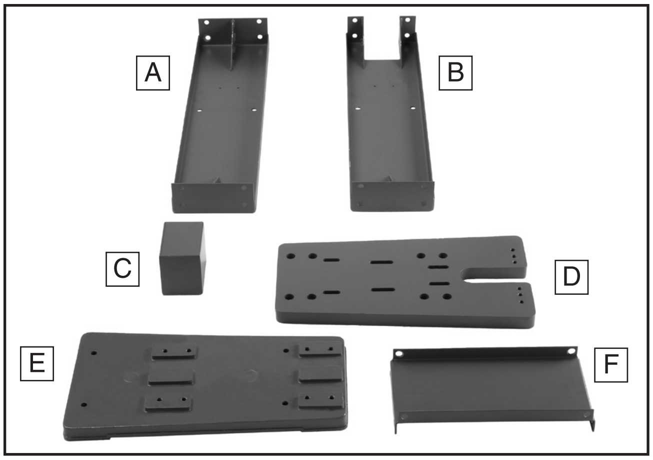


Figure 1. Inventory parts.

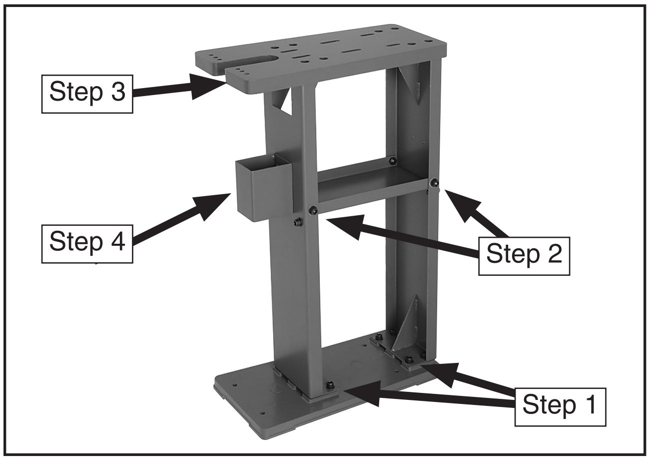


Figure 2. Assembly order.

