Course Material

Chemical Engineering for Non-Chemical Engineers – 5 Days Module

Index

DHARMSINH DESAI UNIVERSITY

Dharmsinh Desai Foundation was established at Nadiad in Gujarat, by an eminent Parliamentarian and a social worker, Late ShriDharmsinh Desai to develop institutions that would improve the quality of life for the people in and around Nadiad. It has schools, colleges, public library and hospitals under its umbrella. The DD Foundation started Dharmsinh Desai Institute of Technology (DDIT) an affiliated college in 1968, offering Degree and Diploma in Chemical Engineering, has now becomeDharmsinh Desai University (DDU), a trusted name amongst a variety of stake holders, namely, students, their parents, researchers, academicians, employers, other academic institutions offering higher level education, National level Institutions and State & Central Government agencies. The key milestones it has crossed in the past 40 plus years of its existence are addition of Degree courses in Civil Engineering (1981), Electronics and Communication Engineering (1981), Computer Engineering (1985), Instrumentation & Control Engineering (1985), and Information Technology (1999). Further it also added undergraduate programs in Commerce (B.Com in 1980 under Dharmsinh Desai Institute of Commerce), Computer (BCA, 1999), Management (BBA, 1999), Dental Sciences (2005), and Pharmacy (2006). It also added Post Graduate level programs like M.E in Chemical Engineering (1981), M.E in Electronics & Communication (1986), M.E in Civil Engineering (1986), MCA (1987), MBA (1994), M.E in Instrumentation & Control Engineering (2002), and M.E in Computer Engineering (2002). Doctoral level programs in Engineering/Technology, Management, Pharmacy, Physical Sciences and Social Science were initiated in 2001. DDU has added Master's Program in Dental Sciences, Master's Program in Pharmacy and also in the process of adding an undergraduate program in Medical Sciences leading to MBBS, in the coming years. DDU (erstwhile DDIT) became the first Autonomous Institute in Gujarat State. Later, in the year of 2000, it was awarded a status of 'Deemed University' by Government of India, in recognition of its commendable standards in Academia. In April 2005, the Government of Gujarat declared this Institute as a 'State University'.DDU has ISO 9001:2008 certification since past eight years.

DDU's Vision is to become a multi-disciplined & 'learner oriented' university to closely associate with & be responsive to the Industry, to create supportive & caring environment for staff & students and to engage in R & D activities in areas of national priority.DDU's Mission is to undertake programs and projects for development of human resources, both through formal and non formal delivery systems, in areas of professional pursuits in all walks of human endeavors, with accent on relevance, value addition, societal needs and futuristic pilot projects.

DDU has recently established The Shah-Schulman Centre for Surface Science and Nanotechnology with the help of a grant of Rs. 3.5 crores from Government of Gujarat. This Centre is headed by a world known scientist, Dr. Dinesh Shah of University of Florida, whohas to has credit 7 books, 6 patents, and has over 250 research papers in referred journals, monographs and books. Dr. Shah has been invited to more than fifty corporate research centers and has presented over 200 seminars at Corporate Research and Development Centers during the past 40 years. He has provided consulting services to the some of the world's best managed corporations on a long-term basis (i.e. several years). This Centre is one of its kinds in the country and is doing pioneering work in association with the Industries and Academia. There are nine corporate members who have pledged Rs. 15 lacs each – totaling to Rs. 1.35 crores for the development of above Centre.

DDU has a very strong Alumni Association (DDU Alumni Association – DDUAA) formerly, DDIT Alumni Association (DDITAA) and it was established in August, 1993, with its headquarters at the DDU having chapters at Ahmedabad, Ankleshwar and Baroda. It has membership strength of about 4310. The association is proud of its members, as most of them have excelled in their respective fields. Many of them have won coveted awards and more than 1000 members are settled abroad. The association has been promoting interaction among industries, ex-students and the university to enhance the cause of technical education. DDUAA has organized and conducted more than 25 seminars, lectures and workshops at various places like Ahmedabad, Baroda, Ankleshwar and Nadiad.

FACULTY OF TECHNOLOGY

The Faculty of Technology (FoT) offers 7 undergraduate programs and 10 post graduate programs in engineering. It is noteworthy that Faculty of Technology is the only grant-in-aid institution in the state to receive World Bank Assistance of Rs.7.8 crores. The NBA-AICTE has also granted Accreditation to the B.E. courses of the Faculty. It also has linked up with the University of IOWA, USA to offer a five year joint B.E+M.S. program where a student goes to University of IOWA for two years – after completing three years at the DDU. The feedback from the University of IOWA is very encouraging and they have given tuition waivers and research grants to our students as they find them very deserving. Through another Memorandum of Understanding with KHS Germany, the final semester engineering students undertake their four months long Industry Project at KHS in Germany and all their expenses are met by the company there and they are also absorbed by their various companies all over the world.

All the students of faculty of technology undertake the full time Industry based project training in their final semester of the program which enables them for employment through campus interviews much before course completion.

FoT has a R&D Centre since 1998 and its main objective is to carry out research activity in the area of Information Technology, Computer Science, Computer Application and Electronics & Communication with the respective faculty members. R & D Center is also giving training to final semester students of the respective discipline to carry out the project in the area of cutting edge technology. It has taken up national level projects from pioneer institutes like National Crime Record Bureau, Institute of Plasma Research, Oil and Natural Gas Corporation Limited, HiRel Reliance Limited, GujartSamachar, Muljibhai Patel Urology Hospital, Forensic Laboratory and many others. It has the distinction of developing a Portrait Building System which is successfully used at every District Police Head Quarters in the Country to arrest criminals. It was first field tested in Rajiv Gandhi Assassination case by National Crime Record Bureau.

Training & Placement is vital for any Educational Institute and DDU has a good track record in this area. INFOSYS has played a key role in this area. We have a large number of repeat companies in campus placements and this indicates their faith in the ability of our students. All the visiting companies have said it time and again that the teaching learning processes at the DDU are the second to none.

DEPARTMENT OF CHEMICAL ENGINEERING

The Department of Chemical Engineering, established in the year 1968 along with the inception of the college, is one of the oldest Chemical Engineering Departments in Gujarat. Since then it has made remarkable contributions in the field of Chemical Engineering and its alumni has occupied eminent positions in the industry, academic and research institutions in India as well as abroad. The first batch of Engineers came out in 1973. In 1983, the roots of Chemical Engineering Department became even stronger with the introduction of Post Graduate Program. In addition to this, department has achieved remarkable milestone of NBA accreditation of five years for both PG and UG program in 1998 due to its best performance at all stages and currently has 5-year NBA accreditation for the UG program (2008-2013).

Because of its excellent infrastructure, with reference to classrooms, laboratories and pilot plant equipment to help in research and development, the department has made a name for itself in the industrial sector. The curriculum of Chemical Engineering is continuously being modified and upgraded in accordance with the industrial requirements.

The IPCL library at the institute possesses a good collection of Chemical Engineering books, journals and periodicals which enables the students to keep track of the latest technological developments. This in turn has given a great impetus to them, hence leading to higher academic involvement. The support has further encouraged students to undergo rigorous work in the field of research.

FACILITIES IN THE DEPARTMENT

The Department of Chemical Engineering at DDU has a well maintained computer laboratory to aid student's in their work. The department is one of the few institutes to possess two Sun Workstations along with advance simulation software such as ASPEN PLUS®, MATLAB®, GAMS, Gambit and HTRI. These softwares are used to design and simulate various processes and process equipments like scrubbers, distillation columns, absorbers, reactors & heat exchangers apart from property estimation. MATLAB®, with its toolboxes like Artificial Neural Networks, Optimization, Simulink, Fuzzy Logic etc., is much needed kit for research. Department also has post graduate simulation laboratory with 20 computers, 2 printers and servers.

The Department has well equipped state of art laboratories; viz. Fluid Flow Operations Lab, Heat Transfer Laboratory, Mechanical Operation Laboratory, Mass Transfer Lab, Process Control Lab, Chemical Reaction Engineering and Transport Phenomena laboratory.Several pilot scale equipments such as vacuum distillation column, extraction column, tray driers, centrifuges, glass lined reactor, SS reactor, thickener, cyclone separator are available.

Advanced Instrumentation laboratory is also a well-equipped with latest advanced instruments to boost the research conducted by PG and PhD students of department. The laboratory is facilitated with instruments like HPLC, GC, FTIR, BET surface area analyzer, TOC, Spectro-fluorometer, UV-VIS Spectrophotometer, Contact Angle, Atomic absorption spectrophotometer.This laboratory also possesses pH meters, turbidity meters, T.D.S measuring devices, and COD and BOD testing equipment for the primary and secondary analysis of industrial effluents. The laboratory also has equipment for Gas Chromatography and UV Spectrophotometer.

With Biotechnology slowly gaining importance, the Biotechnology Laboratory at DDIT offers research facilities like autoclave, automatic computer controlled biofermenter with pH, temperature, and Dissolved oxygen controllers, and incubator, centrifuge, sterilizer, Tissue culture hood, Jar shaker, colony counter, electronic microscope, etc.

RESEARCH & DEVELOPMENT

- The faculty members because of their high academic qualifications from reputed Institutions have a great potential for advanced research and development programs. This was the reason for the introduction of M.E program as early as 1982. Quality projects have been carried out at the M.E. level by the students with good guidance from faculty members. Many of the projects have got awards and have received acceptance in the industry. Thrust areas of the research for the department are Surface Science & Nanotechnology, Catalysis, Computer-aided Design & Control, Pollution prevention through process modifications.

- This department has produced two award winning M.Tech. thesis titled ” Steady State Multiplicity of Hydrolysis of Acetic Anhydride in CSTR in Series ” and ” Heat Transfer Studies in Half Coiled Jacket ” under the able guidance of Dr.N.S.Jayakumar.

GRANTS AND FUNDING

Department has got grants and funding from various sources as under

- The Government of Gujarat has given a grant of Rs. 3.5 crores to establish the Shah-Schulman Centre for Surface Science and Nanotechnology at DDU. March 2009.
- The Council for Science and Technology (GUJCOST) has declared the Department of Chemical Engineering as a Centre of Excellence and given a grant of Rs. 28.5 lakhs for research on nanocatalysis – development and applications, to Prof. P.A. Joshi, Professor of Chemical Engineering, DDU. (April 2009)
- The Industries Commissionerate, Government of Gujarat has given a grant of Rs. 10-crore to DDU and naming it as Anchor Institute to provide manpower training programs in the Chemical & Petrochemical Sector for the state of Gujarat. This is a four year project which has commenced from August 2009.
- The Department of Science and Technology (DST), New Delhi, has chosen Dr. Manish Mishra, of the Department of Chemistry and Chemical Engineering (and Shah-Schulman Centre for Surface Science and Nanotechnology) for the Young Scientist Fast-Track Scheme and will be funding his research (about Rs 21lakh) proposal on acid catalysts. April 2010
- The GSFC Science Foundation has funded the project on ”Nanotechnology to Clean Water in Developing Nations: Poor Man’s Filter” submitted by Dr. Premal R. Shukla , Professor & Head, Department of Chemical Engineering (and Shah-Schulman Centre for Surface Science & Nanotechnology), DDU for a period of three years for Rs. 10.27 lakhs.
- Ministry of Human Resources Development, Government of India, has sanctioned Community Development Polytechnic to us with an outlay of Rs 71 lakh over a period of 5 years commencing from April 2010.
- University Grant Commission, New Delhi, has sanctioned M Tech (ChemEngg) program to Dept of Chem. Engg. with specialization in Surface Science & Nanotechnology with a total budget of Rs 41.5 lakh which will commence from July 2010.

PG PROGRAM

The department has M.TechProgram in Chemical Engineering with a intake of 18 students specializing in Computer Aided Design and Environmental Engineering. A UGC supported M Tech program in Chemical Engineering with specialization in Surface Science & Nanotechnology is being offered from 2010. Seven students are pursuing their PhD from the department.

INDUSTRY INSTITUTE INTERACTION

One of the remarkable features after autonomy is that the students have to undergo training / project work in industry as partial fulfillment of the degree. The training period extends to 16 weeks. During this time, the students get an opportunity to learn about the practical aspects of Chemical Engineering. The faculty members regularly visit the industry to raise and maintain high standard of education through interaction. Campus recruitment takes place every year by reputed industries like Reliance Industries Ltd., GSFC, GNFC, GACL, United Phosphorus Ltd., Tata Chemicals, GHCL, etc as well as the telecom giant MBT. A GSFC Science Foundation Chair has been established in our institute. Every year, this chair is awarded to an outstanding Chemical Engineer of international repute. In 1996, a new separate building for library was built with a generous donation from IPCL. The Institute conducts workshops and seminars for the benefit of industrial personnel. It is good example of industry-institute relationship

Environmental audit cell conducts environmental audit in 41 process industries in state of Gujarat under Gujarat Pollution Control Board and doing consulting activity up to Rs 80 Lakhs per year as a result of good Industry Institute Interaction activity. In addition to this, several industries come forward to solve their technical problems, process modifications and get clearance certificates from the departmental faculty. Industrial experts are also invited to deliver lectures, conduct practical exams, vivas and give their input on course curricula and syllabus.

ANCHOR INSTITUTE-CHEMICALS & PETROCHEMICALS

THE INDUSTRIES & MINES DEPARTMENT, GOVERNMENT OF GUJARATentrusted DHARMSINH DESAI UNIVERSITY to take up the challenge to be an ANCHOR INSTITUTE (AI) for the fastest growing Chemicals & Petrochemicals sector of the state. Its Partners are L. D. College of Engineering, Ahmedabad as Co Anchor Institute, N. G. Patel Polytechnic, Afwa, Bardoli and ITI Ankleshwar as Nodal Institutes. The Anchor Institute has become functional from July, 2009 under Department of Chemical Engineering, FoT.

OBJECTIVES:

The objective of the Anchor Institute and its partners is to take various initiatives in creating readily employable and industry responsive Man Power, at all level for Chemicals & Petrochemicals across the State and can be summarized as under:

- Identifying the training courses and skill development programs as per the need of the industries in Gujarat state for people in the industries and unemployed persons who are seeking jobs in this sector
- Identifying and conducting the training courses and skill development programs and preparation of their course materials as per the need of the industries in Gujarat state for SUCs, ITI, Diploma & Degree Level faculty members and students.
- Organizing faculty development programs (training for trainers) for conducting these training courses through the Nodal Institutes.
- Mentoring and Assisting the Nodal Institutes to run training courses.
- Benchmarking of these training courses.
- Up grading the Courses offered in Chemical & Petrochemical Engineering and make them Industry responsive.
- Identifying new and emerging area in this field and undertaking research activities to keep pace with global development.

THE TARGETED BENEFICIARIES:

- Unemployed technical manpower having completed the formal study
- Technical manpower already in job by up gradation of skills
- Faculty members of the technical institutions

- Students of Technical Institutions

The Anchor Institute has conducted 41 training programs wherein training of 9020 man days has been imparted to total of 2281 persons. This includes 1123 students, 442 faculty and 716 industry personnel. The training covered a variety of courses; some of them are on software, repair and maintenance, plant operation, safety and environment, etc. The details about the Anchor Institute is available on http://www.dduanchor.org

Introduction

In chemical engineering and related fields, a unit operation is a basic step in a process. The different chemical industries were regarded as different industrial processes and with different principles. Arthur Dehon Little proposed the concept of "unit operations" to explain industrial chemistry processes in 1916. In 1923, William H.Walker, Warren K. Lewis and William H. McAdams wrote the book *The Principles of Chemical Engineering* and explained the variety of chemical industries have processes which follow the same physical laws. They summed-up these similar processes into unit operations. Each unit operation follows the same physical laws and may be used in all chemical industries. The unit operations form the fundamental principles of chemical engineering. The study of unit operations provides a unifying and powerful basis for an understanding of the different chemical process industries. Chemical engineering unit operations consist of mainly following classes:

Fluid flow operations - fluids transportation and solids fluidization

Heat transfer operations - evaporation and condensation

Mass transfer operations - gas absorption, distillation, extraction, adsorption, drying, crystallization, humidification

Mechanical operations - solids transportation, crushing and pulverization, screening and sieving, filtration

Fluid Flow Operations

The flow of fluid is important in many of the unit operations of chemical engineering. The handling of liquids is much simpler, cheaper and less troublesome than handling solids. Consequently, the chemical engineer handles everything in the form of liquids, solutions, or suspensions wherever possible; and it is only when these methods fails that he resorts to the handling of solids. Even then, in many operations a solid is handled in a finely subdivided state so that it stays in suspension in a fluid. Such two-phase mixtures behave in many respects like fluids and known as “fluidized” solids.

The fluid may be defined as a substance that does not permanently resist distortion. An attempt to change the shape of a mass of fluid will result in layers of fluid sliding over one another until a new shape is attained. During the change in shape, shear stresses will exist, the magnitude of which depends upon the viscosity of the fluid and the rate of sliding, but when a final shape is reached, and all shear stresses will have disappeared. A fluid term is used to include both liquid and gases.

At any given temperature, a fluid having a definite density (ρ), which is measured in mass per unit volume (kg/m^3). Although the density of a fluid depends on both temperature and pressure, in the case of liquids the density is not appreciably affected by moderate changes in pressure. In the case of gases, density is affected appreciably by both temperature and pressure. If the fluid is inappreciably affected by changes in pressure, it is said to be incompressible. Most liquids are incompressible. The density of liquid can, however, change considerably if there are extreme changes in temperature.

Measurement of fluids: Since the materials used in industrial processes are in the form of liquids or solutions wherever possible, it becomes of prime importance to be able to measure the rate at which a fluid is flowing through a pipe or other channel. Methods of measuring fluids may be classified as follows:

(i) Direct weighing or measuring
(ii) Hydrodynamic methods
  a. Orifice
  b. Venturi meter
  c. Pitot tube
  d. Weirs
  e. Rotameter
(iii) Direct displacement
  a. Disc meters
  b. Current meters
(iv) Miscellaneous : dilution methods

Pumping of fluids:

For the pumping of fluids from one vessel to another or through long pipes, some form of mechanical pump is usually used. The energy required by the pump will depend on the height through which the fluid is raised, the pressure required at delivery point, the length and diameter of the pipe, the rate of flow, together with the physical properties of the fluid, particularly its viscosity and density. The pumping of liquids such as sulphuric acid or petroleum products from bulk store to process buildings, or the pumping of fluids round reaction units and through heat exchangers, are typical illustrations of the use of pumps in the process industries. On the one hand, it may be necessary to inject reactants or catalyst into a reactor at a low, but accurately controlled rate, and on the other to pump cooling water to a power station or refinery at a very high rate. The fluid may be a gas or liquid of low viscosity, or it may be a highly viscous liquid, possibly with non-Newtonian characteristics. It may be clean, or it may contain suspended particles and be very corrosive. All these factors influence the choice of pump.

Because of the wide variety of requirements, many different types of pumps are in use including centrifugal, piston, gear, screw, and peristaltic pumps; though in the chemical and petroleum industries the centrifugal type is by far the most important.

Heat Transfer Operations

Many chemical reactions progress more rapidly or go more to completion if the temperature is other than room temperature. Furthermore, chemical reactions usually release or absorb heat. Therefore, it is necessary to heat or cool the reactants and products in an industrial reaction. This makes heat transfer an extremely important unit operation. Heat transfer is also involved in the vaporization or condensation of a process stream. It is often possible to heat one process stream while cooling another in a piece of equipment known as heat exchanger, in which the fluids flow past each other , separated by a metal wall through which heat is transferred from the hotter stream to the colder. Recovery of heat from product stream is also economically important.

Provided that a temperature difference exists between two parts of a system, heat transfer will take place in one or more of three different mechanisms.

Conduction: In a solid, the flow of heat by conduction is the result of the transfer of vibrational energy from one molecule to another, and in fluids it occurs in addition as a result of the transfer of kinetic energy. Heat transfer by conduction may also arise from the movement of free electrons, a process which is particularly important with metals and accounts for their high thermal conductivities.

Convection: Heat transfer by convection arises from the mixing of elements of fluid. If this mixing occurs as a result of density differences as, for example, when a pool of liquid is heated from below, the process is known as *natural convection*. If the mixing results from eddy movement in the fluid, for example when a fluid flows through a pipe heated on the outside, it is called *forced convection*. It is important to note that convection requires mixing of fluid elements, and is not governed by temperature difference alone as is the case in conduction and radiation.

Radiation: All materials radiate thermal energy in the form of electromagnetic waves. When this radiation falls on a second body it may be partially reflected, transmitted, or absorbed. It is only the fraction that is absorbed that appears as heat in the body.
In any of the applications of heat transfer operations in process plants, one or more of the mechanisms of heat transfer may be involved.

Evaporation, a widely used method for the concentration of aqueous solutions, involves the removal of water from a solution by boiling the liquor in a suitable vessel, an evaporator, and withdrawing the vapor. If the solution contains dissolved solids, the resulting strong liquor may become saturated so that crystals are deposited.

Liquors which are to be evaporated may be classified as follows:
(a) Those which can be heated to high temperatures without decomposition, and those that can be heated only to a temperature of about 330 K.
(b) Those which yield solids on concentration, in which case crystal size and shape may be important, and those which do not.
(c) Those which, at a given pressure, boil at about the same temperature as water, and those which have a much higher boiling point.

Evaporation is achieved by adding heat to the solution to vaporize the solvent. The heat is supplied principally to provide the latent heat of vaporization, and, by adopting methods for recovery of heat from the vapor, it has been possible to achieve great economy in heat utilization. Whilst the normal heating medium is generally low pressure exhaust steam from turbines, special heat transfer fluids or flue gases are also used.

Mass Transfer Operations

In many unit operations one component of a fluid phase is transferred to another phase because the component is more soluble in the latter phase. The distribution of components between phases depends upon the equilibrium of the system. Such transfer of material between phases is called mass transfer. Mass transfer may be used to separate products and reactants after an incomplete chemical reaction; it may be used to remove by-products and other impurities to obtain highly pure products; it may be used to purify raw materials. The various mass transfer operations have different names depending upon the phases being processed.

In ***distillation*** a liquid mixture at its boiling point is contacted with a saturated vapor mixture of the same components in different proportion. The components are transferred between the phases until equilibrium is established or the phases are separated. An important use of distillation is in the separation of crude petroleum into various components, such as gases, gasoline, lubrication oil and fuel oil.

In ***gas absorption*** a component of a gas phase is dissolved by a liquid phase in contact with it. The opposite of gas absorption is ***desorption***, or ***stripping***, where a component of the liquid phase is transferred to the gas phase. Gas absorption is used in the manufacture of sulfuric acid, where SO_3 in a gas stream is dissolved by water.

A number of unit operations involve simultaneous heat and mass transfer. In ***humidification***, water or another liquid is vaporized, and the heat of vaporization must be transferred to the liquid. ***Dehumidification*** is the condensation of water vapor from air, or, in general, the condensation of any vapor from a permanent gas.

As we discussed in heat transfer operations, in evaporation, part of the solvent of a solution is vaporized and the solution concentrated. In ***crystallization***, enough of the solvent is evaporated to give a saturated solution from which solid crystals precipitate. In drying, water or another liquid is evaporated from a solid.

There are several solid-fluid mass-transfer operations. In solid-liquid extraction, or ***leaching***, a soluble component of a solid phase is dissolved by a liquid. A common example of leaching is the preparation of coffee or tea. In ***adsorption***, a component of a gas or liquid adheres to the surface of a solid adsorbent, such as charcoal. In ion exchange, ions in solution are exchanged for ions in the solid ion-exchange resin. Zeolite water softeners are applications of a particular ion-exchange resin.

Mechanical Operations

The mechanical- physical forces will be acting on particle, liquids or mixtures of particles and liquids themselves and not necessarily on the individual molecules. The mechanical-physical forces include gravitational force, centrifugal force and actual mechanical and kinetic forces arising from flow.

Size Reduction: The method in which particles of solid are cut or broken into smaller pieces. Reduction of size of the solid from large size to coarse, fine, very fine or ultra fine particles depending upon the end applications. It is required to increase the surface area of the solid and ultimately reactivity of the solid, permits separation of unwanted ingredients by mechanical methods and reduces the bulk of fibrous materials for easy handling.

Screening: refers to the separation of solids with a variety of sizes into two or more fractions each with less size variation. Screening is used for a variety of operations including cleaning, and removal of solids from liquids.

Size Enlargement: Size enlargement concerns those processes that bring together fine powder particles into larger masses to improve the properties of the powders. Many diverse industries benefit from size enlargement processes. Examples include fertilizer granulation, iron ore pelletization, tablet feeds for pharmaceuticals, instant food products, and the processing of mineral and chemical products.

Filtration: It is the removal of solid particles from a fluid by passing the fluid through a filtering medium or septum on which the solids are deposited using normal or applied pressure. The solid deposited on the filter media is known as filter cake. The clear liquid which is almost free from solid is known as filtrate.

Sedimentation: is the tendency for particles in suspension to settle out of the fluid in which they are entrained, and come to rest against a barrier. This is due to their motion through the fluid in response to the forces acting on them: these forces can be due to either gravitational or centrifugal force.

Industrial Application: Mechanical Operations

- Fertilizer Industries: Filtration, Size Reduction ,Storage and Conveying of Solid

- Cement Industries : Size Reduction, Screening, Sedimentation
- Pharma Industries : Size Enlargement, Filtration, Agitation and mixing
- Paints, Dyes and Intermediates : Agitation and mixing Size Reduction, Filtration
- Coal Mines : Jigging, Screening, Size Reduction
- Food and Food Processing : Size Reduction, Size Enlargement,
- Plastic and Rubber Industries: Size Reduction, Pneumatic
- conveying, Screening, Agitation and Mixing
- Sugar and Starch Industries: Size Reduction, Filtration, Sedimentation, Screening

Chemical Process Calculations

PART I INTRODUCTION TO CHEMICAL ENGINEERING

Products of the chemical process industry are used in all areas of every day life. The raising of food plants and animals require chemical fertilizers, insecticides, food supplements and disinfectants. Many building materials have been chemically processed, for example, metals, concrete, roof materials, paints and plastics. Clothing utilizes many synthetic fibers and dyes. Transportation depends upon gasoline and other fuels. Written communication uses paper and printing ink and electronic communication requires many chemically processed insulators and conductors. The nation's health is maintained be drugs and pharmaceuticals, soaps and detergents, insecticides and disinfectants – all products of chemical industry. In addition, many chemicals never reach the consumer in their original form but are sold within the industries for further processing or use in the production of other chemicals for consumer use. Example for this is ammonia which is used in production of urea. It is often said that the chemical industry is its own best customer.

1. INTRODUCTION

The chemical industry dates back to prehistoric times when men first attempted to control and modify his environment. Any definition of description of the chemical industry is bound to be incomplete. Its development can be divided it to two periods. The prescientific period which extended to the end of eighteen century was largely empirical, with little understanding of basic chemistry. In the scientific period of last 200years the chemical industries have made phenomenal progress based on a sound knowledge of the principles underlying chemical processes. The industry where chemical change takes place is called as the chemical industries. Can one say only "CHEMICAL INDUSTRY". Then there is an example of production of salt, no chemical reaction take place in this production. So it is better to say "CHEMICAL AND PROCESS INDUSTRIES", an industry where chemical and physical changes takes place.

Chemical Industry = f(Chemical change and physical change)

Based on these needs, chemical and process industries are divided into five major categories:

- Inorganic Industries
- Natural Product
- Synthetic organic
- Polymerization
- Metallurgical

Typical Chemical Process will look like as shown below:

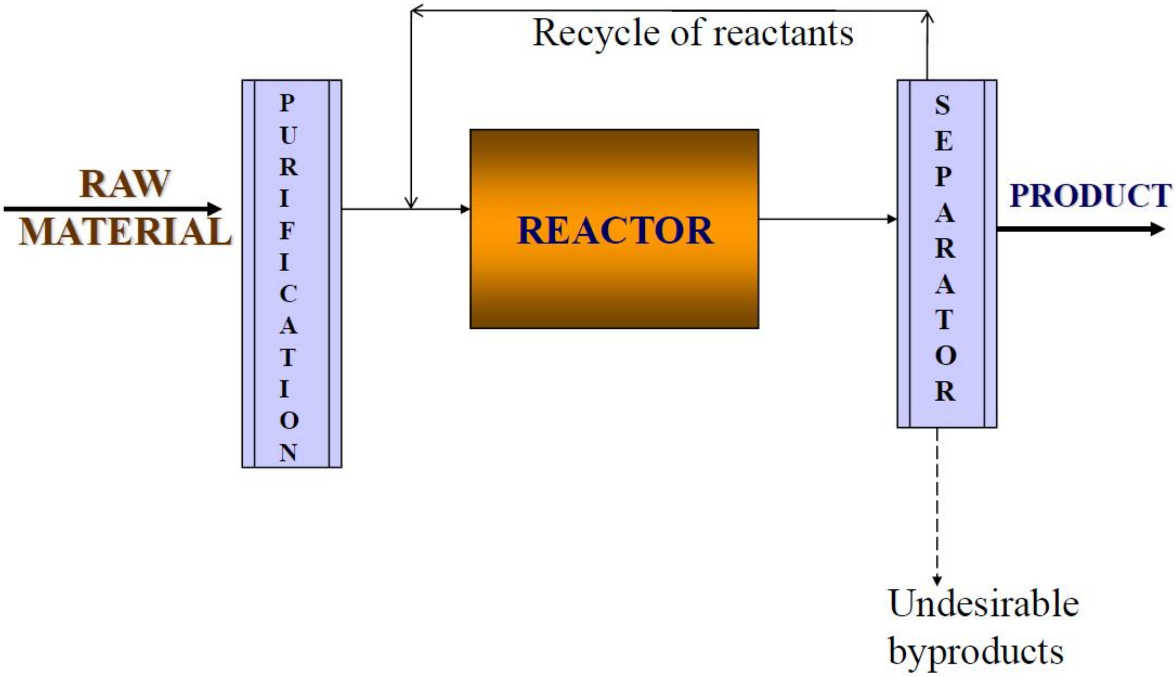


Fig. 1. Chemical Process Plant

For GNFC these products can be any one of Ammonia, Urea, Methanol, Acetic acid, formic acid etc…

In all chemical industries, there will be some purification/separation zone required and will be either one or series of reaction zone required. These separation/purification zone are termed as "UNIT OPERATIONS" and reaction zone are termed as "UNIT PROCESSES".

Table 1: Unit Operations vs Unit process

OUTLINE OF UNIT OPERATIONS	OUTLINE OF UNIT PROCESSES
Distillation	Alkylation (Petroleum organic chemicals)
Evaporation	Calcinations (Cement)
Extraction	Combustion (Process heating, Boiler house)
Fluid Handling	Dehydration (Inorganic Industries)
Heat Exchanger	Esterification (Food, Pharmaceutical)
Size reduction	Halogenations (organic Chemicals)
Membrane separation	Hydrolysis (Organic Chemicals)

General Principles applied in studying chemical and process industries

1. Chemistry
    a. Analytical
    b. Physical
2. Thermodynamics
    a. Laws of thermodynamics

   b. Phase equilibrium
   c. Chemical reaction equilibrium
3. Reaction Kinetics
   a. Type of reaction
   b. Reaction rate and order
   c. Reactor design
4. Process and Mechanical design
   a. Operation and trouble shooting
5. Economics
   a. Depreciation
   b. Pay out period
   c. Profitability analysis
6. Unit operations and unit processes
   a. Fluid flow operation
   b. Heat transfer
   c. Mass transfer

As the chemical industry developed early in the nineteenth century there was little or no intercommunication among various parts of the industries. many products had been made for centuries and the techniques of manufacturing were based on experience. There was o recognition of the element common to several processes and no attempt to systematize the knowledge of chemical engineering. So in latter half of nineteenth century this gap was reduced first by starting a course on the *Industrial Chemistry*. Then in 1880, in Englend George Devis has first recongnize that the problems pertaining to chemical industries are not only requiring chemistry knowledge but also physics. Then in 1888, there was a first course on Chemical Engineering introduced at MIT, US by Prof. Lewis M.Norton.

The one who work in this industry is CHEMICAL ENGINEER. A branch which produces these engineers is called CHEMICAL ENGINEERING. According to AIChE (American Institute of Chemical Engineers) it is defined as:

That branch of engineering which deals with the application of principles of economics and human relations, to fields that pertain directly to processes and process equipments in which matter is treated to effect a change in state, energy content and composition.

According to literature:

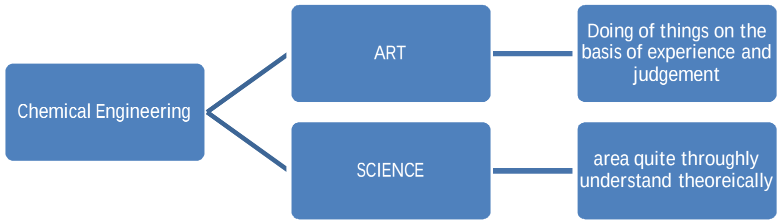


Fig. 2 Chemical Engineering

After defining Chemical Engineering there has to perform a definite task by the Chemical Engineers:

"An engineer carries out on large scale reactions developed in the laboratory by the chemist."

"One who talks engineering in the presence of chemists, chemistry in the presence of engineers and politics in the presence of both."

Typical Tasks performed by chemical engineers are:

1. Process Development
2. Process Design and Evaluation
3. Plant Design
4. Production Supervision
5. Plant Technical Services
6. Construction
7. Plant Operation
8. Product Sales
9. Research

Before going into the details of chemical engineering let us first dedifferentiate between chemistry and chemical engineering:

Table 2. Chemist Vs Chemical Engineer

Chemistry	**Chemical Engineering**
To create new substances	Works with large quantities
To investigate all pathways to produce them and study its properties	Large equipment
Works in test tubes	Continuous mode
Small quantities	Steady state operations (all parameters such as T, P, liquid livel, flow rates, compositions, etc. are all constant with time
Batch constant-T experiments	Feed streams and product streams are continuously fed and withdrawn from the process
Small containers	To investigate most optimal technology and Scaling up operation
A catalyst is added and reactions proceed with time	Works closely with mechanical, electrical, civil, and metallurgical engineers in order to design and operate the physical equipment in a plant

After differentiating a chemist from a chemical engineering one has to study the operations well. So it is at most required to avail knowledge of process which occurs in a chemical industry. So an obvious question comes to any one mind that

"What is a process?"

General meaning of a process:
"*An action or event which causes change*."

Chemical Engineering definition of process:
"*A process is a series of operations involving the physical, chemical, or biological transformation of an input material for the purpose of achieving a desired product material.*"
These processes are basically classified into three categories that are shown below in fig. 3, 4 and 5.

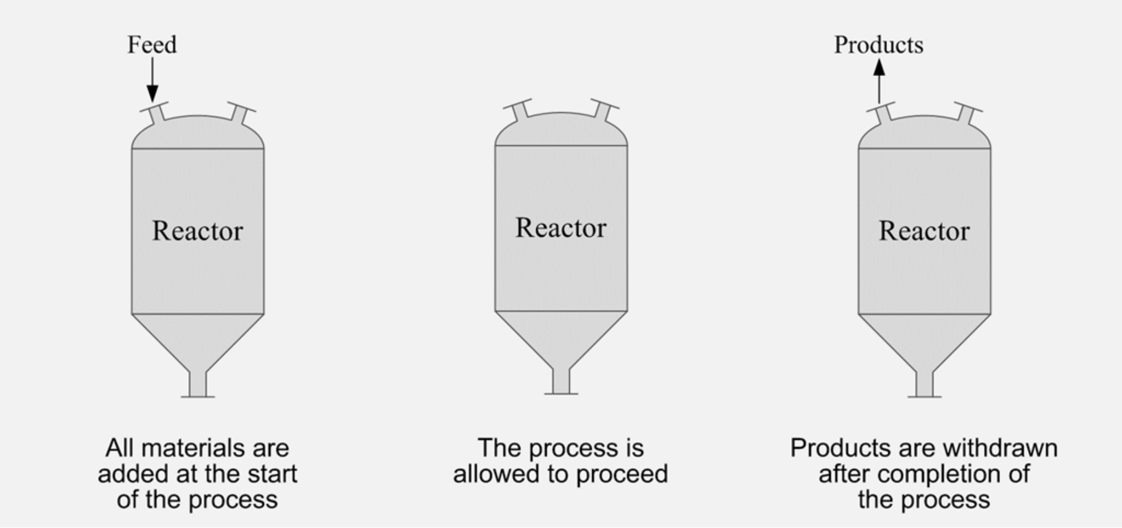


Fig.3 Batch Process

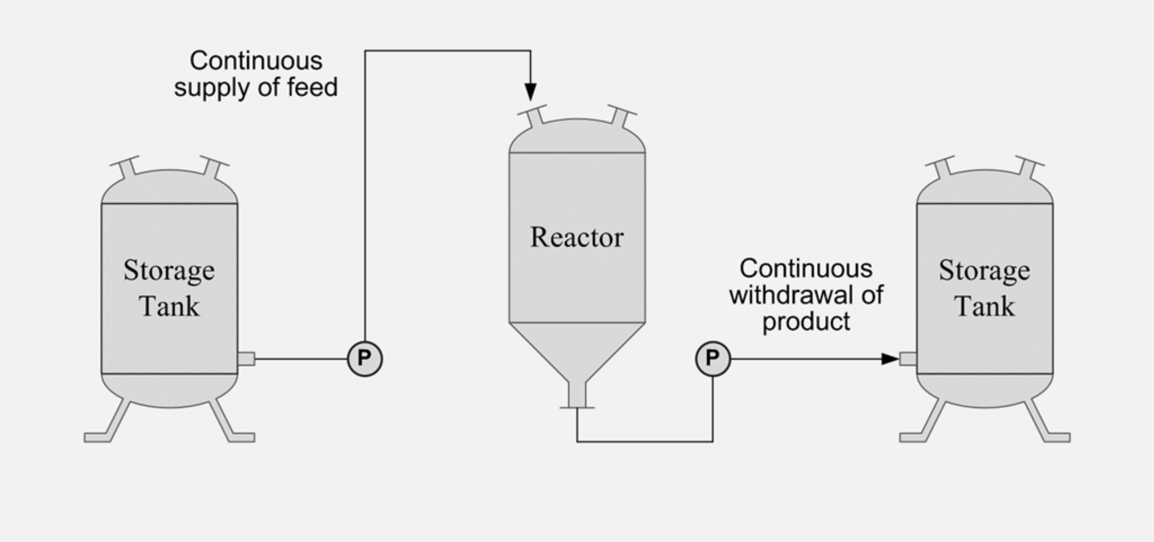


Fig. 4 Continuous Process

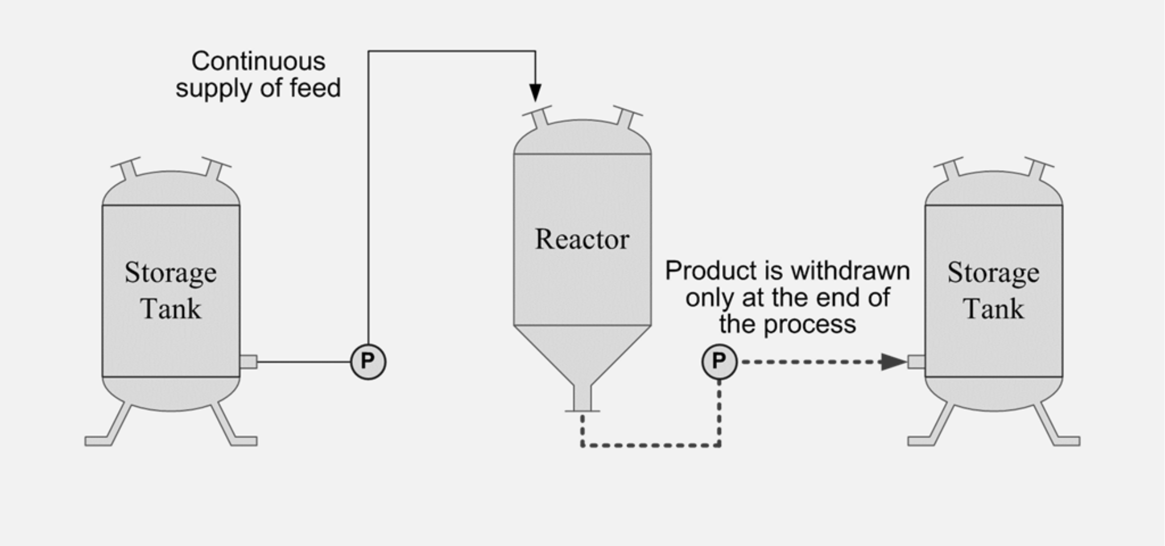


Fig.5 Semi Batch Process

One has to make a choice between the type of operation carried out in a particular industry. Some of the criteria for selection of whether to go for batch or continuous process are shown below in table 2.

Table 2. Criteria for selection of Batch and Continuous Process

Criteria	**Batch**	**Continuous**
Size	Smaller throughput favors batch operations. As throughput increases, the required size of the process equipment increases, and the technical difficulties of moving large amounts of chemicals from equipment to equipment rapidly increase.	Economics of scale favor continuous processes for large throughput.
Batch accountability and product quality	When the product quality of each batch of material must be verified and certified, batch operation are preferred. This is especially true for pharmaceutical and food products. If working (Reprocessing) of off-specification product is not permitted, small batches are favored.	Continuous or periodic testing of product quality is carried out, but some potentially large quantities of off-specification product can be produced. If off-specification material may be blended or stored in dump/ slop tanks and reworked through the process when the schedule permits, continuous processes are favored.
Operation Flexibility	Often the same equipment can be used for multiple operations, for example, a stirred tank can be used as a mixer, then a reactor, then as a stage of a mixer-settler for liquid-liquid extraction.	Operational flexibility can be built in to continuous processes but often leads to inefficient use to capital. Equipment not required for one process but needed for another may sit idle for months. Often continuous processes are designed to produce a fixed suite of products from a well defined feed material. If market forces change the feed/product availability/ demand, then the plant will be "Retrofitted" to accommodate the change.
Standardized equipment – Multiple Products	Often batch processes can be easily modified to produce several different products sing essentially the same equipment. Examples of batch plants that can produce 100 different products are known. For such processes the optimal control and sequencing of operations	The product suite or slate produces from continuous processes is usually fixed. Equipment tends to be designed and optimized for a single or small number of operating conditions.

	are critical to the success of such a plant.	
Processing Efficiency	Operation of batch processes requires strict scheduling and control. Because different products are scheduled back to back, changes in schedules have a ripple effect and may cause serious problems with product availability for customers. If the same equipment is used to produce many different products, then this equipment will not be optimized for any new product. Energy integration is usually not possible, so utility usage tends to be higher than for continuous processes. Separation and reuse of raw materials is more difficult than for continuous processes.	Generally as throughput increases, continuous processes become more efficient. For example, fugitive energy losses are reduced, and rotating equipment (Pumps. Compressors etc.) operate with higher efficiency. Recycle of unused reactants and the integration of energy within the process or plant is standard practice and relatively easy to achieve.
Maintenance and operating Labor	There are higher operating Labor costs in standard batch plants due to equipment cleaning and preparation time. These costs have been shown to be reduced for the so called “Pipe less Batch Plants”.	For the same process, operating labor will be lower for continuous processes.
Feedstock Availability	Batch operations are favored when feedstock availability is limited, for example, seasonally. Canneries and wineries are examples of batch processing facilities that often operate for only part of the year.	Continuous plants tend to be large and need to operate throughout the year to be profitable. The only way that seasonal variations in feeds can be accommodated is through the use of massive storage facilities that are very expensive or if possible by blending with the other streams.
Product demand	Seasonal demand for products such as fertilizers, gas-line antifreeze, deicing chips for roads and pavements, and so on, can be easily accommodated. Because batch plants are flexible, other products can be made during the “Off-season”	Difficult to make other products during the “Off-Season”. However, similar but different products, for example, a family of solvents can be produced using the same processes through a series of “Campaigns” at different times during the year. Each campaign may last several months.
Rate of reaction to produce	Batch operations favors	Very slow reactions require

products	processes that have very slow reaction rates and subsequently require long residence time. Examples include fermentation, aerobic and anaerobic wastewater treatment, and many other biological reactions.	very large equipment. The flow through this equipment will be slow and dispersion can be a problem if very high conversion is desired and plug flow is required.
Equipment Fouling & Waste Generation	When there is significant equipment fouling, batch operations are favored because cleaning of equipment is always a standard operating procedure in a batch process and can be accommodated easily in the scheduling the process. Amount of waster generated will of higher quantity.	Significant fouling in continuous operations is a serious problem and is difficult to handle. Operating identical units in parallel, one on-line and the other off-line for cleaning, can solve this problem. However, capital investment is higher, additional labor is required, and safety problems are more likely.
Safety	Generally, worker exposure to chemicals and operator error will be higher (Per pound of product) than for continuous processes. Operator training in chemical exposure and equipment operation is critical.	Large chemical plants operating continuously have excellent safety records, and safety procedures are well established. Operator training is still of great importance, but many of the risks associated with opening equipment containing chemicals are eliminated.
Controllability	This problem arises because batch processes often use the same equipment for different unit operations and sometimes to produce different products. This efficient scheduling of equipment becomes very important. The control used for this scheduling is complicated.	Generally, continuous processes are easier to control. Also, more work/ research has been done for these processes. For complicated and highly integrated plants, the control becomes complex, and operational flexibility is greatly reduced.

Processes explained above are phenomena associated with manipulation of various components generally called as “***CHEMICALS***”.

These Chemicals are classified according to their needs and functionality in the market.

(i) Commodity Chemicals: Sulphuric acid, nitrogen, ethylene, chlorine etc…

(ii) Fine Chemicals: : Chloropropylene Oxide (Used in production of epoxy resins), Dimethyl Formamide (used as a solvent, reaction medium, and intermediate in manufacturing of pharmaceuticals), n-butyric acid (used in beverages, flavoring, fragrance), barium titanate powder (used in manufacturing of electronic capacitors)

(iii) Specialty Chemicals: pharmaceuticals, pesticides, dyestuffs, perfumes and flavorings.

These products are selected based on market need and life cycle assessment. Typical lifecycle assessment diagram is shown in below in the figure 6.

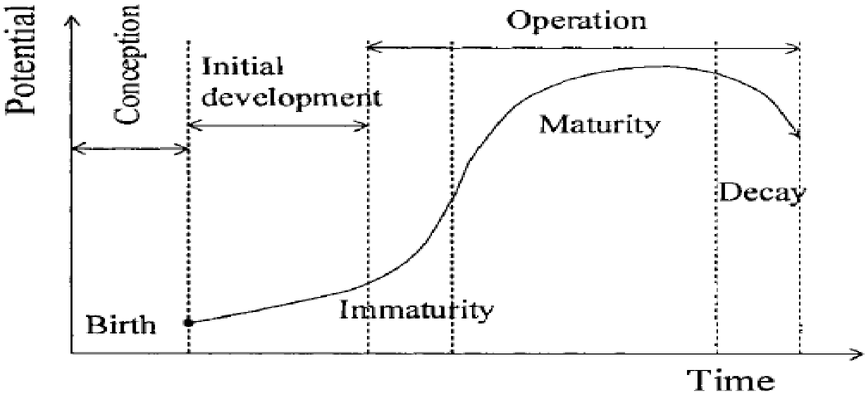
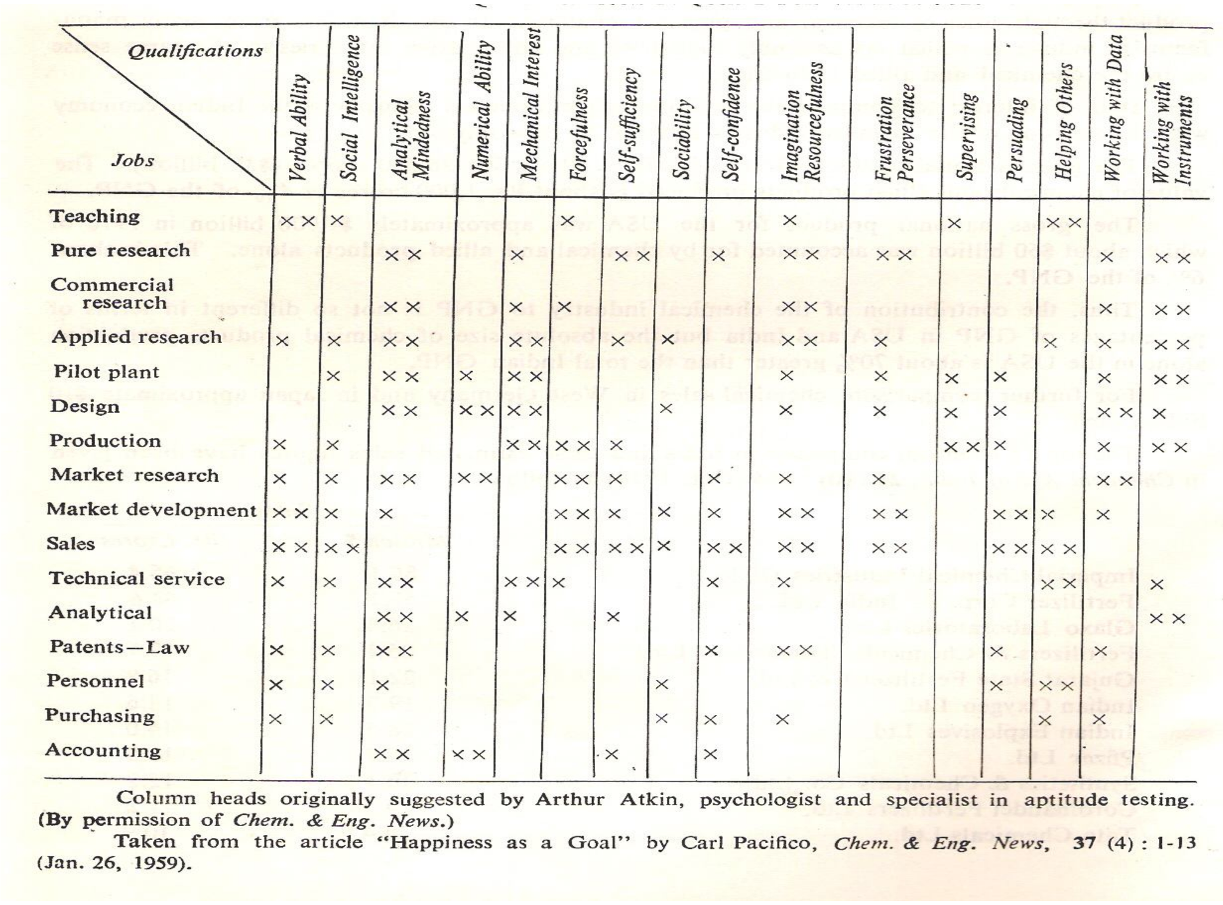


Fig.6 Life Cycle Assessment of a chemical

With this knowledge following are the skills required for job in chemical industries:



Qualifications / Jobs	Verbal Ability	Social Intelligence	Analytical Mindedness	Numerical Ability	Mechanical Interest	Forcefulness	Self-sufficiency	Sociability	Self-confidence	Imagination Resourcefulness	Frustration Perseverance	Supervising	Persuading	Helping Others	Working with Data	Working with Instruments
Teaching	××	×				×				×		×		××		
Pure research			××		×		××		×	××	××				×	××
Commercial research			××		×	×				××					×	××
Applied research	×	×	××		××		×	×		××	×			×	×	××
Pilot plant		×	××	×	××					×	×	×	×		×	××
Design			××	××	××			×		×	×	×	×		××	×
Production	×	×			××	××	×					××	×		×	××
Market research	×	×	××	××		××	×		×	×	×				××	
Market development	××	×	×			××	×	×	×	××	××		××	×	×	
Sales	××	××				××	××	×	××	××	××		××	××		
Technical service	×	×	××		××	×			×	×				××		×
Analytical			××	×	×		×									××
Patents—Law	×	×	××						×	××			×		×	
Personnel	×	×	×					×					×	××		
Purchasing	×	×						×	×	×				×	×	
Accounting			××	××			×		×							

Column heads originally suggested by Arthur Atkin, psychologist and specialist in aptitude testing. (By permission of *Chem. & Eng. News.*)

Taken from the article "Happiness as a Goal" by Carl Pacifico, *Chem. & Eng. News,* **37** (4) : 1-13 (Jan. 26, 1959).