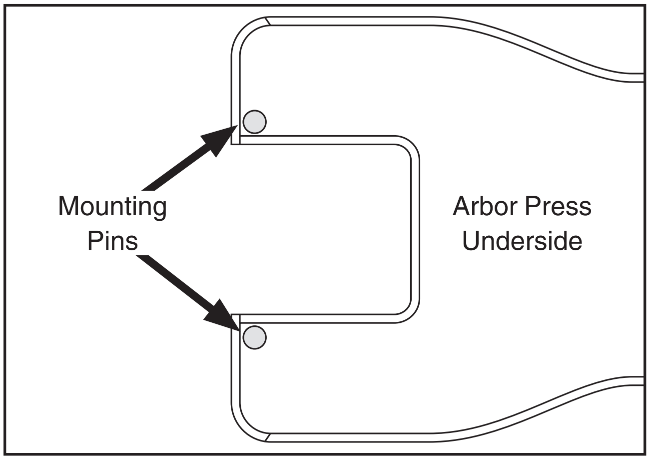
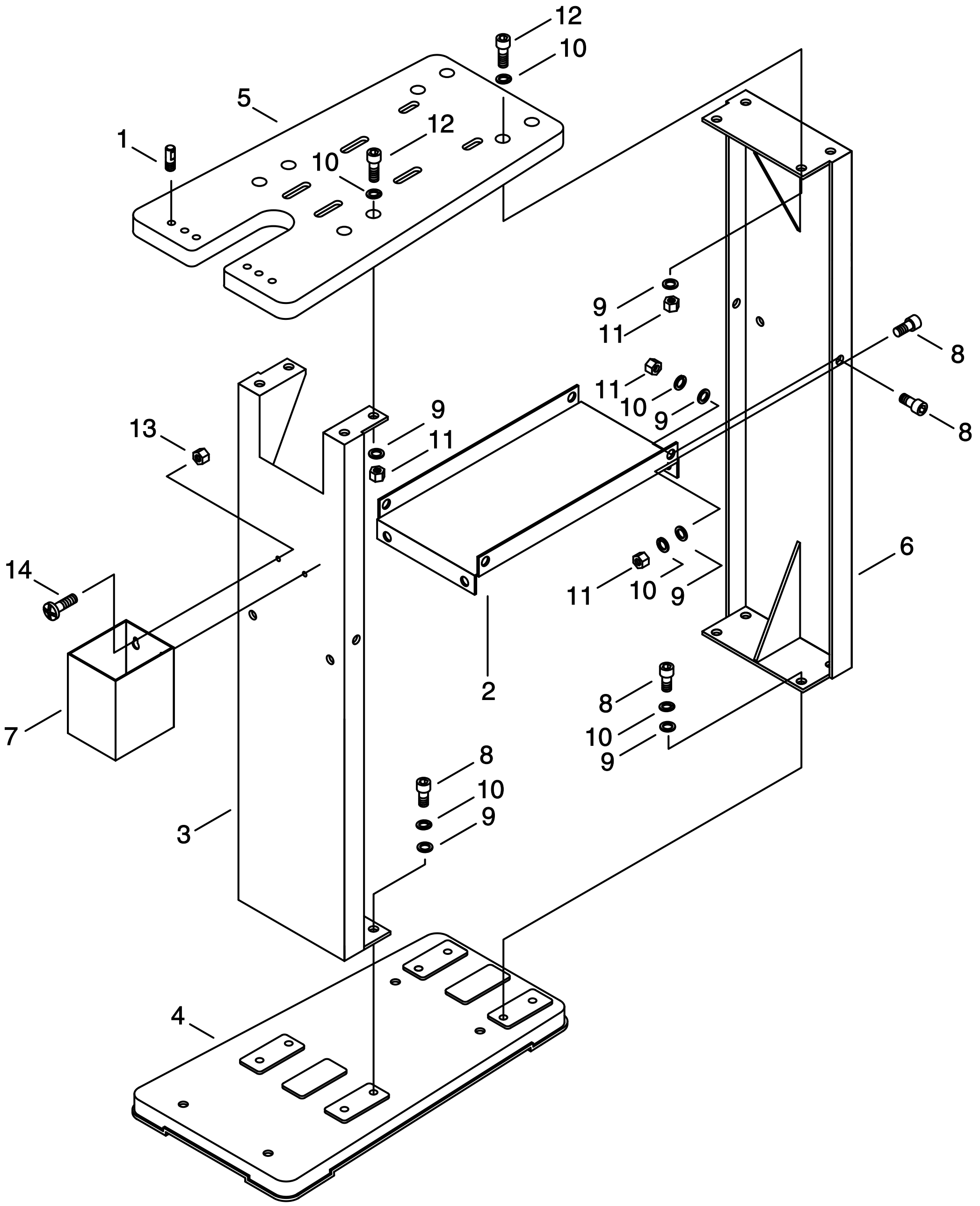


Figure 3. Mounting pin placement.

If you need additional help with this assembly, call our Tech Support at: (570) 546-9663.

H7832 Parts Breakdown and List



REF	PART #	DESCRIPTION
1	PH7832001	MOUNTING PIN M10-1.5 X 40
2	PH7832002	TRAY
3	PH7832003	FRONT PANEL
4	PH7832004	BASE
5	PH7832005	TOP PANEL
6	PH7832006	REAR PANEL
7	PH7832007	CUP

REF	PART #	DESCRIPTION
8	PSB36M	CAP SCREW M12-1.75 X 25
9	PW06M	FLAT WASHER 12MM
10	PLW05M	LOCK WASHER 12MM
11	PN09M	HEX NUT M12-1.75
12	PSB111M	CAP SCREW M12-1.75 x 35
13	PN01M	HEX NUT M6-1
14	PS26M	PHLP HD SCR M6-1 X 20

[redacted]

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