Fig. 7 Qualification required for job in chemical industries

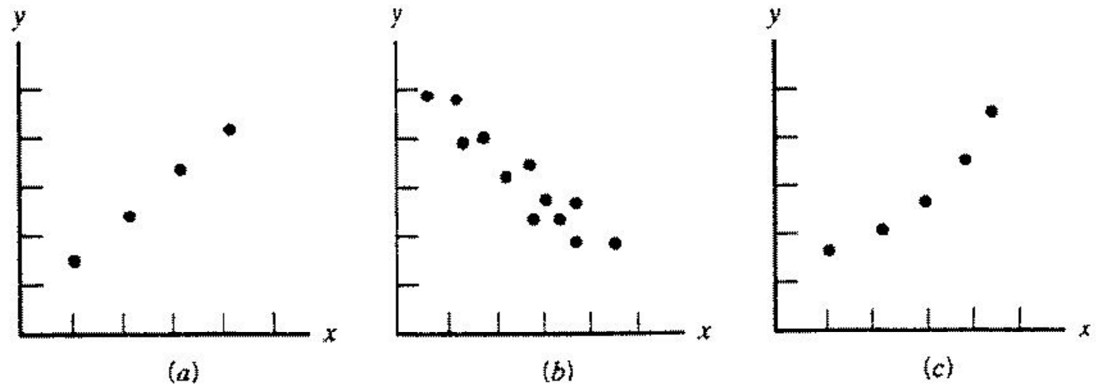
PART II MATHEMATICAL TECHNIQUES IN CHEMICAL ENGINEERING

In many chemical engineering problems, it is quite common to get experimental data in a complex situation. It become quite often necessary to generalize the relations between various parameters involved in the phenomena. Some of the techniques involved in this generalization are given below.

1. Representation of data
2. Average and mean
3. Numerical method of data fitting
4. Trial and error

1. Presentation of Data

The data obtained in the experiments can be presented (i) in a tabular form (ii) by graphs and equations representing the results.



x	1.0	2.0	3.0	4.0
y	0.3	0.7	1.2	1.8

Fig. 8 Representation of experimental Data

(i) The tabular form is most accurate form of presenting the data, as it retains the experimental results without any change. The disadvantages are
   - (a) They may be too large or long
   - (b) It may not be possible to draw any conclusion for the nature of the variation between variables.
   - (c) Interpolation and extrapolation will be very difficult.
   - (d) It may not be possible to smoothen the out liers (Error of experiments).

(ii) Graphical representation: The main advantages of graphical presentation of the data are
   - (a) General trend of variation between different variables can be easily seen.

(b) The amount of experimental errors can be easily known by the magnitude of deviation.

Different graph sheets:

a. Rectangular graph sheet
Useful in presenting data for the equations of the nature of $y = mx + c$ and $y = a + b/x$
b. Semi log and log-log graph sheet
Useful when relation between the dependent and independent variable is exponential in nature. The data can be represented as a semi logarithmic graph sheet to obtain a straight line. The equation represented in this form are $y = ae^{bx}$ and $y = cx^n$
c. Triangular graph sheet
These graph sheets which consist of an equilateral triangle with its three sides representing the composition of a three component system. These graphs are best suite for (i) graphical evaluation of mass balance between liquid mixtures made up of same three components (ii) phase equilibrium (Extraction/absorption/ stripping)
d. Isosceles triangular graph sheet
A right angled isosceles triangle is constructed using rectangular graph sheet. The x axis is represented by mass fraction of component A from 0 to 1 and y axis by mass fraction of B. This graphs are best used in application where separability of one component in presence of two solvents is to be studied.

The technique of graphical addition and subtraction of three component mixtures is very convenient than cumbersome algebraic solutions. Any series of operations of additions and subtractions can be done graphically noting that two quantities can be added or subtracted graphically at one time.

2. Average and Mean

These are generally misused one for the other. Referring to the arithmetic average and mean values only, the averages are usually taken for discrete quantities only, the weighted average of mean is usually referred to smooth (a continuous of not discrete) variable only. The mean of dependent variable $y = f(x)$ is given by the relation

$$\bar{y} = \frac{\int_{x_1}^{x_2} f(x)dx}{\int_{x_1}^{x_2} dx} = \frac{\int_{x_1}^{x_2} ydx}{x_2 - x_1}$$

Graphical Integration: To calculate the mean value of a dependent variable it usually becomes necessary to perform graphical integration. If there is analytical expression representing the functional relationship between y and x; the integration can be done analytically. For eg.$y = 8x^2$ and calculate mean between $x_1 = 1$ and $x_2 = 2$.

If the relationship between y and x is represented by a curve then, the mean y is given by the area bounded by the curve between limits x1 and x2. In general calculation of the area by counting the squares is a tedious and time consuming process.

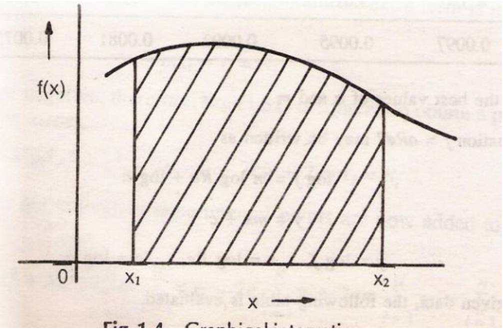


Fig. 9. Graphical Integration

In such cases the following two techniques are used conveniently.

(a) The method of rectangles

This method makes use of dividing the area into a series of rectangles not necessarily of same width. The upper end of each rectangle is so placed that area included below the curve but excluded from the rectangle is just equal to the area above the curve included in the rectangle. This is shown in the figure below and two shaded areas are to be equal.

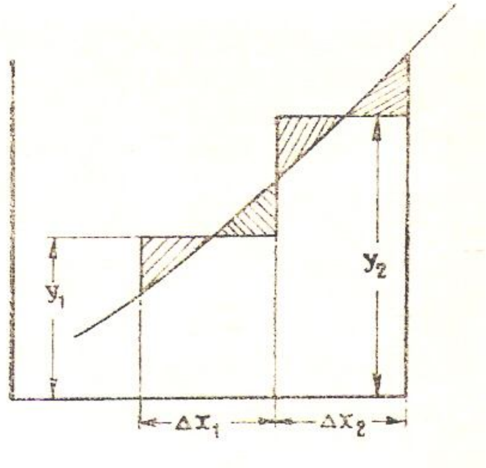


Fig.10 Method of Rectangles

$$\bar{y} = \int_{x_1}^{x_2} y\,dx = \sum_{i=1}^{n} y_i \Delta x_i$$

(b) The method of trapezoids

In this method the smooth curve is replaced by a series of straight line segments and constructing the trapezoids as shown. The area of the trapezoids is evaluated and y is given by the sum of these areas.

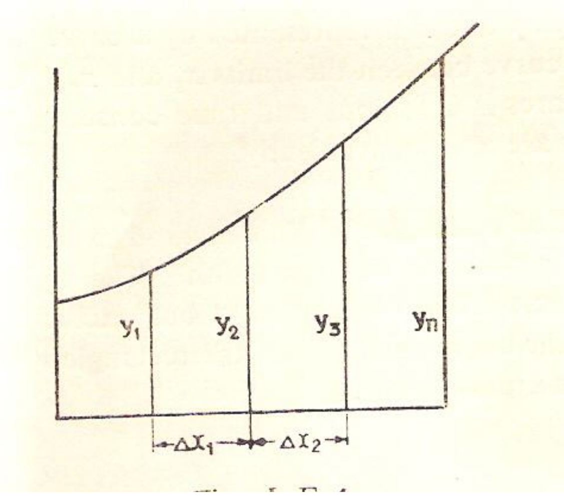


Fig.11. Trapezoidal Method

so

$$\bar{y} = \int_{x_1}^{x_2} y\,dx = \Delta x\left(\frac{y_1 + y_n}{2} + y_2 + y_3 .... + y_{n-1}\right)$$

Graphical Differentiation: When the relation between y and x cannot be represented by an analytical function, the proper slope of the tangent can be best obtained by graphical differentiation. This is all the more important when the experimental data are inaccurate. This technique is used in calculate rate constant and order in reaction engineering and constant of filtration operation.

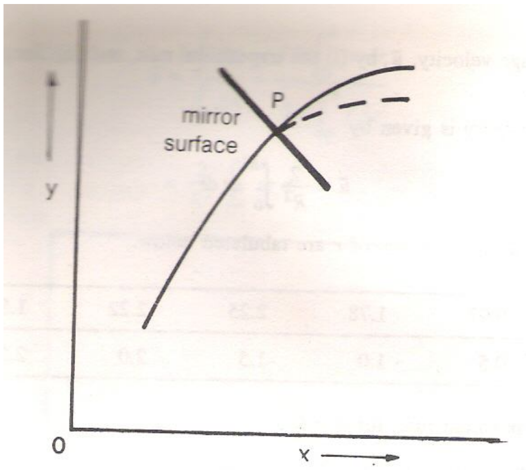


Fig. 12 Mirror Method

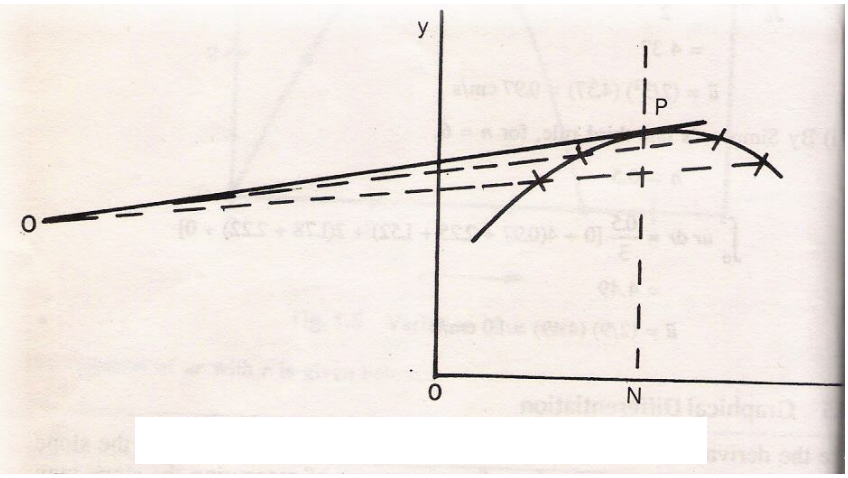


Fig. 13 Chord Method

3. **Numerical Method of Data Fitting**

Graphical methods are not always useful in correlating experimental data. Noting that any function can be represented by a polynomial series, the numerical methods described below aim at deriving best polynomial in x which correlates the experimental data obtained between y and x.

Virial Equation: The experimental data can be correlated by two possible virial equations

Y = a + bx + cx2 + dx3 +.....

Y = a + b/x + c/x2 + d/x3 + ...

In order to calculate the number of constants a, b, c and d in the equations given above at least as many data points are required as there are number of constants.

The first polynomial is used when the absolute values of dy/dx calculated from experimental data points increases as x increases. The second polynomial is used when dy/dx calculated from experimental data points approaches zero as x increases.

Lagrangian Interpolation method: If number of data points are available, the development and solving of an equation with corresponding number of terms as the data points, becomes very tedious process. In such cases Lagrangian method can be used conveniently. If n data points are available, then the polynomical with n terms for y is given by the equation:

$$y = \sum_{i=1}^{n} y_i \frac{(x - x_1)\ldots(x - x_{i-1})(x - x_{i+1})\ldots(x - x_n)}{(x_i - x_1)\ldots(x_i - x_{i-1})(x_i - x_{i+1})\ldots(x_i - x_n)}$$

This procedure gives a smooth curve between the data points and as such is called as Lagrangian interpolation method.

Least square method: this method is based on the principle of least square derived from probability consideration. This states that “From a given set of measurements of equal precision, the most probable obtainable value is one for which the sum of squares of errors is a minimum”.

As given in the definition, when the experimental data is obtained, with equal precisions the best possible polynomial is obtained by this method. Considering a three term polynomial be,

$$y_i = a + bx_i + cx_i^2$$

$$V_i = a + bx_i + cx_i^2 - y_i$$

$$V^2 = \sum V_i^2$$ Minimize this function

$$\sum_{i=1}^{n}\left(a + bx_i + cx_i^2 - y_i\right)^2 = F(a,b,c)$$

Doing this will produce three simultaneous equations in a,b and c. These are solved for a,b and c to get polynomial of best fit.

4. **Trial and Error Method:**
   Sometimes it is required to obtain the solution of an equation in x. Sometimes there may not be any analytical solution and the trial and error procedure is best employed. In this a value is assumed for x and the value of x is calculated from the equation. The best solution of the equation is that one which gives a minimum value for the difference in the assumed and calculated value of x. The procedure is explained by a problem.

PART III BASIC CHEMICAL CALCULATIONS

INTRODUCTION

In this section of interaction basic techniques for expressing the values of system variables and for setting up and solving equations that relate these variables will be discussed. Further we will also discuss the variables of specific concern in process analysis – temperature, pressure, chemical composition, and amounts or flow rates of process streams – describing how they are defined, calculated and in some cases measured.

The primary focus of this course is on understanding and solving problems based on *balance equations*. These concepts and solution techniques are used to determine the distribution of material and energy flows in a chemical process.

Balance computations are based on the principles of conservation of mass and energy. They are probably the most common computation performed by chemical engineers -- almost all chemical engineering problems, no matter how simple or complex, start out by *closing* the material and energy balances. By "closing", mean applying the balance equations to determine the flows, compositions, and temperatures of all streams in a flowsheet; starting from what one know or is able to measure.

The course will also address issues of *stoichiometry*: the analysis of how chemical compounds combine.

Clearly, much of what is going to be done in this course is not entirely new. Concepts and tools from chemistry, physics, thermo, and the ChE intro course as building blocks for this course. One has to start with "bare bones" problems and gradually add layers of complexity as move through this course. This means it is very important to keep up! Success in this course will depend on individual’s ability to solve problems.

UNITS AND DIMENSIONS

Physical quantities serve to describe clearly the natural laws. These physical quantities are defined by measuring instructions and determined by the basic or primary measuring units. The *Dimension* represents the generalization of a physical quantity and signifies its nature qualitatively without the knowledge of its unit. The dimensional formula of a quantity express only the way in which primary units enter into operation by which the quantity in question is defined. So *Dimension* is description of physical extent and *units* are measure of that extent. *Dimension* is qualitative representation of physical system and *units* quantify that system. Several systems of dimensions are used by academics and industries. Most common is ***Absolute*** system of dimensions and ***Metric*** system of dimension. Even today many industries are following ***English*** system of dimensions.

Every physical quantity can be expressed as a product of pure number and a unit. When defining any physical quantity one must answer two questions: (a) what would be most convenient unit? (b) What would be the best form and material for the standard, physically representing that unit?

One needs to study these units and dimension for the process variables that encountered during the production of particular chemicals. So one must define and understand the meaning of process variables. Process variable is any measurement used to characterize or describe a chemical process.

There is a statement written by someone for a chemical engineer starting their carrier

“***Take care of your units and they will take care of you***”

The fundamental process variables

1. Measurements to quantify a material or specify a chemical composition.

Mass and Volume absolute values or flow rate, and composition

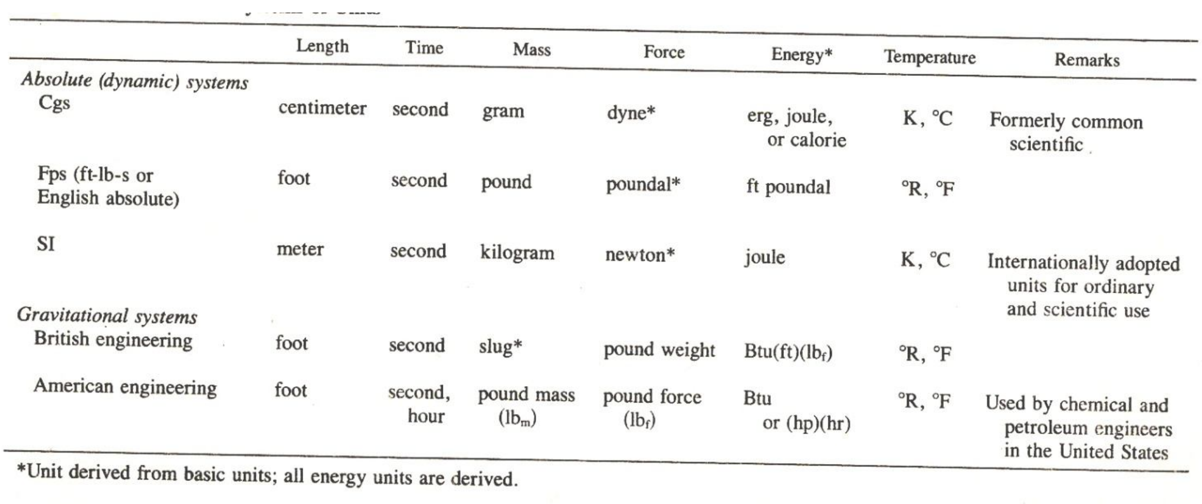
2. Measurements used to specify process conditions.

Pressure and Temperature

These physical quantities are classified in three categories:

1. Fundamental quantities
2. Derived quantities
3. Multiplication quantities

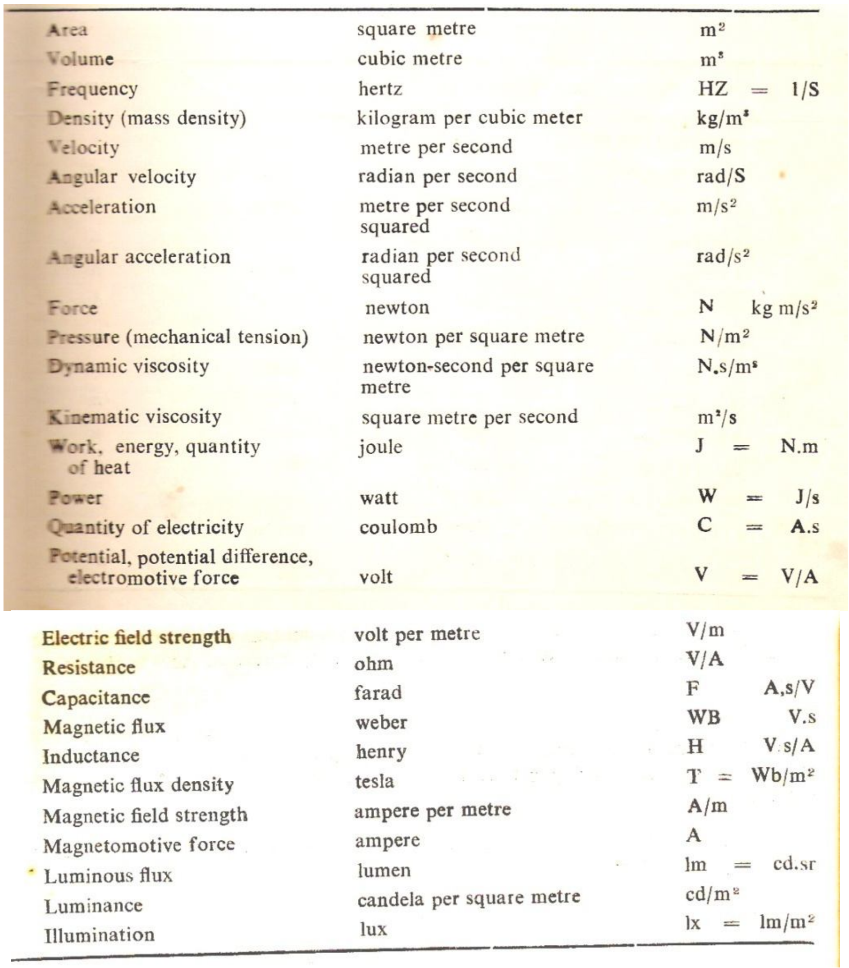
Below mentioned tables shows the fundamental, derived and multiplication quantities:



	Length	Time	Mass	Force	Energy*	Temperature	Remarks
Absolute (dynamic) systems							
Cgs	centimeter	second	gram	dyne*	erg, joule, or calorie	K, °C	Formerly common scientific
Fps (ft-lb-s or English absolute)	foot	second	pound	poundal*	ft poundal	°R, °F	
SI	meter	second	kilogram	newton*	joule	K, °C	Internationally adopted units for ordinary and scientific use
Gravitational systems							
British engineering	foot	second	slug*	pound weight	Btu(ft)(lb_f)	°R, °F	
American engineering	foot	second, hour	pound mass (lb_m)	pound force (lb_f)	Btu or (hp)(hr)	°R, °F	Used by chemical and petroleum engineers in the United States

*Unit derived from basic units; all energy units are derived.

Fig. 14 Fundamental Dimensions with common unit systems



Area	square metre	m^2
Volume	cubic metre	m^3
Frequency	hertz	HZ = 1/S
Density (mass density)	kilogram per cubic meter	kg/m^3
Velocity	metre per second	m/s
Angular velocity	radian per second	rad/S
Acceleration	metre per second squared	m/s^2
Angular acceleration	radian per second squared	rad/s^2
Force	newton	N kg m/s^2
Pressure (mechanical tension)	newton per square metre	N/m^2
Dynamic viscosity	newton-second per square metre	$N.s/m^2$
Kinematic viscosity	square metre per second	m^2/s
Work, energy, quantity of heat	joule	J = N.m
Power	watt	W = J/s
Quantity of electricity	coulomb	C = A.s
Potential, potential difference, electromotive force	volt	V = V/A
Electric field strength	volt per metre	V/m
Resistance	ohm	V/A
Capacitance	farad	F A,s/V
Magnetic flux	weber	WB V.s
Inductance	henry	H V.s/A
Magnetic flux density	tesla	T = Wb/m^2
Magnetic field strength	ampere per metre	A/m
Magnetomotive force	ampere	A
Luminous flux	lumen	lm = cd.sr
Luminance	candela per square metre	cd/m^2
Illumination	lux	lx = lm/m^2

Fig.15 Derived quantities

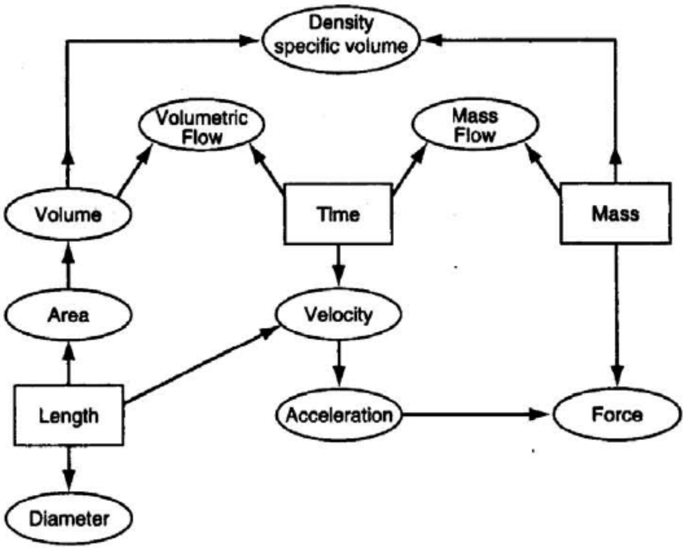
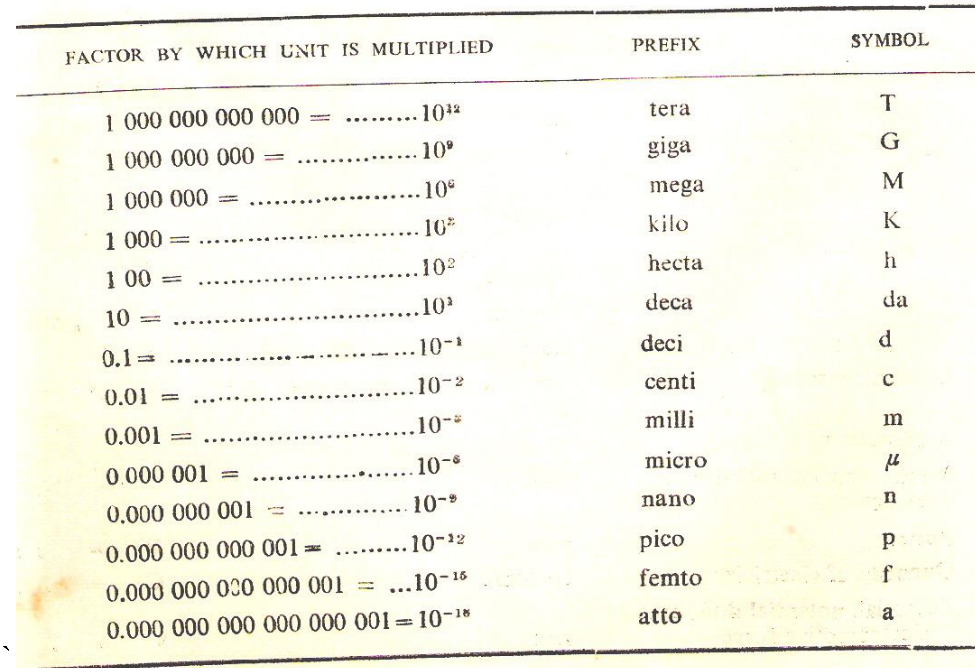


Fig.16 Relation between various fundamental properties and derived properties



FACTOR BY WHICH UNIT IS MULTIPLIED	PREFIX	SYMBOL
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	K
1 00 = 10^{2}	hecta	h
10 = 10^{1}	deca	da
0.1 = 10^{-1}	deci	d
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

Fig. 17 Multiplication Quantities

Table: 3 Difference between unit and dimension

Value	Unit	Dimension
110	mg	mass
24	hand	length
5	gal	volume (length3)

Operations with Units

Answers to a question such as: how much is 2 + 2 can sometimes be debatable. You might state 4 . A bad calculator might show 3.99999. What about 9 + 5? Can the answer for 9 + 5 = 2 possibly be correct? Hint: Look at a wall clock.

Every fresh man knows that what you get from adding an apple to an orange is fruit salad! The rule of handling units is quite similar and easy.

(i) Addition and Subtraction equality

One can add, subtract or equate numerical quantities only if the associated units of the quantities are the same. Thus the operation

5 kilograms + 3 joules

Cannot be carried out because the units as well as the dimensions of the two terms are different. The numerical operation

10 pounds + 5grams

Can be performed (because the dimensions are same, mass) only after the units are transformed to be the same, either pounds, grams or ounces, or some other mass unit.

(ii) Multiplication and Division equality

It is possible to multiply or divide unlike units at will such as

50(kg)(m)/sec

But it is not possible to cancel or merge units unless they are identical even of same dimensions. Thus $3m^2/60cm$ can be converted to $3m^2/0.60m$ and then to 5m but in m/s^2, the units cannot be cancelled or combined.

CONVERSION OF UNITS AND CONVERSION FACTORS

In industry the physical quantities are expressed by a number associated with its unit. This is called as *dimensional equation*. These quantities are expressed in terms of any units having appropriate dimensions. A particular velocity, for instance, may be expressed in ft/s, miles/h, cm/yr, or any other ratio of a length unit to a time unit. The numerical value of the velocity naturally depends on the units chosen.

The equivalence between two expressions of the same quantity may be defined in terms of a ratio:

$$\frac{1\ \text{cm}}{10\ \text{mm}}$$

$$\frac{10\ \text{mm}}{1\ \text{cm}}$$

$$\left[\frac{10\ \text{mm}}{1\ \text{cm}}\right]^2 = \frac{100\ \text{mm}^2}{1\ \text{cm}^2}$$

Ratios of these form are called conversion factor. So to convert a quantity expressed in terms of one unit to its equivalent in terms of another unit, multiply the given quantity by the conversion factor (New unit/old unit). Like to convert 36 mg to its equivalent in grams write

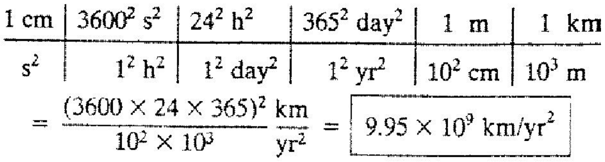
$$\left.\frac{36\ \text{mg}}{}\right|\frac{1\ \text{g}}{1000\ \text{mg}} = 0.036\ \text{g}$$

Example: A plane travels twice as the speed of sound (1100ft/sec). Express this physical quantity in miles per hour.

$$\left.\frac{2(1100)\cancel{\text{ft}}}{\cancel{\text{s}}}\right|\left.\frac{1\ \text{mile}}{5280\ \cancel{\text{ft}}}\right|\left.\frac{60\ \cancel{\text{s}}}{1\ \cancel{\text{min}}}\right|\frac{60\ \cancel{\text{min}}}{1\ \text{hr}}$$

= 1500miles/hr

Example: Convert an acceleration of 1 cm/s^2 to its equivalent in km/yr^2.



$$\begin{array}{l|l|l|l|l|l} 1\ \text{cm} & 3600^2\ \text{s}^2 & 24^2\ \text{h}^2 & 365^2\ \text{day}^2 & 1\ \text{m} & 1\ \text{km} \\ \hline \text{s}^2 & 1^2\ \text{h}^2 & 1^2\ \text{day}^2 & 1^2\ \text{yr}^2 & 10^2\ \text{cm} & 10^3\ \text{m} \end{array}$$

$$= \frac{(3600 \times 24 \times 365)^2}{10^2 \times 10^3} \frac{\text{km}}{\text{yr}^2} = \boxed{9.95 \times 10^9\ \text{km/yr}^2}$$

DIMENSIONAL CONSISTENCY OR HOMOGENEITY

As we have already discussed about units and dimensions by saying that quantities can be added and subtracted only if their units are the same. If units are the same, it follows that the dimensions of each term must be the same. For example, if two quantities can be expressed in terms of grams/second, both must have the dimensions (mass/time). This suggest the following rule:

Every valid equation must be dimensionally homogeneous: that is, all additive terms on both sides of the equation must have the same dimensions.

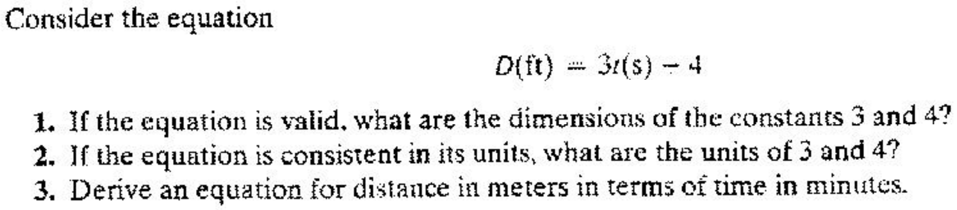
Consider the equation

$$u(\text{m/s}) = u0(\text{m/s}) + g(\text{m/s}^2)t(\text{s})$$

This equation is dimensionally homogeneous, since each of the terms u, u_0 and g_t has the same dimension (length/time). On the other hand, the equation $u = u_0 + g$ is not dimensionally homogeneous and therefore cannot possibly valid.

Above equation is dimensionally homogeneous as well as consistent, because all the terms are having same unit m/s. But if one put t in min, then equation will be dimensionally homogeneous but not consistent. So to make it consistent t in min should be converted to t in sec by using proper conversion factor studied in previous section.

Example:

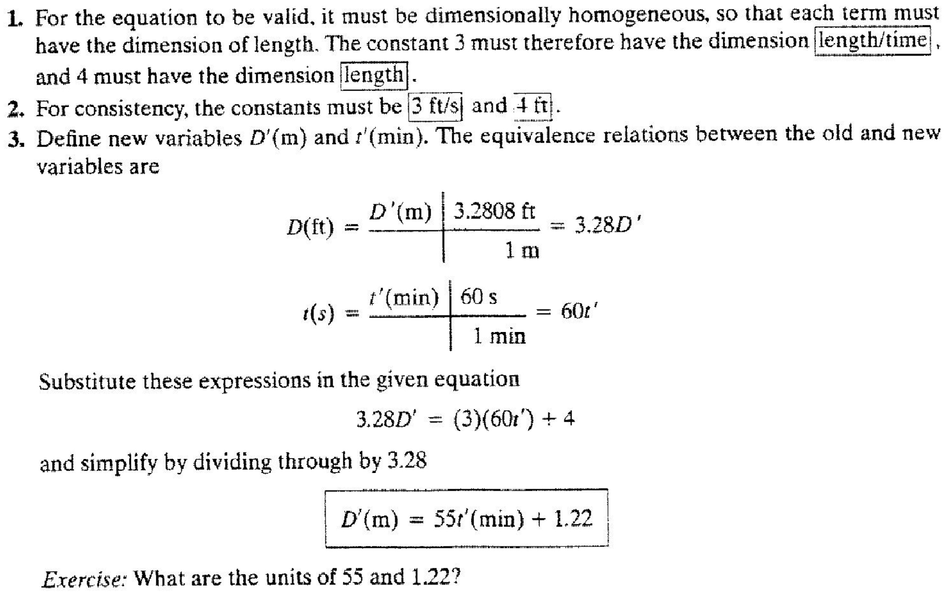


Consider the equation

$$D(\text{ft}) = 3t(\text{s}) - 4$$

1. If the equation is valid, what are the dimensions of the constants 3 and 4?
2. If the equation is consistent in its units, what are the units of 3 and 4?
3. Derive an equation for distance in meters in terms of time in minutes.

Solution:



1. For the equation to be valid, it must be dimensionally homogeneous, so that each term must have the dimension of length. The constant 3 must therefore have the dimension $\boxed{\text{length/time}}$, and 4 must have the dimension $\boxed{\text{length}}$.
2. For consistency, the constants must be $\boxed{3\ \text{ft/s}}$ and $\boxed{4\ \text{ft}}$.
3. Define new variables $D'(\text{m})$ and $t'(\text{min})$. The equivalence relations between the old and new variables are

$$D(\text{ft}) = \frac{D'(\text{m})}{} \left| \frac{3.2808\ \text{ft}}{1\ \text{m}} \right. = 3.28D'$$

$$t(s) = \frac{t'(\text{min})}{} \left| \frac{60\ \text{s}}{1\ \text{min}} \right. = 60t'$$

Substitute these expressions in the given equation

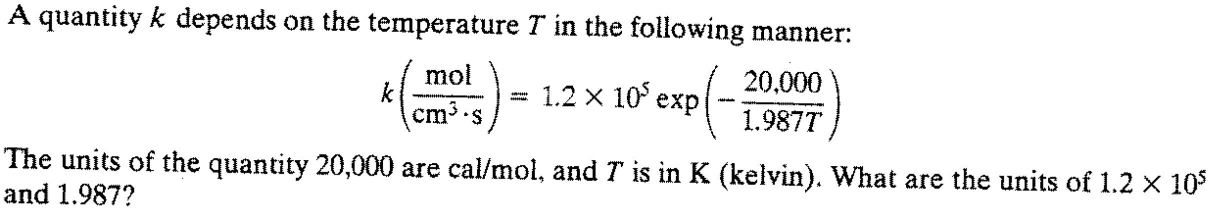
$$3.28D' = (3)(60t') + 4$$

and simplify by dividing through by 3.28

$$\boxed{D'(\text{m}) = 55t'(\text{min}) + 1.22}$$

Exercise: What are the units of 55 and 1.22?

Example:

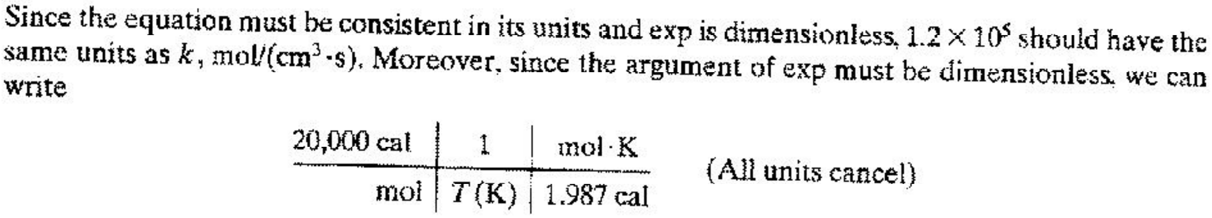


A quantity k depends on the temperature T in the following manner:

$$k\left(\frac{\text{mol}}{\text{cm}^3\cdot\text{s}}\right) = 1.2\times10^5\exp\left(-\frac{20{,}000}{1.987T}\right)$$

The units of the quantity 20,000 are cal/mol, and T is in K (kelvin). What are the units of 1.2×10^5 and 1.987?

Solution:



Since the equation must be consistent in its units and exp is dimensionless, 1.2×10^5 should have the same units as k, mol/(cm^3·s). Moreover, since the argument of exp must be dimensionless, we can write

$$\begin{array}{r|c|c} 20{,}000\ \text{cal} & 1 & \text{mol}\cdot\text{K} \\ \hline \text{mol} & T\,(\text{K}) & 1.987\ \text{cal} \end{array} \qquad \text{(All units cancel)}$$

1.2×10^5 mol/cm^3.s and 1.987 cal/mol.k

PROCESS VARIABLES

Temperature

The physical or chemical state of most substances changes when they are heated or cooled. If one want to correlate state with conditions, it requires some sort of way to measure the relative "hotness" of the substance.

Temperature is defined as the degree of hotness or coldness of a substance measured on some definite scale.

Hotness (and coldness) results from molecular activity. As molecules take up energy, they start to move faster, and the temperature of the substance increases. Thus it can be said that temperature is a measure of the average kinetic energy of the molecules of a substance.

In order to compare the hotness (temperature) of two substances, one need to define a scale of relative temperatures. This is done by assigning values to two points and dividing up the interval between the fixed points into smaller intervals called "degrees".

Temperature Scales

The two most common temperature scales are the Fahrenheit scale and the Celsius scale. Both are examples of *relative* Temperature scales.

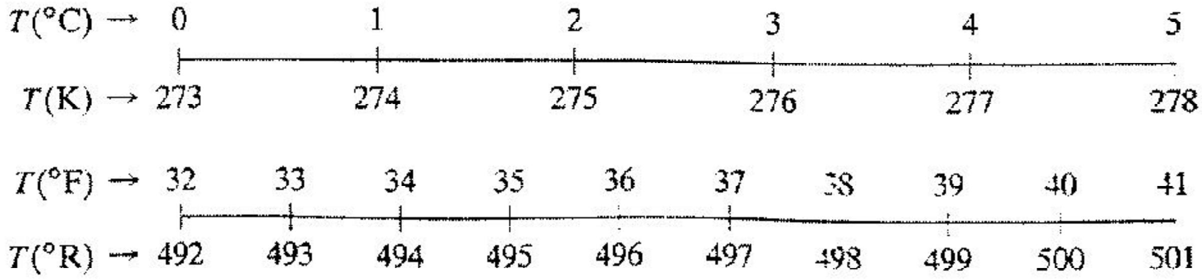
Gabriel Daniel Fahrenheit (1686-1736), a German physicist, fixed one point using a mixture of salt, water, and ice (0 degrees F) and the other using body temperature (96 degrees F) -- chosen because it is divisible by 2, 3, 4, 6, 8). On this scale, water freezes at 32 degrees F and boils at 212 degrees F.

Anders Celsius (1701-1744), a Swedish astronomer fixed the freezing point of water (0 degrees C) and the boiling point of water (100 degrees C). Because it has 100 degrees, this scale has also been called the centigrade scale.

The Celsius scale is more commonly used in scientific applications in the US, as well as in the rest of the world.

To convert between the scales, first you need to look at the size of the degrees:

$$\frac{212^\circ F - 32^\circ F}{100^\circ C - 0^\circ C} = \frac{180F^\circ}{100C^\circ} = 1.8\frac{F\ \text{degrees}}{C\ \text{degrees}}$$



and then you need to remember that they don't start at the same place

$$32^\circ F = 0^\circ C$$

So to convert from one to the other you use a calculation like

$$T_{(^\circ F)} = 1.8T_{(^\circ C)} + 32$$

EXAMPLE: What is the temperature in Fahrenheit when it is 70 degrees C?

$$T_F = 1.8(70) + 32 = 158^\circ F$$

Absolute Temperature Scales

It was said that temperature is based on molecular motion. Theoretically, there is a condition of no molecular motion (so cold that the molecules stop moving, or zero kinetic energy in the molecules). This point is called absolute zero, and is the lowest conceivable temperature.

$$T_{(Absolute\ Zero)} = -459.67^\circ F = -273.15^\circ C$$

As thermodynamics developed, it became useful to define temperature scales which began at absolute zero (so you didn't have to mess with negative temperatures). These scales are called absolute Temperature scales. Two scales are commonly used, set up so that the degree intervals are the same size as the common relative scales.

The Kelvin scale has the same size degree as the Celsius scale. Thus,

$$0\,K - -273.15^\circ C \qquad 0^\circ C - 273.15K$$

The Rankine scale has the same size degree as the Fahrenheit scale, so:

$$0^\circ R - -459.67^\circ F \qquad 0^\circ F - 459.67^\circ R$$

Often, we round the endpoints off to 273 and 460.

Since the degrees are the same "thickness" between Celsius and Kelvin (or between Fahrenheit and Rankine) we need only make an "additive" conversion to adjust between the two.

*EXAMPLE:*What is the freezing point of water on the absolute temperature scales?

$$T_{fp} = 32^\circ F + 460 = 492^\circ R$$

$$T_{fp} - 0^\circ C + 273 - 273 K$$

On the other hand, if it is required to convert from Kelvin to Rankine, both start at absolute zero, and we only need to use the "multiplicative" conversion to switch (1.8 R/K).

Temperature Intervals

It is important to keep straight that "degree" has a double meaning. It means both a temperature "96 degrees Fahrenheit" and an interval "96 Fahrenheit degrees". In practice, this means that when converting an interval, you don't need to compensate for the zero shift.

EXAMPLE: You have a mixture at 50 degrees F and increase its temperature by 30 C degrees. What is the final temperature?

$$50^\circ F + 30^\circ C\left(\frac{1.8 F^\circ}{C^\circ}\right) = 104^\circ F$$

Don't make the mistake of thinking this is the same as:

$$50^\circ F + \left[1.8(30) + 32\right] = 136^\circ F$$

PRESSURE

"Pressure" is the ratio of a normal force to the area on which the force acts. Units are thus

$${}^{lb_f}\!/_{in^2} \quad \text{or} \quad {}^{N}\!/_{m^2} = \text{Pa} \quad .$$

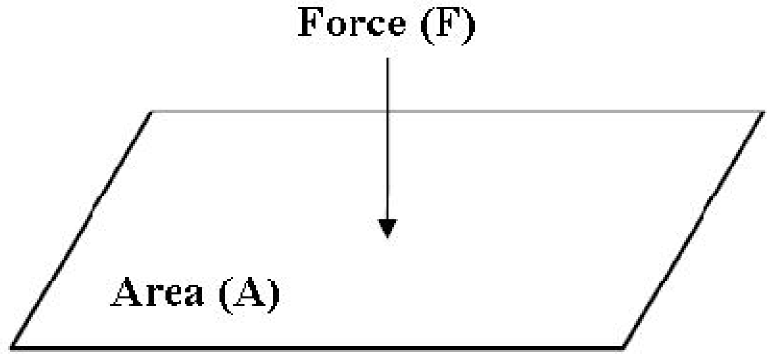


Fig.18 Pressure Definition

Hydrostatic Pressure :

Think of a column of fluid of height *h* and cross sectional area *A*. The fluid has a density rho (ρ). The pressure *P* at the base of the column is by definition the force exerted on the base divided by the area *A*; that force is the weight of the column plus any force acting on the top.

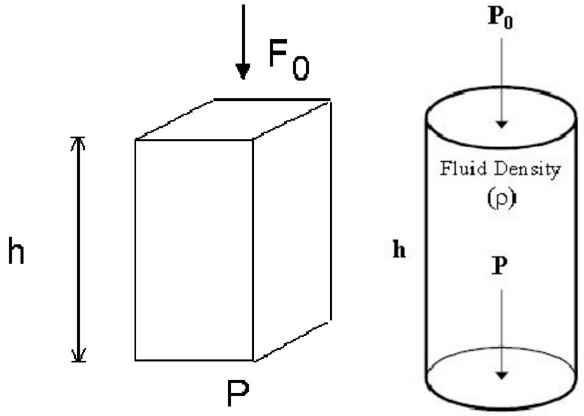


Fig.19 Hydrostatic Pressure

$$P = \frac{F_{base}}{A} = \frac{1}{A}\left(F_o + W\right) = \frac{1}{A}\left(F_o + \frac{mg}{g_c}\right) = \frac{F_0}{A} + \frac{\rho hg}{g_c} = P_0 + \frac{\rho hg}{g_c}$$

This is the formula for the pressure due to a column of fluid, or "hydrostatic pressure".

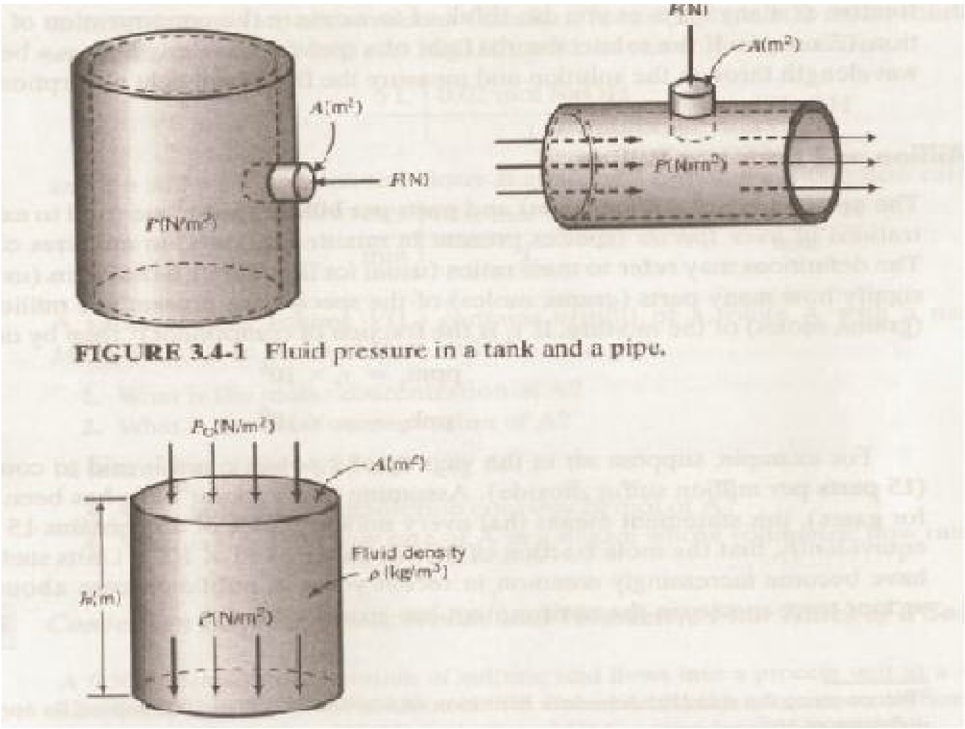


FIGURE 3.4-1 Fluid pressure in a tank and a pipe.

Fig.20 Pressure in Vessel and in pipe

EXAMPLE: What is the hydrostatic pressure exerted by the water in a 6.00 ft diameter cylindrical tank which contains 90.0 gal?

Look at the hydrostatic pressure formula, one need the pressure at the top of the column, the density of the fluid, and the height of the column.
The density we look up: 62.4 lbm/ft^3 for water
The height of the column is not given, but dimensions on the tank are given. Since the volume is the product of the area and the height, one is able to back out the desired number.
Assume: tank has constant cross-section

$$A = \frac{\pi(6.0\ \text{ft})^2}{4} = 28.3\ \text{ft}^2$$

$$h = (90\ \text{gal})\left(\frac{1}{28.3\ \text{ft}^2}\right)\left(\frac{\text{ft}^3}{7.48\ \text{gal}}\right) = 0.426\ \text{ft}$$

Assume: no pressure acting on top of column
Actually, the air above the column exerts a pressure.

$$P = P_0 + \rho h \frac{g}{g_c} = 0 + \left(62.4 \frac{\text{lb}_m}{\text{ft}^3}\right)(0.426\ \text{ft})\left(1 \frac{\text{lb}_f}{\text{lb}_m}\right)$$

$$= 26.6 \frac{\text{lb}_f}{\text{ft}^2}\left(\frac{\text{ft}^2}{144\ \text{in}^2}\right) = 0.184\ \text{psi}$$

Atmospheric Pressure
Air is a fluid -- so the air above the earth exerts a hydrostatic pressure on the surface. This is *atmospheric pressure*. If you look at the hydrostatic pressure equation, you can see that the pressure exerted will depend on the height of the column and the density of the air. At sea level the standard atmospheric pressure is

$$\begin{aligned} P_{atm} &= \mathbf{1.000\ atm} \\ &= \mathbf{760.0\ mmHg} \\ &= \mathbf{101.3\ kPa} \\ &= \mathbf{29.92\ in\ Hg} \\ &= \mathbf{33.91\ ft\ H_2O} \\ &= \mathbf{14.7\ psi\ (lbf/in^2)} \end{aligned}$$

It will decrease as as the altitude increases. The reduced pressure is why breathing is more difficult ("at altitude" for athletes).

For many calculations, it is useful to have a fixed reference value for atmospheric pressure. The sea-level value is used. It is called the "standard atmosphere". This value is also used as a unit of pressure measurement (*atm*). It may be used in homework problems, etc., *if there is no other information given about atmospheric conditions*.

Head

In chemistry classes, one has probably seen pressures measured in *mm Hg* (a.k.a. Torr). These aren't "natural" pressure units (force/area) -- so where did they come from? It has been observed that a column of fluid produces a pressure, so that the height of the column is an indicator of the pressure produced. This principle is the basis of one of the traditional methods of measuring pressure: the *manometer*. When pressure is expressed in terms of a height of fluid, it is called fluid "head". Usually, water or mercury is used.

$$14.7\,\frac{\text{lb}_f}{\text{in}^2} = 14.7\text{ psi} = 33.9\text{ ft H}_2\text{O (head)} = 760\text{ mmHg (head)}$$

Head units are mostly used for very low pressures and expressed as "mm Hg" or "in H2O".

Converting between force/are and head units is simple. Use the fluid weight term from the hydrostatic pressure equation:

$$P_{\left(\frac{force}{area}\right)} = \frac{\rho_{fluid}\,g}{g_c}\,P_{(head)}$$

EXAMPLE: Take the result from above and express it in "head".

$$0.184\frac{\text{lb}_f}{\text{in}^2}\left(1\frac{\text{lb}_m}{\text{lb}_f}\right)\left(\frac{\text{ft}^3\text{ H}_2\text{O}}{62.4\text{ lb}_m}\right)\left(\frac{12^3\text{ in}^3}{\text{ft}^3}\right) = 5.11\text{ in H}_2\text{O}$$

$$0.184\frac{\text{lb}_f}{\text{in}^2}\left(\frac{\text{kg}}{9.807\text{N}}\right)\left(\frac{\text{m}^3\text{ Hg}}{13600\text{ kg}}\right)\left(\frac{\text{N}}{0.22481\text{ lb}_f}\right)\left(\frac{10^9\text{ mm}^3}{\text{m}^3}\right)\left(\frac{\text{in}^2}{25.4^2\text{ mm}^2}\right) - 9.53\text{ mm Hg}$$

Manometers

An old, simple way of measuring pressure is with a "manometer". A U-shaped tube is partially filled with liquid, usually water or mercury. Each end is connected to a pressure source, and the difference in liquid height corresponds to the difference in pressure. Usually used for pressure below 3atm.

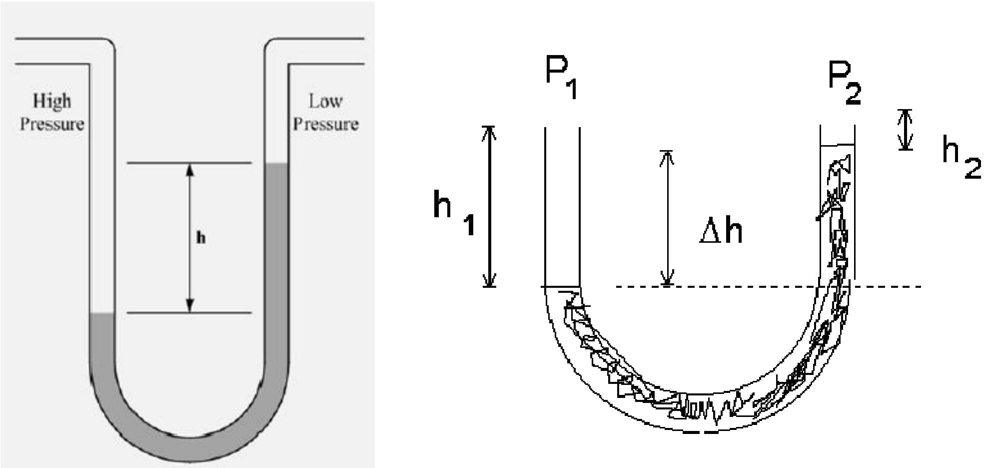


Fig.21 U-tube Manometers

At the bottom of the manometer, the force exerted by one leg balances against the force exerted by the other. The force balance equation can be written:

$$P_1 + \rho_1\left(\frac{g}{g_c}\right)h_1 = P_2 + \rho_2\left(\frac{g}{g_c}\right)h_2 + \rho_f\left(\frac{g}{g_c}\right)(h_1 - h_2)$$

This is the general form of the "manometer equation" and can be used to solve just about any manometer type problem. If one learns this equation, it can readily simplified for any case -- multiple fluids, tap pressures, etc.

Often, a manometer is connected so that the same fluid is present at the tops of both legs. In this case, and if only a single manometer fluid is used, there are only two densities, and the terms can be lumped together. It is also possible to group the two height terms and express them as a difference. This gives the "differential manometer equation":

$$P_1 - P_2 = (\rho_f - \rho)\left(\frac{g}{g_c}\right)\Delta h$$

The differential manometer equation is frequently used to help determine a flow rate. If a restriction (an orifice, valve, etc.) is placed in a line carrying a flowing fluid, it will produce a pressure drop. A manometer can then be used to measure the pressure drop. The pressure difference is proportional to the flow rate squared.

Types of Manometers:

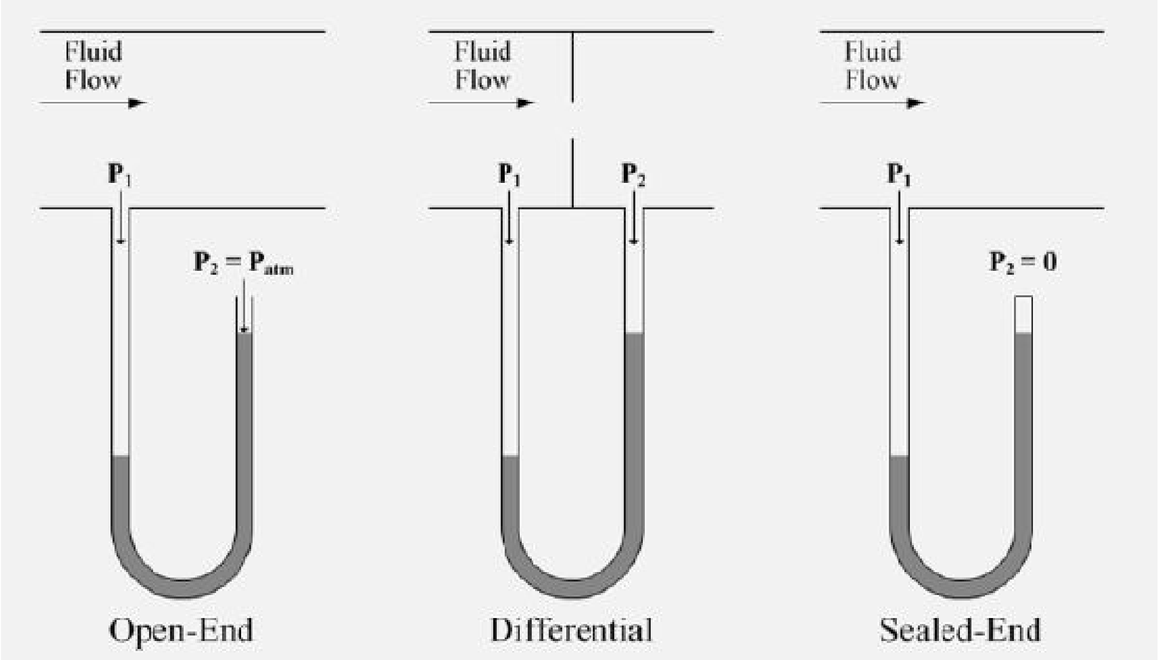


Fig.22 Type of Manometers

Absolute *vs.* Gage

If you look at the manometer, you'll see that it doesn't really measure a pressure, but instead detects the difference in pressure between the taps. Almost all pressure measurement devices have the same limitation. Thus, most pressures are measured with reference to some known value.

Getting "zero" pressure can be complicated and expensive. For most measurements, it is more practical to measure with respect to atmospheric pressure. For example, to use a manometer, you may attach one end to the pressure source to be measured and leave the other open to the atmosphere. This is so common that pressures measured in this way are designated *gage pressure*. If *absolute pressure* is to be measured, it is necessary to evacuate one end of the manometer so that the fluid works against vacuum.

$$P_{absolute} = P_{gage} + P_{atm}$$

$$\text{psia} = \text{psig} + 14.696$$

$$1 \text{ atm absolute} = 0 \text{ atm gage}$$

Thus, a "closed end" manometer measures absolute pressure, while an "open end" manometer measures gage pressure. A "barometer" measures atmospheric pressure.

Pressures less than atmospheric are "vacuums". Common practice is to state negative gage pressures as positive vacuum. Vacuums are frequently listed in head units.

$$-1 \text{ in } H_2O \text{ gage} = +1 \text{ in } H_2O \text{ vacuum} \quad (\text{or 'draft'})$$

The chart below may help keep track of things.

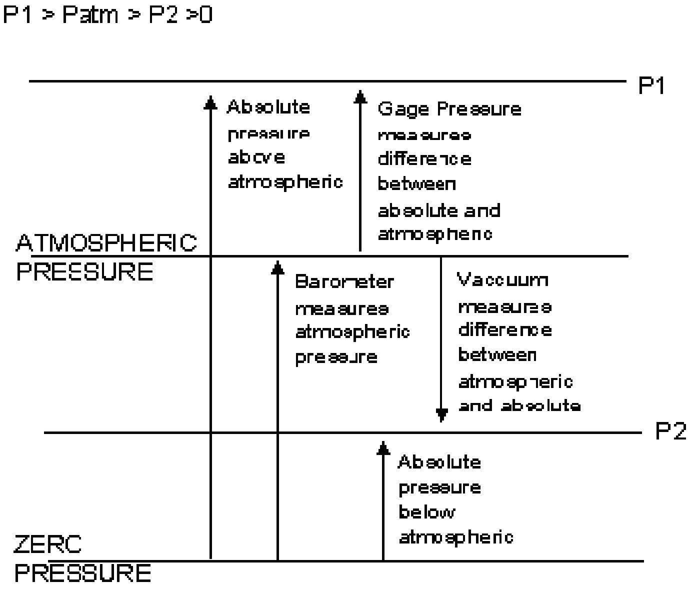


Fig.23 Pressure Scale

FLOW RATES

One generally want to know how much material is coming into or out of a process, so one measure the "flow rate":

- the *mass flow rate*, mass per time
- the *volumetric flow rate*, volume per time
- the *molar flow rate*, moles per time

The symbols for mass and molar flow rates are typically *m*s or *n*s, sometimes with a dot overhead. The dot is often used to mark a "rate" (per unit time). Volumetric flowrates are indicated by *V*, *Q*, or *F*.

Usually, the volumetric flow rate is the easiest to measure. It can then be converted to mass flow rate using the density:

$$\dot{m} = \rho F$$

Most industrial flow measurement devices really measure the flow velocity. The volumetric flow rate is then calculated from the velocity and the cross-sectional area of the pipe:

$$F = vA$$

Doing this makes some assumptions about the *velocity distribution*, but for the most part we'll wait until our fluid mechanics course to worry about those.

COMPOSITION

Most material streams in process units are mixtures of compounds. They are described by the composition of the stream in various ways.

Composition Fractions

Composition fractions can be based on mass or on moles.

Mass Fraction

$$x_i = \frac{\text{mass component } i}{\text{total mass}}$$

Mole Fraction

$$\tilde{x}_i = \frac{\text{moles component } i}{\text{total moles}}$$

One can convert from "fraction" to "percent" by multiplying by 100.

The units of mass measurement used don't make a difference, as long as the top and bottom of the ratio use the same units:

$$x = 0.25 = 0.25\frac{\text{lb}}{\text{lb total}} = 0.25\frac{\text{kg}}{\text{kg total}} = 0.25\frac{\text{tons}}{\text{tons total}} = \text{etc.}$$

EXAMPLE: A stream contains 20 g of oxygen gas, 70 g of nitrogen, 5 g of helium, and 5 g of hydrogen. Find the mass and mole fractions, mass and mole percent compositions.

First, it is needed to find the mass of each component (given), the total mass (add them up). Then calculate the moles of each component (divide mass by molecular weight) and the total moles.

$$\begin{array}{rcl}
20\ \text{g } O_2 & \div 32 & = 0.625\ \text{mol } O_2 \\
70\ \text{g } N_2 & \div 28 & = 2.5\ \text{mol } N_2 \\
5\ \text{g He} & \div\ 4 & = 1.25\ \text{mol He} \\
5\ \text{g } H_2 & \div\ 2 & = 2.5\ \text{mol } H_2 \\
\hline
100\ \text{g total} & & 6.875\ \text{mol total}
\end{array}$$

Now everything is available to calculate the composition fractions.

$$x_{O_2} = \frac{20}{100} = 0.2 \qquad \tilde{x}_{O_2} = \frac{0.625}{6.875} = 0.09$$

$$x_{N_2} = \frac{70}{100} = 0.7 \qquad \tilde{x}_{N_2} = \frac{2.5}{6.875} = 0.36$$

$$x_{He} = 0.05 \qquad \tilde{x}_{He} = 0.18$$

$$x_{H_2} = 0.05 \qquad \tilde{x}_{H_2} = 0.36$$

The fraction results can be checked by adding them up -- they must equal 1.0.

$$0.2 + 0.7 + 0.05 + 0.05 = 1.0 \quad \checkmark$$

$$0.09 + 0.36 + 0.18 + 0.36 = 0.99 \quad \checkmark$$

Multiply the fractions by 100 to get the percent composition.

20 mass % O_2	9 mol % O_2
70 mass % N_2	36 mol % N_2
5 mass % He	18 mol % He
5 mass % H_2	36 mol % H_2

A concentration unit often seen in environmental usage is *parts per million* or *ppm*. It is the grams of solute in 1 million grams of solution. PPM (or ppb) is a special kind of mass fraction.

Often a composition in percent or fraction form will be given, but to solve the problem it is required to know the masses of the individual components (if only to convert to molar composition). Take care of this by assuming a *basis* of 1 kg, 100 mol, etc. and work from there. After all, if a mixture is 21 mole percent oxygen, it doesn't make a difference if you've got 5 g or 30 lb or 200 mol -- the percentage or fractional composition is the same.

EXAMPLE: Air is about 78 mole percent nitrogen, 21 mole percent oxygen, and 1 percent argon. What is its composition by mass?

Choose a basis amount that will make the calculation easy. When compositions are given in percentages, a basis of 100 is always nice since it requires no multiplication or division. Let's work this in lbmoles.

BASIS: 100 moles air **WRITE IT DOWN!**

$$\begin{array}{ll}
78 \text{ mole } N_2 \times 28 \dfrac{\text{lb}}{\text{lbmole}} & = 2184 \text{ lb } N_2 \\
21 \text{ mole } O_2 \times 32 & = 672 \text{ lb } O_2 \\
1 \text{ mole Ar} \times 40 & = 40 \text{ lb Ar} \\
\hline
100 \text{ mole total} & 2896 \text{ lb total}
\end{array}$$

$$x_{N_2} = \frac{2184}{2896} \times 100 = 75 \text{ mass \%}$$

$$x_{O_2} = \frac{672}{2896} \times 100 = 23 \text{ mass \%}$$

$$x_{Ar} = \frac{40}{2896} \times 100 = 1.4 \text{ mass \%}$$

$$75 + 23 + 1.4 = 99.4 \quad \surd$$

The *Average Molecular Weight* of a mixture is computed from the molar composition and the molecular weight. It is a *weighted average* -- the molecular weights are averaged using the mole fractions as weights.

EXAMPLE: Calculate the average molecular weight of air.

Assume air is 79 mole % nitrogen, 21 mole % oxygen.

BASIS: 1 gmol air

$$\begin{aligned}
AMW_{air} &= \left(0.79 \frac{\text{mol } N_2}{\text{mol air}} \times 28 \frac{\text{g } N_2}{\text{mol } N_2}\right) + \left(0.21 \frac{\text{mol } O_2}{\text{mol air}} \times 32 \frac{\text{g } O_2}{\text{mol } O_2}\right) \\
&= 22.12 \frac{\text{g } N_2}{\text{mol air}} + 6.72 \frac{\text{g } O_2}{\text{mol air}} \\
&= 28.84 \frac{\text{g}}{\text{mol air}}
\end{aligned}$$

So the answer is 29 g/mol after we allow for significant digits.

One should NOT try to calculate average densities or average specific gravities using a weighted arithmetic mean. If one look at what this does, the units don't work out. You have to use a weighted harmonic mean.

$$\frac{1}{\bar{\rho}} = \sum_{i=1}^{NC} \frac{x_i}{\rho_i}$$

Concentration

A lot of times, the terms "composition" and "concentration" are used interchangeably. At this point, let’s make clear the difference. *Concentration* is based on volume and is one way of expressing composition. The *mass concentration* is the mass of a component per unit volume, similarly *molar concentration* is the moles per unit volume.

EXAMPLE: If I dissolve 1 g of salt in 1000 liters of water, what is the concentration of the mixture?

Assume additive volumes.
Concentration is grams solute divided by the volume of the mixture (water and solute).

$$c_{salt} = \frac{1\ \text{g salt}}{1000\ \text{l}\ H_2O + \dfrac{1\ \text{g salt}}{\rho\ \text{salt}}}$$

To simplify the problem, notice that the volume of the salt is probably much much less than that of the water; consequently, let's neglect the volume of the salt. WRITE DOWN "Assume volume of salt is negligible".

$$\frac{1\ \text{g salt}}{1000\ \text{l}\ H_2O} = 0.001\frac{g}{l}$$

In the example, It was assumed that volumes are additive. Generally, if one add 1 m^3 of component A to 1 m^3 of component B, it is not sure to get 2 m^3 of the mixture. When it is true, it is saied that the "volumes add" or that "volume is additive".
Volumes are additive only if the mixture is "ideal". This is probably ok if all components are similar and if the temperatures and pressures are not extreme, but the assumption of ideality needs to be stated.
When concentration is calculated in terms of gmol/liter, it is called *Molarity*, abbreviated M.
EXAMPLE: How much KOH is in 5 ml of a 2 M solution?

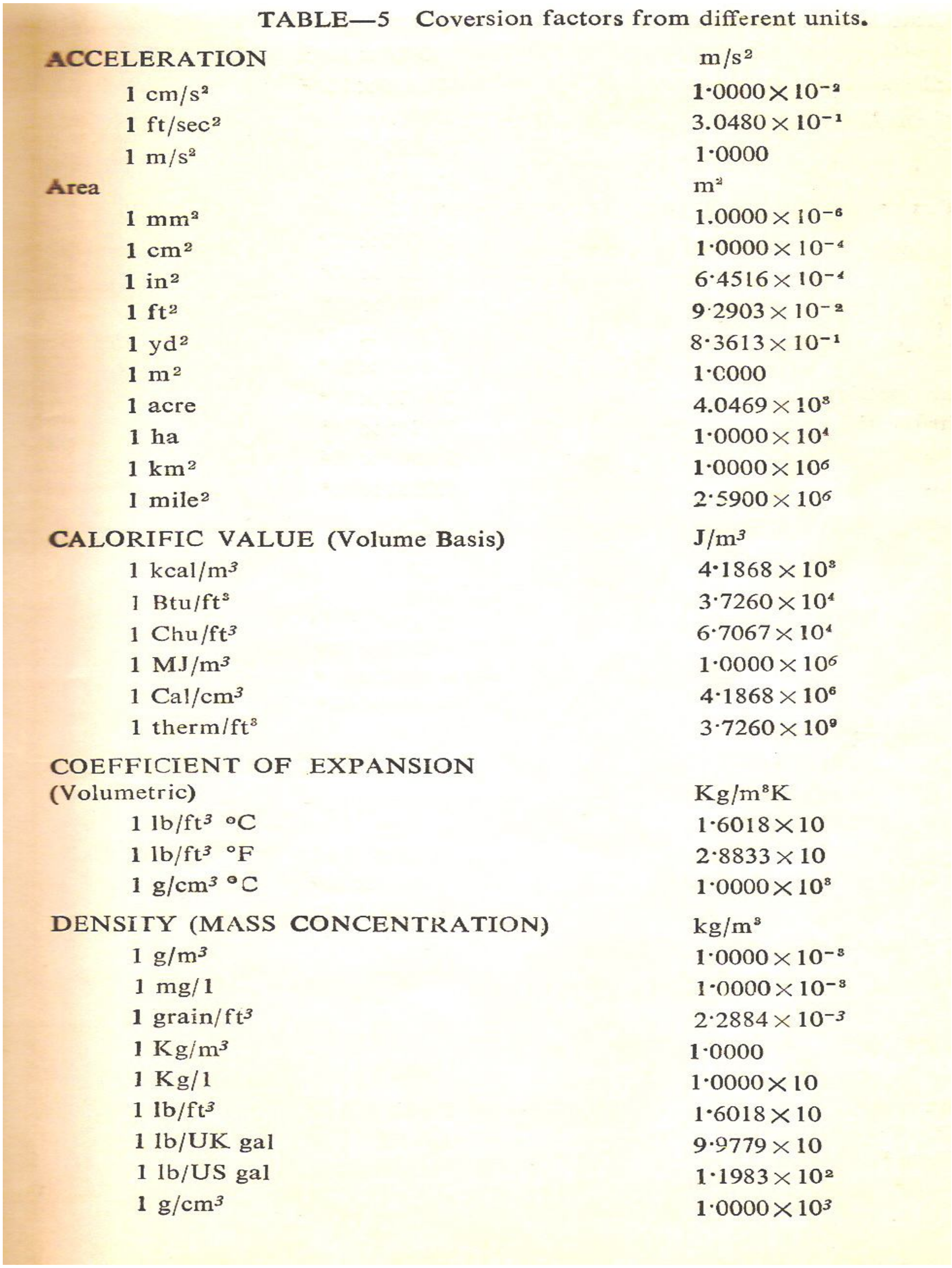
Concentration is grams solute divided by the volume of the mixture (water and solute).

$$5\ \text{m}l \times 2\frac{\text{gmol}}{l} \times \frac{l}{1000\ \text{m}l} = 0.01\ \text{gmol KOH}$$

$$0.01\ \text{gmol} \times 56\frac{\text{g}}{\text{gmol}} = 0.56\ \text{g KOH}$$

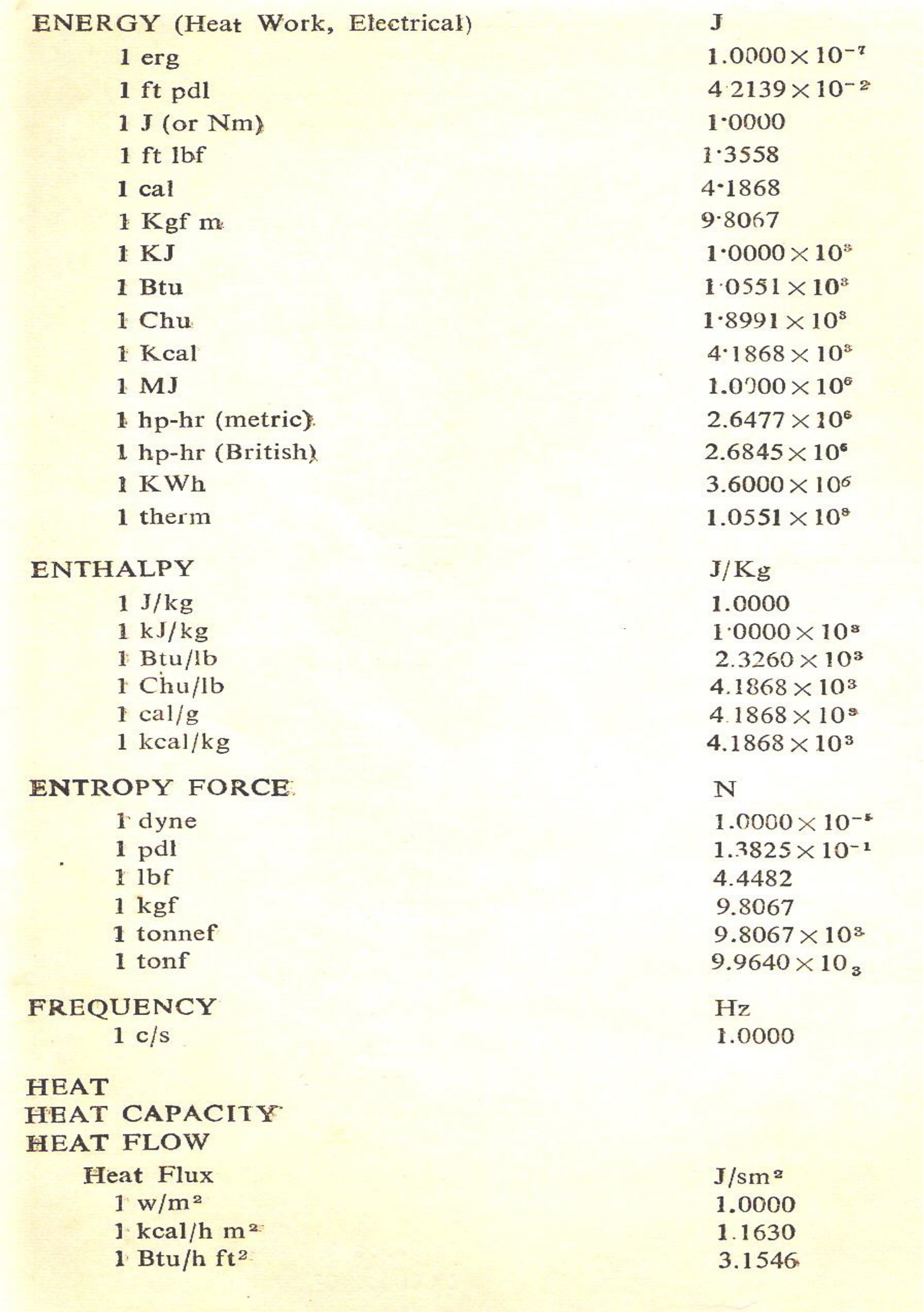
One MUST be able to switch between volumetric, mass, and molar compositions and flows quickly and without struggle. Otherwise all the problems in this class will take a lot longer than they should.
The smart engineer will usually work problems in mass or mole units, converting in and out of volume units if necessary. Trying to work problems primarily in volume units is often a source of problems.

Appendix I Conversion Factors for Various Unit Systems



TABLE—5 Coversion factors from different units.

ACCELERATION	m/s^2
1 cm/s^2	1·0000 × 10^{-2}
1 ft/sec^2	3.0480 × 10^{-1}
1 m/s^2	1·0000
Area	m^2
1 mm^2	1.0000 × 10^{-6}
1 cm^2	1·0000 × 10^{-4}
1 in^2	6·4516 × 10^{-4}
1 ft^2	9·2903 × 10^{-2}
1 yd^2	8·3613 × 10^{-1}
1 m^2	1·0000
1 acre	4.0469 × 10^{3}
1 ha	1·0000 × 10^{4}
1 km^2	1·0000 × 10^{6}
1 $mile^2$	2·5900 × 10^{6}
CALORIFIC VALUE (Volume Basis)	J/m^3
1 $kcal/m^3$	4·1868 × 10^{3}
1 Btu/ft^3	3·7260 × 10^{4}
1 Chu/ft^3	6·7067 × 10^{4}
1 MJ/m^3	1·0000 × 10^{6}
1 Cal/cm^3	4·1868 × 10^{6}
1 $therm/ft^3$	3·7260 × 10^{9}
COEFFICIENT OF EXPANSION (Volumetric)	Kg/m^3K
1 lb/ft^3 °C	1·6018 × 10
1 lb/ft^3 °F	2·8833 × 10
1 g/cm^3 °C	1·0000 × 10^{3}
DENSITY (MASS CONCENTRATION)	kg/m^3
1 g/m^3	1·0000 × 10^{-3}
1 mg/1	1·0000 × 10^{-3}
1 $grain/ft^3$	2·2884 × 10^{-3}
1 Kg/m^3	1·0000
1 Kg/1	1·0000 × 10
1 lb/ft^3	1·6018 × 10
1 lb/UK gal	9·9779 × 10
1 lb/US gal	1·1983 × 10^{2}
1 g/cm^3	1·0000 × 10^{3}



ENERGY (Heat Work, Electrical)	J
1 erg	$1{\cdot}0000 \times 10^{-7}$
1 ft pdl	4.2139×10^{-2}
1 J (or Nm)	1·0000
1 ft lbf	1·3558
1 cal	4·1868
1 Kgf m	9·8067
1 KJ	$1{\cdot}0000 \times 10^{3}$
1 Btu	$1{\cdot}0551 \times 10^{3}$
1 Chu	$1{\cdot}8991 \times 10^{3}$
1 Kcal	$4{\cdot}1868 \times 10^{3}$
1 MJ	1.0000×10^{6}
1 hp-hr (metric)	2.6477×10^{6}
1 hp-hr (British)	2.6845×10^{6}
1 KWh	3.6000×10^{6}
1 therm	1.0551×10^{8}

ENTHALPY	J/Kg
1 J/kg	1.0000
1 kJ/kg	$1{\cdot}0000 \times 10^{3}$
1 Btu/lb	2.3260×10^{3}
1 Chu/lb	4.1868×10^{3}
1 cal/g	4.1868×10^{3}
1 kcal/kg	4.1868×10^{3}

ENTROPY FORCE	N
1 dyne	1.0000×10^{-5}
1 pdl	1.3825×10^{-1}
1 lbf	4.4482
1 kgf	9.8067
1 tonnef	9.8067×10^{3}
1 tonf	$9.9640 \times 10_{3}$

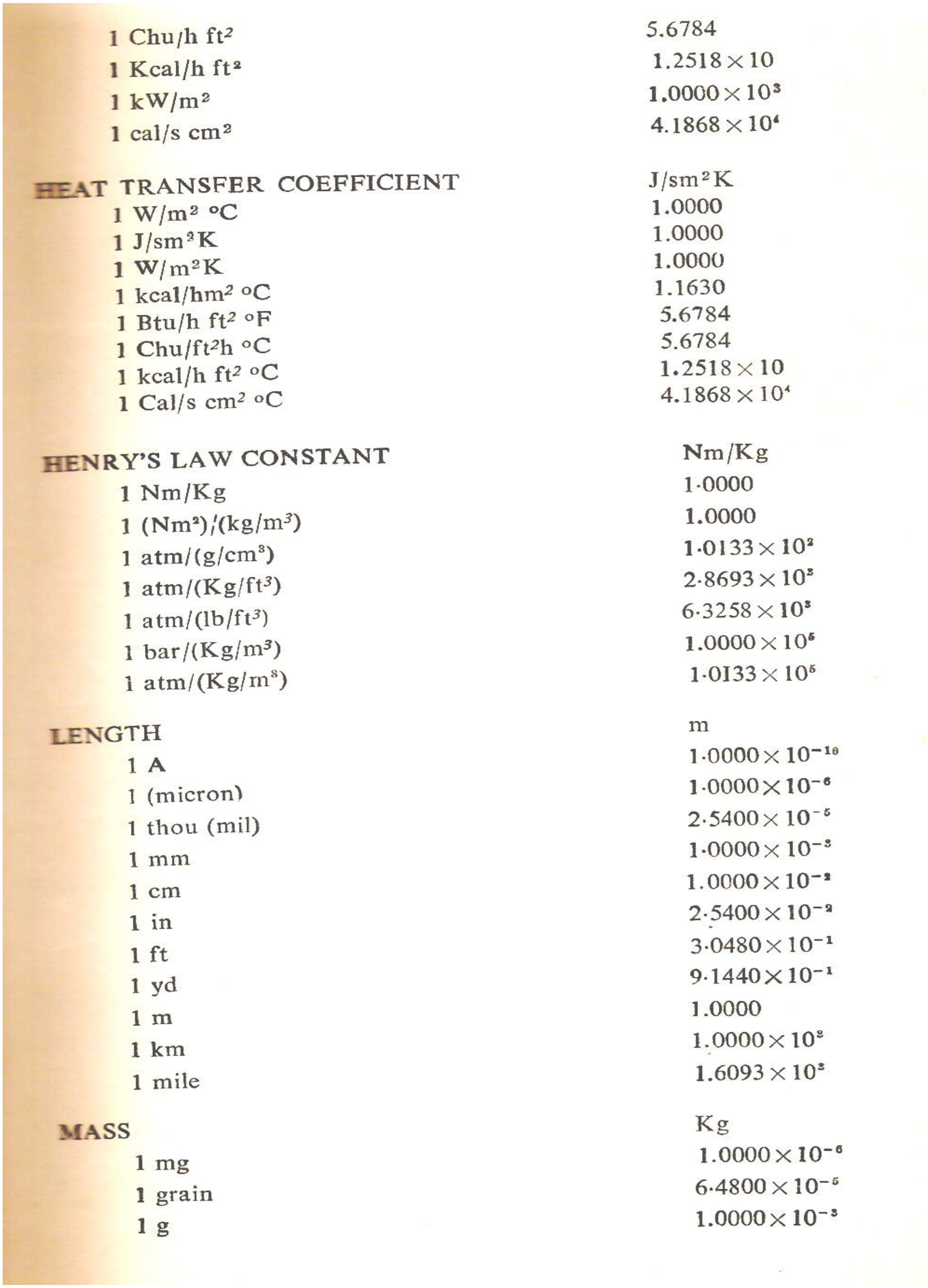
FREQUENCY	Hz
1 c/s	1.0000

HEAT

HEAT CAPACITY

HEAT FLOW

Heat Flux	J/sm^2
$1\ w/m^2$	1.0000
$1\ kcal/h\ m^2$	1.1630
$1\ Btu/h\ ft^2$	3.1546



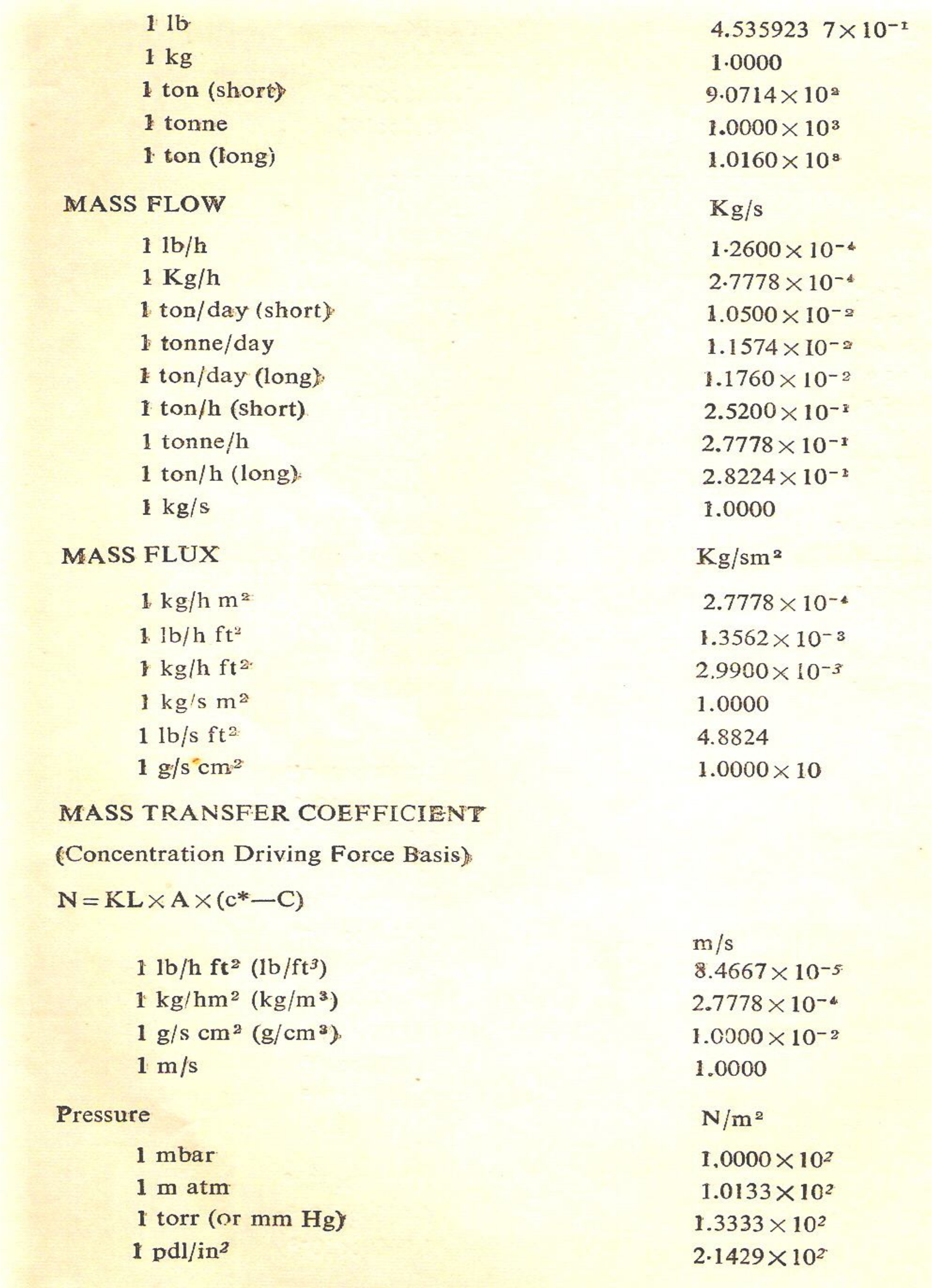
1 Chu/h ft^2	5.6784
1 Kcal/h ft^2	1.2518×10
1 kW/m^2	1.0000×10^{3}
1 cal/s cm^2	4.1868×10^{4}

HEAT TRANSFER COEFFICIENT	J/sm^{2}K
1 W/m^2 °C	1.0000
1 J/sm^{2}K	1.0000
1 W/m^{2}K	1.0000
1 kcal/hm^2 °C	1.1630
1 Btu/h ft^2 °F	5.6784
1 Chu/ft^{2}h °C	5.6784
1 kcal/h ft^2 °C	1.2518×10
1 Cal/s cm^2 °C	4.1868×10^{4}

HENRY'S LAW CONSTANT	Nm/Kg
1 Nm/Kg	1.0000
1 (Nm^2)/(kg/m^3)	1.0000
1 atm/(g/cm^3)	1.0133×10^{2}
1 atm/(Kg/ft^3)	2.8693×10^{3}
1 atm/(lb/ft^3)	6.3258×10^{3}
1 bar/(Kg/m^3)	1.0000×10^{5}
1 atm/(Kg/m^3)	1.0133×10^{5}

LENGTH	m
1 A	1.0000×10^{-10}
1 (micron)	1.0000×10^{-6}
1 thou (mil)	2.5400×10^{-5}
1 mm	1.0000×10^{-3}
1 cm	1.0000×10^{-2}
1 in	2.5400×10^{-2}
1 ft	3.0480×10^{-1}
1 yd	9.1440×10^{-1}
1 m	1.0000
1 km	1.0000×10^{3}
1 mile	1.6093×10^{3}

MASS	Kg
1 mg	1.0000×10^{-6}
1 grain	6.4800×10^{-5}
1 g	1.0000×10^{-3}



1 lb	$4.535923\ 7\times10^{-1}$
1 kg	$1{\cdot}0000$
1 ton (short)	$9{\cdot}0714\times10^{2}$
1 tonne	1.0000×10^{3}
1 ton (long)	1.0160×10^{3}

MASS FLOW	Kg/s
1 lb/h	$1{\cdot}2600\times10^{-4}$
1 Kg/h	$2{\cdot}7778\times10^{-4}$
1 ton/day (short)	1.0500×10^{-2}
1 tonne/day	1.1574×10^{-2}
1 ton/day (long)	1.1760×10^{-2}
1 ton/h (short)	2.5200×10^{-1}
1 tonne/h	2.7778×10^{-1}
1 ton/h (long)	2.8224×10^{-1}
1 kg/s	1.0000

MASS FLUX	Kg/sm²
1 kg/h m²	2.7778×10^{-4}
1 lb/h ft²	1.3562×10^{-3}
1 kg/h ft²	2.9900×10^{-3}
1 kg/s m²	1.0000
1 lb/s ft²	4.8824
1 g/s cm²	1.0000×10

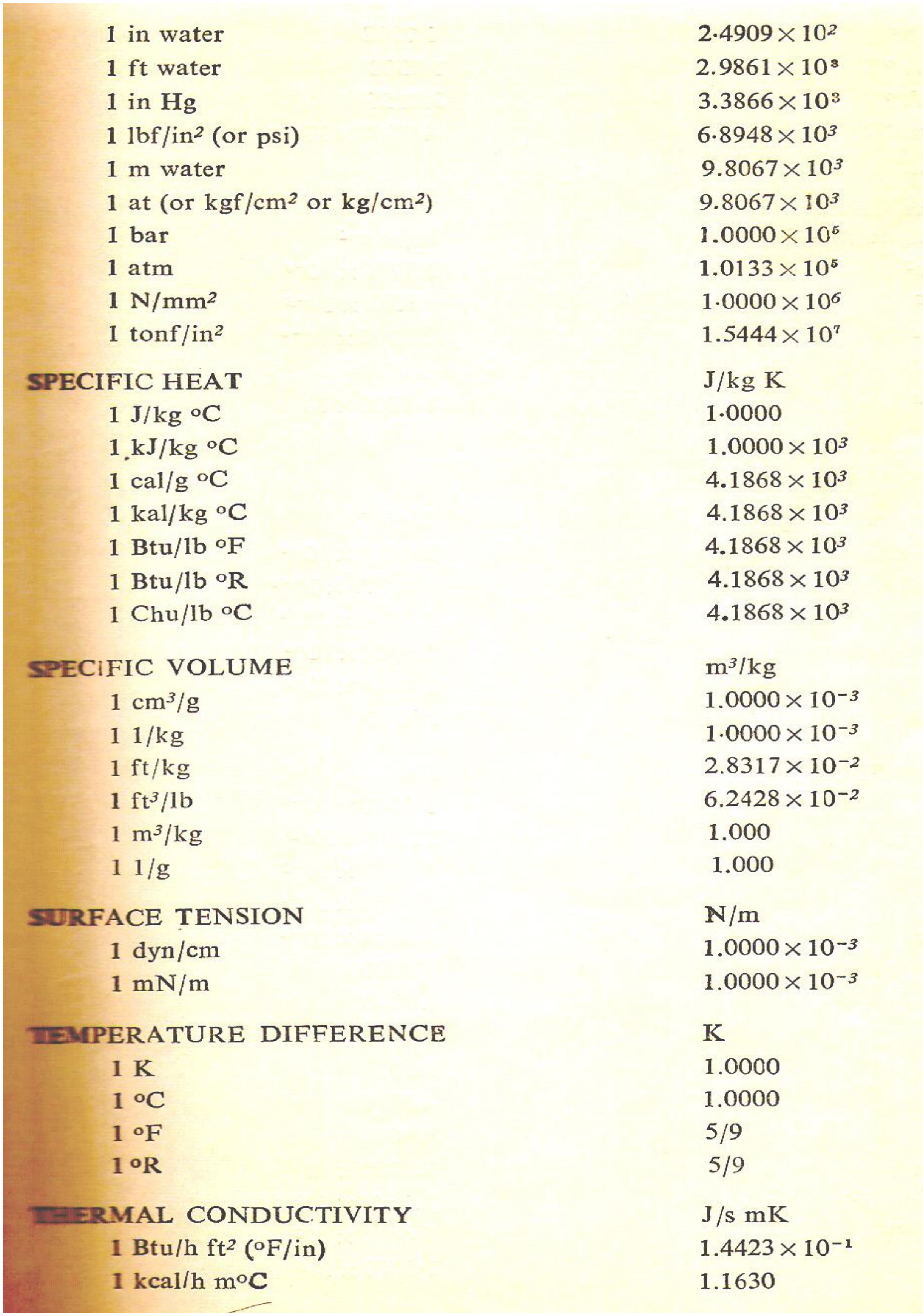
MASS TRANSFER COEFFICIENT

(Concentration Driving Force Basis)

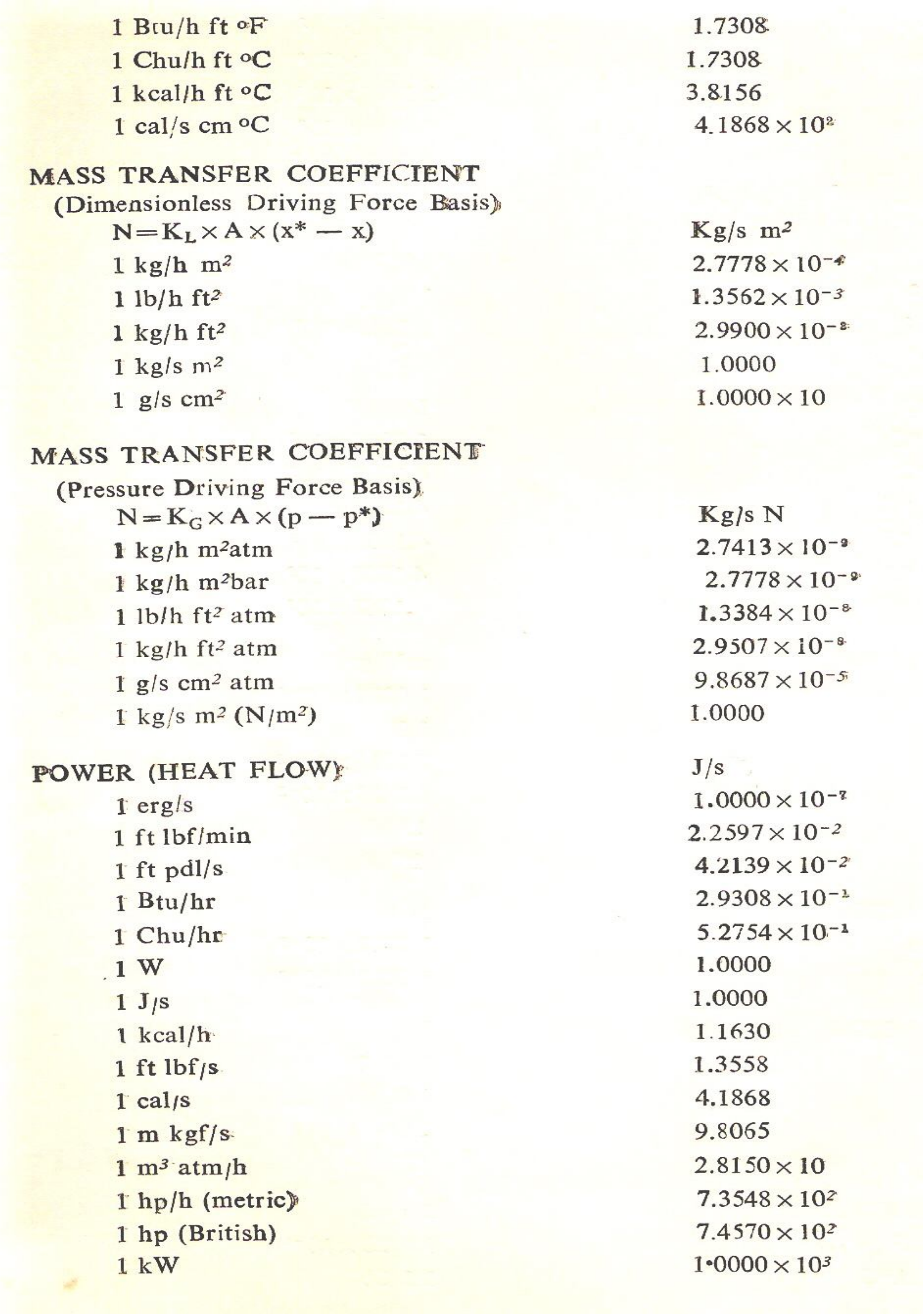
$N = KL \times A \times (c^* - C)$

	m/s
1 lb/h ft² (lb/ft³)	8.4667×10^{-5}
1 kg/hm² (kg/m³)	2.7778×10^{-4}
1 g/s cm² (g/cm³)	1.0000×10^{-2}
1 m/s	1.0000

Pressure	N/m²
1 mbar	1.0000×10^{2}
1 m atm	1.0133×10^{2}
1 torr (or mm Hg)	1.3333×10^{2}
1 pdl/in²	$2{\cdot}1429\times10^{2}$



1 in water	2·4909 × 10^{2}
1 ft water	2.9861 × 10^{3}
1 in Hg	3.3866 × 10^{3}
1 lbf/in² (or psi)	6·8948 × 10^{3}
1 m water	9.8067 × 10^{3}
1 at (or kgf/cm² or kg/cm²)	9.8067 × 10^{3}
1 bar	1.0000 × 10^{5}
1 atm	1.0133 × 10^{5}
1 N/mm²	1·0000 × 10^{6}
1 tonf/in²	1.5444 × 10^{7}
SPECIFIC HEAT	J/kg K
1 J/kg °C	1·0000
1 kJ/kg °C	1.0000 × 10^{3}
1 cal/g °C	4.1868 × 10^{3}
1 kal/kg °C	4.1868 × 10^{3}
1 Btu/lb °F	4.1868 × 10^{3}
1 Btu/lb °R	4.1868 × 10^{3}
1 Chu/lb °C	4.1868 × 10^{3}
SPECIFIC VOLUME	m³/kg
1 cm³/g	1.0000 × 10^{-3}
1 l/kg	1·0000 × 10^{-3}
1 ft/kg	2.8317 × 10^{-2}
1 ft³/lb	6.2428 × 10^{-2}
1 m³/kg	1.000
1 l/g	1.000
SURFACE TENSION	N/m
1 dyn/cm	1.0000 × 10^{-3}
1 mN/m	1.0000 × 10^{-3}
TEMPERATURE DIFFERENCE	K
1 K	1.0000
1 °C	1.0000
1 °F	5/9
1 °R	5/9
THERMAL CONDUCTIVITY	J/s mK
1 Btu/h ft² (°F/in)	1.4423 × 10^{-1}
1 kcal/h m°C	1.1630



1 Btu/h ft °F	1.7308
1 Chu/h ft °C	1.7308
1 kcal/h ft °C	3.8156
1 cal/s cm °C	4.1868×10^{2}

MASS TRANSFER COEFFICIENT
(Dimensionless Driving Force Basis)

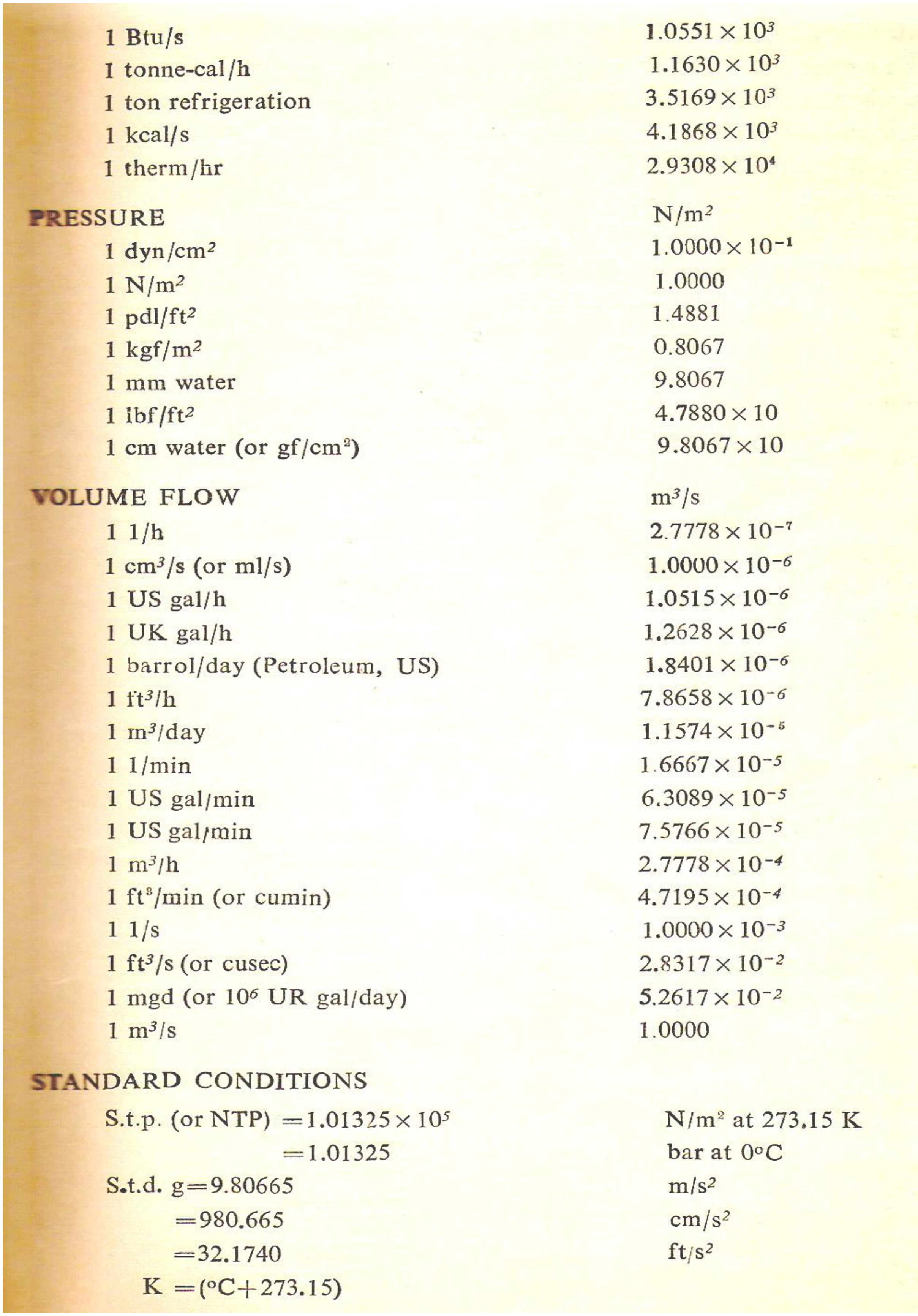
$N = K_L \times A \times (x^* - x)$	Kg/s m²
1 kg/h m²	2.7778×10^{-4}
1 lb/h ft²	1.3562×10^{-3}
1 kg/h ft²	2.9900×10^{-3}
1 kg/s m²	1.0000
1 g/s cm²	1.0000×10

MASS TRANSFER COEFFICIENT
(Pressure Driving Force Basis)

$N = K_G \times A \times (p - p^*)$	Kg/s N
1 kg/h m²atm	2.7413×10^{-9}
1 kg/h m²bar	2.7778×10^{-9}
1 lb/h ft² atm	1.3384×10^{-8}
1 kg/h ft² atm	2.9507×10^{-8}
1 g/s cm² atm	9.8687×10^{-5}
1 kg/s m² (N/m²)	1.0000

POWER (HEAT FLOW)

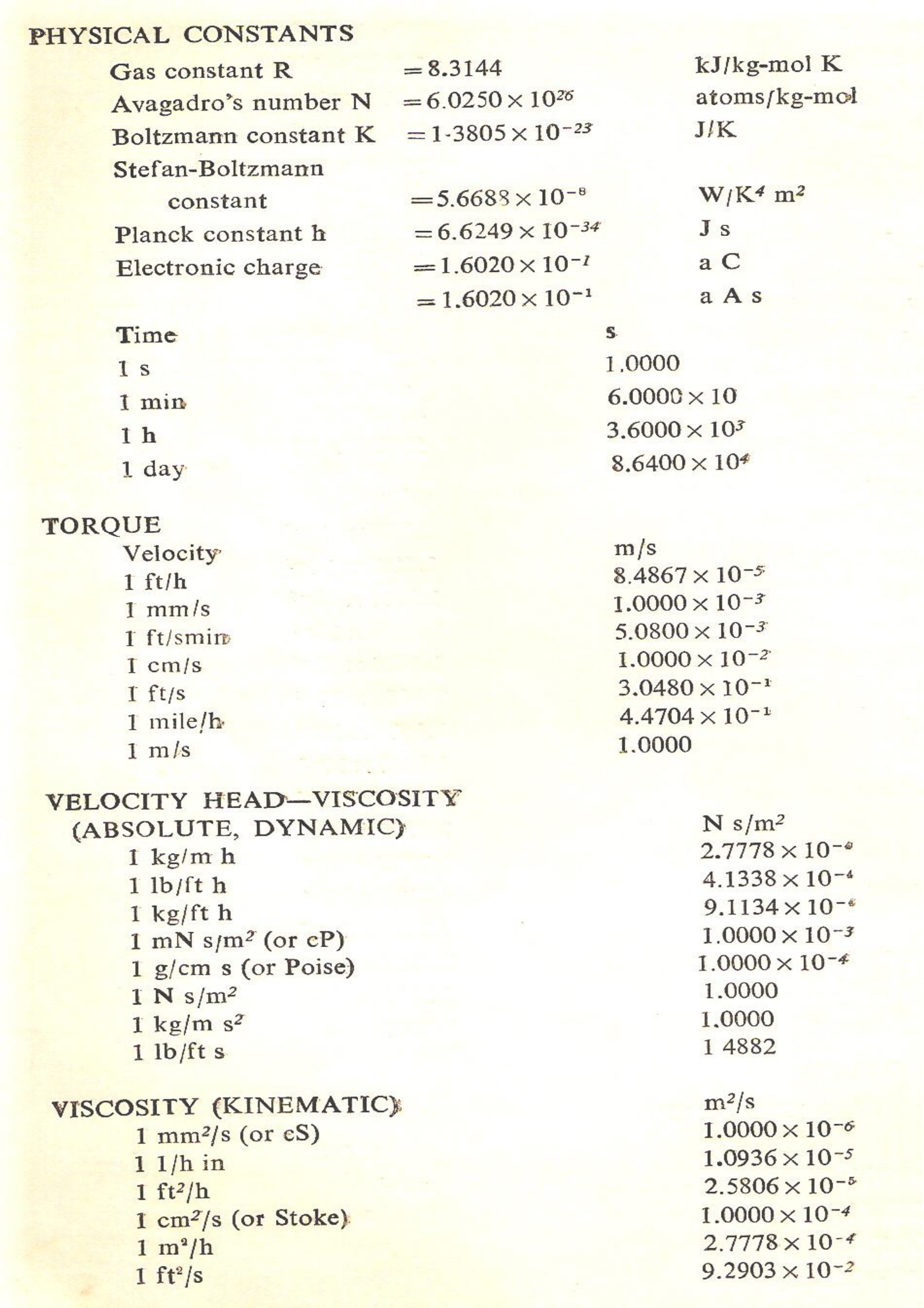
	J/s
1 erg/s	1.0000×10^{-7}
1 ft lbf/min	2.2597×10^{-2}
1 ft pdl/s	4.2139×10^{-2}
1 Btu/hr	2.9308×10^{-1}
1 Chu/hr	5.2754×10^{-1}
1 W	1.0000
1 J/s	1.0000
1 kcal/h	1.1630
1 ft lbf/s	1.3558
1 cal/s	4.1868
1 m kgf/s	9.8065
1 m³ atm/h	2.8150×10
1 hp/h (metric)	7.3548×10^{2}
1 hp (British)	7.4570×10^{2}
1 kW	$1{\cdot}0000 \times 10^{3}$



1 Btu/s	1.0551×10^3
1 tonne-cal/h	1.1630×10^3
1 ton refrigeration	3.5169×10^3
1 kcal/s	4.1868×10^3
1 therm/hr	2.9308×10^4
PRESSURE	N/m^2
1 dyn/cm^2	1.0000×10^{-1}
1 N/m^2	1.0000
1 pdl/ft^2	1.4881
1 kgf/m^2	0.8067
1 mm water	9.8067
1 lbf/ft^2	4.7880×10
1 cm water (or gf/cm^2)	9.8067×10
VOLUME FLOW	m^3/s
1 l/h	2.7778×10^{-7}
1 cm^3/s (or ml/s)	1.0000×10^{-6}
1 US gal/h	1.0515×10^{-6}
1 UK gal/h	1.2628×10^{-6}
1 barrol/day (Petroleum, US)	1.8401×10^{-6}
1 ft^3/h	7.8658×10^{-6}
1 m^3/day	1.1574×10^{-5}
1 l/min	1.6667×10^{-5}
1 US gal/min	6.3089×10^{-5}
1 US gal/min	7.5766×10^{-5}
1 m^3/h	2.7778×10^{-4}
1 ft^3/min (or cumin)	4.7195×10^{-4}
1 l/s	1.0000×10^{-3}
1 ft^3/s (or cusec)	2.8317×10^{-2}
1 mgd (or 10^6 UR gal/day)	5.2617×10^{-2}
1 m^3/s	1.0000

STANDARD CONDITIONS

S.t.p. (or NTP) $= 1.01325 \times 10^5$	N/m^2 at 273.15 K
$= 1.01325$	bar at 0°C
S.t.d. $g = 9.80665$	m/s^2
$= 980.665$	cm/s^2
$= 32.1740$	ft/s^2
$K = (°C + 273.15)$	



PHYSICAL CONSTANTS

Gas constant R	$= 8.3144$	kJ/kg-mol K
Avagadro's number N	$= 6.0250 \times 10^{26}$	atoms/kg-mol
Boltzmann constant K	$= 1{\cdot}3805 \times 10^{-23}$	J/K
Stefan-Boltzmann constant	$= 5.6688 \times 10^{-8}$	$W/K^4\ m^2$
Planck constant h	$= 6.6249 \times 10^{-34}$	J s
Electronic charge	$= 1.6020 \times 10^{-1}$	a C
	$= 1.6020 \times 10^{-1}$	a A s

Time	s
1 s	1.0000
1 min	6.0000×10
1 h	3.6000×10^{3}
1 day	8.6400×10^{4}

TORQUE

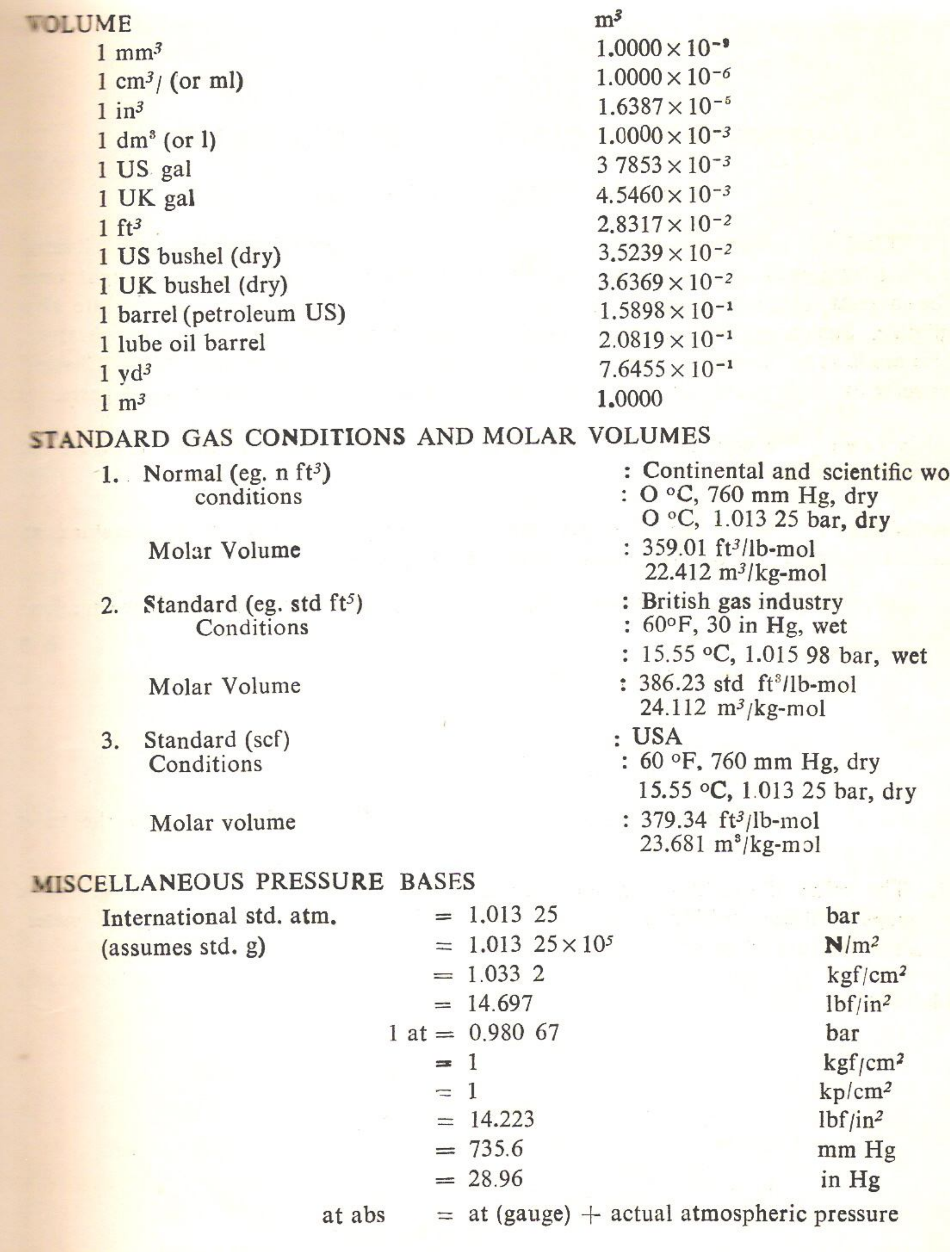
Velocity	m/s
1 ft/h	8.4867×10^{-5}
1 mm/s	1.0000×10^{-3}
1 ft/smin	5.0800×10^{-3}
1 cm/s	1.0000×10^{-2}
1 ft/s	3.0480×10^{-1}
1 mile/h	4.4704×10^{-1}
1 m/s	1.0000

VELOCITY HEAD—VISCOSITY (ABSOLUTE, DYNAMIC)

	$N\ s/m^2$
1 kg/m h	2.7778×10^{-4}
1 lb/ft h	4.1338×10^{-4}
1 kg/ft h	9.1134×10^{-4}
1 $mN\ s/m^2$ (or cP)	1.0000×10^{-3}
1 g/cm s (or Poise)	1.0000×10^{-4}
1 $N\ s/m^2$	1.0000
1 $kg/m\ s^2$	1.0000
1 lb/ft s	1 4882

VISCOSITY (KINEMATIC)

	m^2/s
1 mm^2/s (or cS)	1.0000×10^{-6}
1 1/h in	1.0936×10^{-5}
1 ft^2/h	2.5806×10^{-5}
1 cm^2/s (or Stoke)	1.0000×10^{-4}
1 m^2/h	2.7778×10^{-4}
1 ft^2/s	9.2903×10^{-2}



VOLUME	m^3
1 mm^3	1.0000×10^{-9}
1 cm^3/ (or ml)	1.0000×10^{-6}
1 in^3	1.6387×10^{-5}
1 dm^3 (or l)	1.0000×10^{-3}
1 US gal	$3\ 7853 \times 10^{-3}$
1 UK gal	4.5460×10^{-3}
1 ft^3	2.8317×10^{-2}
1 US bushel (dry)	3.5239×10^{-2}
1 UK bushel (dry)	3.6369×10^{-2}
1 barrel (petroleum US)	1.5898×10^{-1}
1 lube oil barrel	2.0819×10^{-1}
1 yd^3	7.6455×10^{-1}
1 m^3	1.0000

STANDARD GAS CONDITIONS AND MOLAR VOLUMES

1. Normal (eg. n ft^3) : Continental and scientific wo
   conditions : O °C, 760 mm Hg, dry
   O °C, 1.013 25 bar, dry
   Molar Volume : 359.01 ft^3/lb-mol
   22.412 m^3/kg-mol
2. Standard (eg. std ft^5) : British gas industry
   Conditions : 60°F, 30 in Hg, wet
   : 15.55 °C, 1.015 98 bar, wet
   Molar Volume : 386.23 std ft^3/lb-mol
   24.112 m^3/kg-mol
3. Standard (scf) : USA
   Conditions : 60 °F, 760 mm Hg, dry
   15.55 °C, 1.013 25 bar, dry
   Molar volume : 379.34 ft^3/lb-mol
   23.681 m^3/kg-mol

MISCELLANEOUS PRESSURE BASES

International std. atm.	=	1.013 25	bar
(assumes std. g)	=	$1.013\ 25 \times 10^5$	N/m^2
	=	1.033 2	kgf/cm^2
	=	14.697	lbf/in^2
1 at	=	0.980 67	bar
	=	1	kgf/cm^2
	=	1	kp/cm^2
	=	14.223	lbf/in^2
	=	735.6	mm Hg
	=	28.96	in Hg
at abs	=	at (gauge) + actual atmospheric pressure	

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Transportation and Processing of Fluid
Prof H R Shah

Fluid mechanics- Principles

(I) Fluid Statics

Chemical Engineering operations are divided basically in two classes.

a. Unit operations
b. Unit processes

Unit Operations are those carried out in process industries without chemical reactions .

- Fluid flow operation or momentum transfer
- Heat transfer
- Mass transfer

The Governing laws for these operations are

Fluid Flow or Momentum transfer	Newton's of viscosity	$\tau = \frac{\mu}{g_c} x \frac{du}{dy}$	τ = momentum flux kgf/m^2 μ = Fluid Viscosity kg/sec. m g_c = conversion factor kg-m/kgf.sec^2 u = velocity m/sec y = distance m du/dy = shear velocity or rate of shear deformation
Heat transfer	Fourier's law	$\frac{Q}{A} = k\, x \frac{-dT}{dy}$	Q/A = Thermal flux kcal/sec.m^2 k= Thermal Conductivity kcal/sec.m.^{o}C T = Temerature ^{o}C Y = distance m
Mass Transfer	Fic's law	$N = D\, x \frac{-dC}{dy}$	N= Mass flux mole/sec.m^2 D = diffusivity m^2 /sec C= concentration mole/m^3 Y= distance m

- **What is Fluid Flow or fluid Mechanics or Momentum Transfer?**
  - It is the branch of engineering science that deals with the behavior of fluids.
  - It is classified as Fluid Statics and Fluid Dynamics.
  - Fluid Statics treats fluid in the equilibrium state of no shear stress
  - Fluid Dynamics treats the fluid in motion relative to stationary solid walls or boundaries.
- **What is Fluid?**

  Fluid is defined as a substance, which does not resist distortion permanently or A Fluid is a substance which deforms continuously, or flows, when subjected to shearing forces.

- When an attempt made to change the shape of a mass of fluid will result in layers of fluid sliding over one another till the new shape is attained while fluid undergoes change in shape shear stresses will exist, the magnitude of shear stresses depend upon the viscosity of the fluid and the rate of sliding. All shear stresses will be disappeared when the final shape is reached. A fluid when at equilibrium is free from shear stresses.

- **Compressible & Incompressible fluids:**

- A fluid possesses a definite density, which is usually measured in kg / m^3, at a given temperature and pressure. Based upon the density variation the fluids: large or negligible with temperature and pressure the fluids are classified into two groups which are as follows:
  1. Compressible.
  2. Incompressible.

Incompressible Fluid:
When the density of fluid is not appreciably affected by moderate changes in temperature and pressure the fluid is said to be Incompressible.

Compressible fluid:
When the density of fluid is sensitive to changes in temperature and pressure the fluid is said to be Compressible.

In most cases all liquids are Incompressible and all gases are Compressible.

- **Newtonian and Non Newtonian Fluids:**

The most important physical property of the fluid, which affects the stress distribution, is the viscosity of the fluid. For many gases and pure liquids the ratio of the shear stress to shear rate is constant and equal to the viscosity of the fluid. Such fluids are called **Newtonian Fluids.**

In case of some liquids, especially those containing second phase in suspension the ratio of shear stress to shear rate is not constant and apparently viscosity of the fluid is a function of shear rate. They are **Non-Newtonian.**

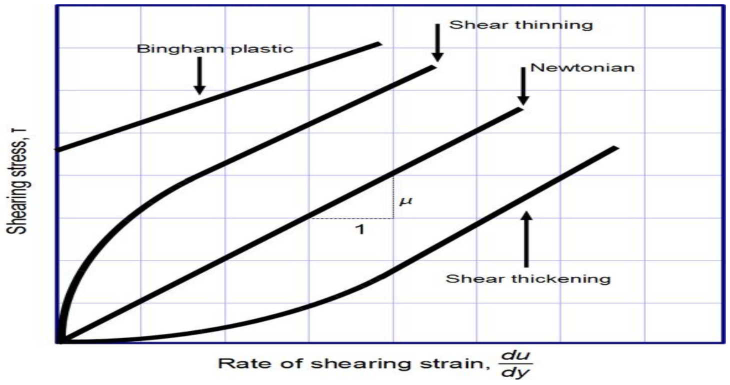


Figure 1 Shear strain vs Shear stress

Each of these lines can be represented by the equation $\tau = A + B\left(\frac{du}{dy}\right)^n$

where A, B and n are constants. For Newtonian fluids A = 0, B = μ and n = 1.

Comparison of non-Newtonian, Newtonian, and viscoelastic properties

Viscoelastic	Kelvin material	"Parallel" linearstic combination of elastic and viscous effects	Some lubricants, whipped cream
	Thixotropic	Apparent viscosity decreases with duration of stress	Yogurt, xanthan gum solutions, aqueous iron oxide gels, gelatin gels,pectin gels, synovial fluid, hydrogenated castor oil, some clays(including bentonite, and montmorillonite), carbon black suspension in molten tire rubber, some drilling muds, many paints, many flocsuspensions, many colloidal suspensions
Time-independent viscosity	Shear thickening (dilatant)	Apparent viscosity increases with increased stress	Suspensions of corn starch in water, sand in water, Silly Putty
	Shear thinning(pseudo plastic)	Apparent viscosityd ecreases with increased stress	Nail polish, whipped cream, ketchup, molasses, syrups, paper pulp in water, latex paint, ice, blood, some silicone oils, some silicone coatings
	Generalized Newtonian fluids	Viscosity is constant Stress depends on normal and shear strain rates and also the pressure applied on it	Blood plasma, custard, water

Note :

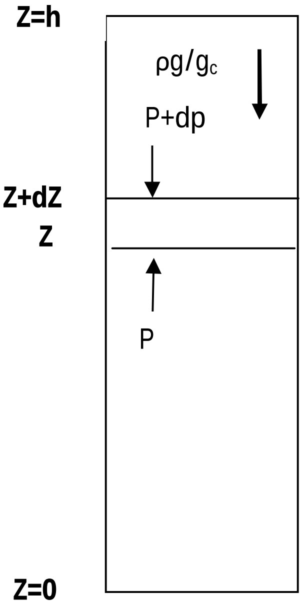
- Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Viscous materials, like honey, resist shear flow and strain linearly with time when a stress is applied. Elastic materials strain when stretched and quickly return to their original state once the stress is removed. Viscoelastic materials have elements of both of these properties and, as such, exhibit time-dependent strain
- *Rheopectic substances:* Viscosity increases with length of time shear force is applied

- **Pressure:**

The basic property of static fluid is pressure, which is familiar as the surface force exerted by a fluid against the walls of container. It exists at every point with in a volume of fluid and always acts normal to any surface.

In case of Static Fluid, the pressure at any given points is the same in all the directions. If pressure at a given points are not the same in all the directions there would be non-equilibrium

and a resultant force should exist. As the fluid is in equilibrium there is no net unbalanced force at any point. Hence, the pressure in all the directions is same and thus independent of direction.



- **Hydrostatic Equilibrium:**

a fluid is said to be in hydrostatic equilibrium or hydrostatic balance when it is at rest, or when the flow velocity at each point is. This occurs constant over time when external forces such as gravity are balanced by a pressure gradient force

Consider a vertical column of single static fluid as shown in Figure 3. The pressure at any horizontal plane is constant and changes along the height of column.

Let the cross-sectional area of the column be A m^2 and Density of the fluid be ρ kg / m^3. Let the pressure be P kg f / m^2 at a height 'Z' m from the base of the column. At the height Z + dZ from base (another horizontal plane).

Let the pressure be P + dP kg f / m^2.

The forces acting on small element of fluid between these two planes are:

I. Forces of [P + dP] A is acting down ward ↓
II. Force of P * A is acting upwards ↑
III. Force due to gravity is acting downwards and is equal to mass times acceleration due to gravity - (A * dZ * ρ) g / g_c. ↓

As the fluid element is in equilibrium the resultant of all three forces acting on it must be zero. Thus

$$Px\ A - (p + dp)\ x\ A - \frac{g}{g_c}\ \rho\ Adz = 0 \qquad (1)$$

$$(dp) + \frac{g}{g_c}\rho\ dz = 0 \qquad (2)$$

Equation (2) is basic equation to get pressure at any height and further can be use for incompressible and compressible fluids as under

i. For Incompressible Fluids:

Integrate equation (2)

$$\int dP + \frac{g}{gc}\rho \int dZ = 0$$

$$\therefore P + \rho\frac{g}{gc}Z = \text{Constant} \qquad (3)$$

From the equation (3) we can say that the pressure is maximum at the base of the container of fluid and decreases as we move up the column.

If the pressure at base of column is P_1 where Z = 0 and pressure at any height h (Z = h) is P_2 such that ($P_1 > P_2$) then,

$$\int_{P1}^{P2} dP = -\frac{g}{gc} * \rho * \int_0^h dZ \qquad (4)$$

Integrating and putting the limits we get,

$$\boldsymbol{(P_1 - P_2) = h\rho\frac{g}{g_c}} \qquad \boldsymbol{(5)}$$

Where P_1 and P_2 are expressed in kg-f / m^2, Density in kg / m^3, height(h) in meter, g is in m / sec^2 and g_c in kg-m/(kg_f –sec^2

$$\boldsymbol{P_{abs} = h\rho\frac{g}{g_c} + P_{atm}} \qquad \boldsymbol{(6)}$$

Here $\boldsymbol{h\rho \frac{g}{g_c} = P_{guage}}$ (7)

With the help of equation (5) the pressure difference can be expressed in terms of the height of a vertical column of the fluid.

Example:

Calculate gauge pressure of $500K\,N\,m^{-2}$ in terms of the (i) height of a column of water of density, $\rho = 1000$ kgm^{-3} and (ii) And in terms of Mercury with density, $\rho = 13.6\times10^3\ kgm^{-3}$

Equation & applies : $\boldsymbol{h\rho \frac{g}{g_c} = P_{guage}}$ **(8)**

Inserting the given values

i. In terms of Water Head : $\rho = 1000$ kgm^{-3}

$$h\ x\ 1000\ \frac{kg}{m^3} x \frac{9.81\ {}^{m}/_{sec^2}}{1} = 500\ x\ 1000\ \frac{N}{m^2}$$

$$\therefore h\ x\ 1000\ x 9.81\ \frac{kg-m}{m^3\ .sec^2} = 500\ x\ 1000\ \frac{N}{m^2}$$

$$\therefore h\ x\ 1000\ x 9.81\ \frac{N}{m^3} = 500\ x\ 1000\ \frac{N}{m^2}$$

$$\therefore \boldsymbol{h} = \frac{500\ x\ 1000\ \frac{N}{m^2}}{1000\ x 9.81\ \frac{N}{m^3}} = \boldsymbol{50.97\ m\ \ Water\ head \quad Ans}.$$

ii. In Terms of Mercury Head: $\rho = 13.6\times10^3\ kgm^{-3}$

$$\boldsymbol{h} = \frac{500\ x\ 1000\ \frac{N}{m^2}}{13.6\ x\ 1000\ x 9.81\ \frac{N}{m^3}} = \boldsymbol{3.75\ m\ \ Hg\ head \quad Ans}.$$

(B) For Compressible Fluids:

For Compressible fluids density varies with pressure. For Ideal gas the density is given by a equation.

$$PV = nRT$$

$$\therefore \frac{PM}{RT} = \frac{M}{V} = \rho$$

Where,
P = Pressure
T = Temperature
n = mole of gas
M = Molecular Weight of gas
R = Universal gas constant
V = Molar Volume

Put value of ρ in equation (2),

$$(dp) + \frac{g}{g_c}\frac{PM}{RT}\ dz = 0 \qquad (9)$$

$$\therefore \frac{dP}{P} + \frac{g}{g_c}\frac{PM}{RT}\ dz = 0$$

Integrating

$$\therefore \ln P + \frac{g}{g_c}\frac{PM}{RT}\ Z = constant \qquad (10)$$

$$also\ \int_{P_1}^{P_2} \frac{dP}{P} + \frac{g}{g_c}\frac{PM}{RT}\int_{Z_1}^{Z_2} dZ = 0$$

$$Or \int_{P_1}^{P_2} \frac{dP}{P} = -\frac{g}{g_c}\frac{PM}{RT}\int_{Z_1}^{Z_2} dZ$$

$$ln\frac{P_2}{P_1} = -\frac{g}{g_c}\frac{PM}{RT}(Z_2 - Z_1)$$

$$\therefore \frac{P2}{P1} = \exp\left[-\frac{g}{gc} * \frac{M}{RT} * (Z2 - Z1)\right] \qquad (11)$$

Equation (10) is Barometric equation and gives the idea of pressure distribution within an ideal gas for isothermal conditions.

- **The Piezometer Tube Manometer**

The simplest manometer is a tube, open at the top, which is attached to the top of a vessel containing liquid at a pressure (higher than atmospheric) to be measured. An example can be seen in the figure below. This simple device is known as a Piezometer tube. As the tube is open to the atmosphere the pressure measured is relative to atmospheric so is **gauge pressure**.

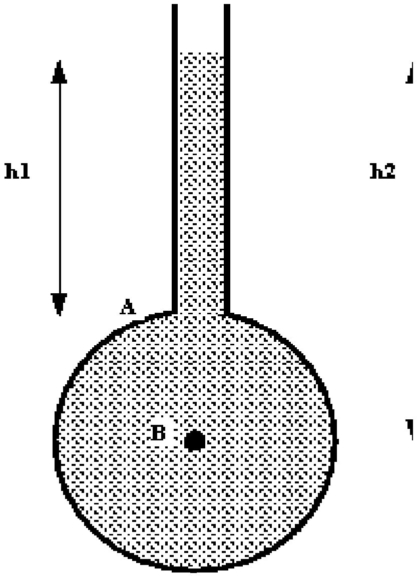


figure 3 A simple piezometer tube manometer

pressure at A = pressure due to column of liquid above A

$$P_A = \rho \frac{g}{g_c} h_1 \qquad (11)$$

pressure at B = pressure due to column of liquid above B

$$P_B = \rho \frac{g}{g_c} h_2 \qquad (12)$$

This method can only be used for liquids (i.e. **not** for gases) and only when the liquid height is convenient to measure. It must not be too small or too large and pressure changes must be detectable.

The "U"-Tube Manometer

Using a “U”-Tube enables the pressure of both liquids and gases to be measured with the same instrument. The “U” is connected as in the figure below and filled with a fluid called the *manometric fluid*. The fluid whose pressure is being measured should have a mass density less than that of the manometric fluid and the two fluids should not be able to mix readily - that is, they must be immiscible.

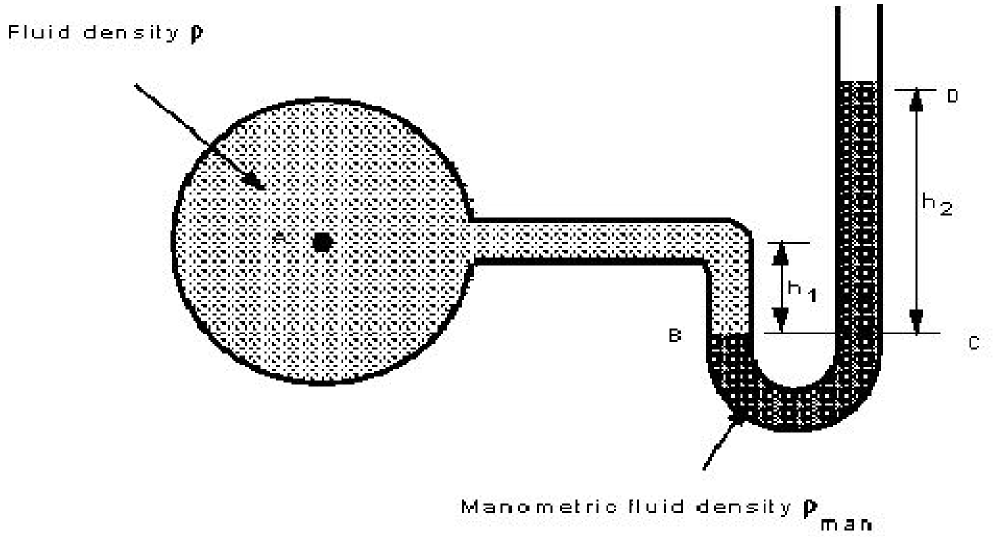


Figure 4 U tube Manometer

Pressure in a continuous static fluid is the same at any horizontal level so,
pressure at B = pressure at C

$P_B = P_C$ (13)

For the **left hand** arm
pressure at B = pressure at A + pressure due to height h of fluid being measured $_1$

$$P_B = P_A + \rho \frac{g}{g_c} h_1 \qquad (14)$$

For the **right hand** arm
pressure at C = pressure at D + pressure due to height h of manometric

$$P_C = P_{atm} + \rho_{man0metric} \frac{g}{g_c} h_2 \qquad (15)$$

From Equation 13, 14 and 15

$$P_{A\,gauge} = \rho_{man0metric} \frac{g}{g_c} h_2 - \rho \frac{g}{g_c} h_1 \qquad (16)$$

If $\rho_{manometric} >> \rho$

$$\boldsymbol{P_{A\,gauge} = \rho_{man0metric} \frac{g}{g_c} h_2} \qquad (\mathbf{17})$$

Measurement Of Pressure Difference Using a “U”-Tube Manometer.

If the “U”-tube manometer is connected to a pressurized vessel at two points the *pressure difference* between these two points can be measured

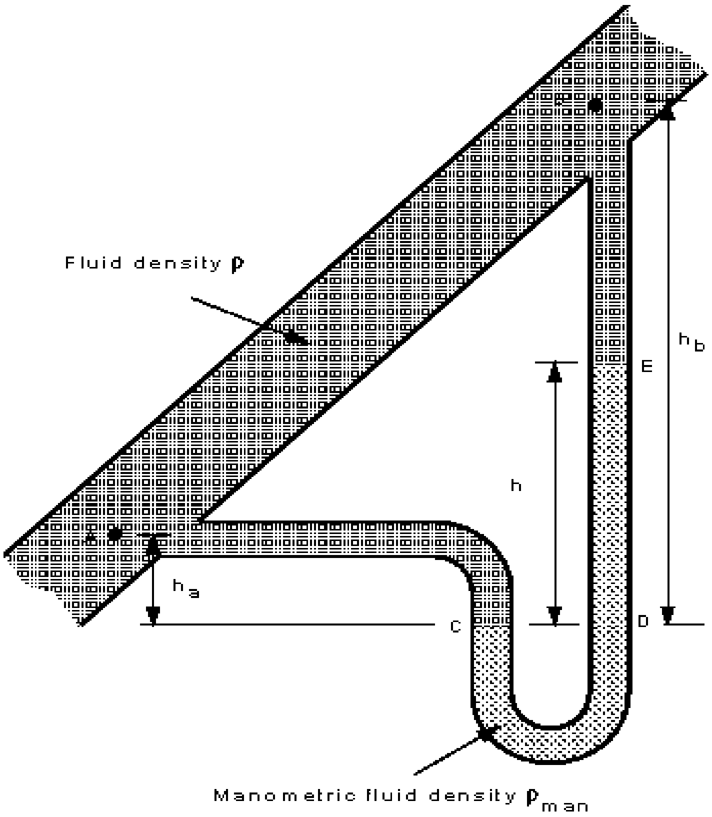


Figure 5

Here Pressure difference across fluid point A and B is

$$\boldsymbol{P_A - P_B = (\rho_{man} - \rho)\frac{g}{g_c}h} \qquad \textbf{(18)}$$

Choice Of Manometer

Care must be taken when attaching the manometer to vessel, no burrs must be present around this joint. Burrs would alter the flow causing local pressure variations to affect the measurement.

Some disadvantages of manometers:

- Slow response - only really useful for very slowly varying pressures - no use at all for fluctuating pressures
- For the "U" tube manometer two measurements must be taken simultaneously to get the h value. This may be avoided by using a tube with a much larger cross-sectional area on one side of the manometer than the other.
- It is often difficult to measure small variations in pressure - a different manometric fluid may be required - alternatively a sloping manometer may be employed; It cannot be used for very large pressures unless several manometers are connected in series;
- For very accurate work the temperature and relationship between temperature and r must be known.

Some advantages of manometers:

- They are very simple.
- No calibration is required - the pressure can be calculated from first principles

(II) <u>Fluid Flow Phenomena(Fluid Dynamics)</u>

- **Potential Flow:**

The behavior of a flowing fluid depends strongly on whether or not the fluid is under the influence of solid boundaries. In the region where the influence of the wall is small, the shear stress may be negligible and the fluid behavior may approach that of an ideal fluid, one that is incompressible and has zero viscosity. The flow of such an ideal fluid is called Potential Flow.

***Potential flow has two important characteristics*:**

(i) Neither circulations nor eddies can form within the stream, so that potential flow is also called Irrotational Flow.
(ii) Friction cannot develop, so that there is not dissipation of mechanical energy in to heat.

- **Boundary Layer:**

Except for fluids moving at low velocities or possessing high viscosities, the effect of the solid boundary on the flow is confined to a layer of the fluid immediately adjacent to the solid wall. This layer is called the Boundary Layer.

Shear and Shear forces are confined to this part of the fluid. Outside the boundary layer, potential flow survives. Most technical flow processes are best studied by considering the fluid stream as two parts, the boundary layer and remaining fluid.

In some situations such as flow in a Converging Nozzle, the boundary layer may be negated and in others such as flow through pipes, the boundary layer fills the entire channel and there is no Potential Flow.

- **The Velocity Field:**

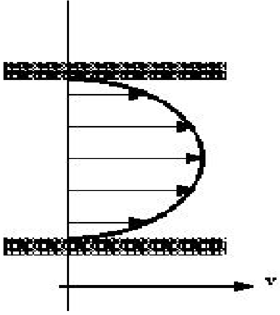


Figure 7 velocity profile

Because particles of fluid next to each other are moving with different velocities there are shear forces in the moving fluid i.e. shear forces are normally present in a moving fluid.

Thus When a stream of fluid is flowing in bulk past a solid wall, the fluid adheres to the solid at the actual interface between solid and fluid. The adhesion is a result of the force fields at the boundary, which are also responsible for the interfacial tension between solid and fluid. If, therefore, the wall is at rest in the reference frame chosen for solid-fluid system, the velocity of the fluid at the interface is Zero.

Since at distances away from the solid velocity is finite, there must be variations in velocity from point to point in the flowing stream. Therefore, the velocity at any point is a function of the space coordinates of that point and a velocity field exists in the space occupied by the fluid.

The velocity at a given location may also vary with time. When the velocity at each location is constant, the field is invariant with time and the flow is said to be steady.

- **One Dimensional Flow:**

Velocity is a vector and in general the velocity at a point has three components, one of each space co-ordinate. In many simple situations all velocity in the field are parallel or practically so, and only one velocity component, which may be taken as a scalar is required. This simple situation is One-Dimensional Flow. An example is steady flow through a straight pipe**.**

- **Newton's Law of Viscosity:**

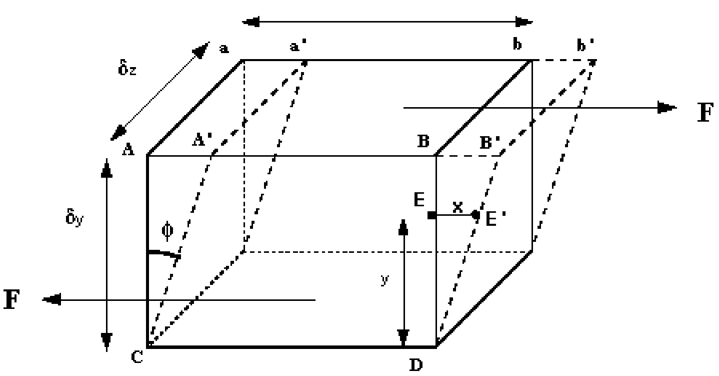


Figure 8 Fluid element under shear Force

The Shear force (F)is acting on area normal to the direction of Flow. Hence the element deforms through angle ϕ(phi) . $\tau = F/(\delta y \times \delta z)$.

If the particle at point E (in the above figure) moves under the shear stress to point E' and it takes time *t* to get there, it has moved the distance **"** x**"**. For small deformations we can write

Shear Strain $\phi = x/y$

$$\therefore Rate\ of\ shear\ strain = \frac{\phi}{t} = \frac{1}{y}\frac{x}{t} = \frac{u}{y} \qquad (19)$$

Using the experimental result that shear stress(τ) is proportional to rate of shear strain then

$$\therefore shear\ stress\ \tau = constant\ \frac{u}{y} \qquad \textbf{(20)}$$

As the velocity u changes with y u/y should be written as du/dy. The proportionality constant is known as dynamic viscosity (μ)

The equation 10 can be written as

$$\therefore shear\ stress\ \tau = \mu\frac{du}{dy} \qquad \textbf{(21)}$$

Equation 11 is known as Newton's law of Viscosity .

- **Viscosity in Fluids**

Viscosity in Gases

The molecules of gasses are only weakly kept in position by molecular cohesion (as they are so far apart).

As adjacent layers move by each other there is a continuous exchange of molecules. Molecules of as lower layer move to faster layers causing a drag, while molecules moving the other way exert an acceleration force. Mathematical considerations of this momentum exchange can lead to Newton law of viscosity.

If temperature of a gas increases the momentum exchange between layers will increase thus increasing viscosity.

Viscosity will also change with pressure - but under normal conditions this change is negligible in gasses.

Viscosity in Liquids

The **temperature dependence of liquid viscosity** is the phenomenon by which liquid viscosity tends to decrease (or, alternatively, its *fluidity* tends to increase) as its temperature increases. This can be observed, for example, by watching how cooking oil appears to move more fluidly upon a frying pan after being heated by a stove

Viscisity of liquid at other temperature can be found using following models.

- **Exponential model**

An exponential model for the temperature-dependence of shear viscosity (μ) was first proposed by Reynolds in 1886.

$$\mu_T = \mu_0 \exp(-bT) \qquad (22)$$

where T is temperature and μ_0 and b are coefficient. This is an empirical model that usually works for a limited range of temperature

Arrhenius model

The model is based on the assumption that the fluid flow obeys the Arrhenius equation for molecular kinetics:

$$\mu_T = \mu_0 \, exp\left(\frac{E}{RT}\right) \qquad (23)$$

where T is temperature, μ_0 is a coefficient, E is the activation energy and R is the universal gas constant

Units: Newton seconds per square meter, $N\,sm^{-2}$ or Kilograms per meter per second, $kgm^{-1}\,s^{-1}$.
(Although note that μ is often expressed in Poise, P, where 10 P = 1 $kgm^{-1}\,s^{-1}$.)
Typical values:
Water =1.14×10^{-3} $kgm^{-1}\,s^{-1}$, Air =1.78×10^{-5} $kgm^{-1}\,s^{-1}$ Mercury =1.552 $kgm^{-1}\,s^{-1}$,
Paraffin Oil =1.9 $kgm^{-1}\,s^{-1}$.

- **Kinematic Viscosity**

Kinematic Viscosity(ν), is defined as the ratio of dynamic viscosity to mass density.

$$\upsilon = \frac{\mu}{\rho} \qquad (24)$$

Units: square meters per second, $m^2\,s^{-1}$
(Although note that ν is often expressed in Stokes, St, where 10^{-4} St = 1 $m^2\,s^{-1}$.)
Typical values:

Water $=1.14 \times 10^{-6}\ m^2 s^{-1}$, Air $=1.46 \times 10^{-5} m^2 s^{-1}$, Mercury $=1.145 \times 10^{-4}\ m^2 s^{-1}$
Paraffin Oil $=2.375 \times 10^{-3} m^2 s^{-1}$

- **Other Properties of Fluids**

Density

The density of a substance is the quantity of matter contained in a unit volume of the substance. It can be in three different ways.

(a) Mass Density

Mass Density, r , is defined as the mass of substance per unit volume.
Units: Kilograms per cubic meter, kg / m3
Typical values:
Water = 1000 kgm-3 , Mercury = 13546 kgm-3 Air = 1.23 kgm-3 , Paraffin Oil = 800 kgm-3 .
(at pressure =1 atm and Temperature = 288.15 K.)

(b) **Specific Weight** ω, (sometimes γ, and sometimes known as *specific gravity*) is defined as the weight per unit volume

(c) **Relative** Density, σ, is defined as the ratio of mass density of a substance to some standard mass density.

For solids and liquids this standard mass density is the maximum mass density for water (which occurs at 4 °C) at atmospheric pressure.

$$\sigma = \frac{\rho}{\rho_{water}}\ for\ liquids \quad (25)$$

Typical values: Water = 1, Mercury = 13.5, Paraffin Oil =0.8

Streamlines and streamtubes

In analyzing fluid flow it is useful to visualize the flow pattern. This can be done by drawing lines joining points of equal velocity - velocity contours. These lines are know as *streamlines*. Here is a simple example of the streamlines around a cross-section of an aircraft wing shaped body:

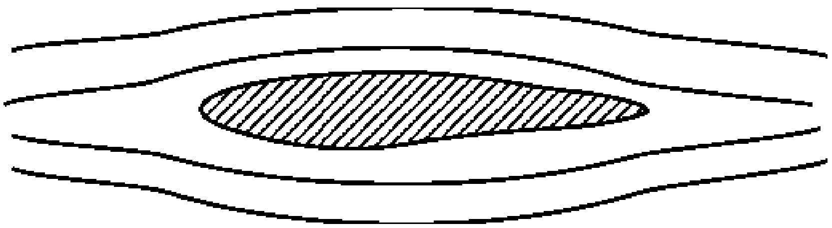


Figure 9 Streamlines around a wing shaped body

When fluid is flowing past a solid boundary, e.g. the surface of an aerofoil or the wall of a pipe, fluid obviously does not flow into or out of the surface. So very close to a boundary wall the flow direction must be parallel to the boundary. (*Close to a solid boundary streamlines are parallel to that boundary)*

At all points the direction of the streamline is the direction of the fluid velocity: this is how they are defined. Close to the wall the velocity is parallel to the wall so the streamline is also parallel to the wall. It is also important to recognize that the position of streamlines can change with time - this is the case in unsteady flow. In steady flow, the position of streamlines does not change.

Some things to know about streamlines

- Because the fluid is moving in the same direction as the streamlines, fluid can not cross a streamline.
- Streamlines can not cross each other. If they were to cross this would indicate two different Velocities at the same point. This is not physically possible.
- The above point implies that any particles of fluid starting on one streamline will stay on that Same streamline throughout the fluid.

A useful technique in fluid flow analysis is to consider only a part of the total fluid in isolation from the rest. This can be done by imagining a tubular surface formed by streamlines along which the fluid flows. This tubular surface is known as a ***streamtube.***

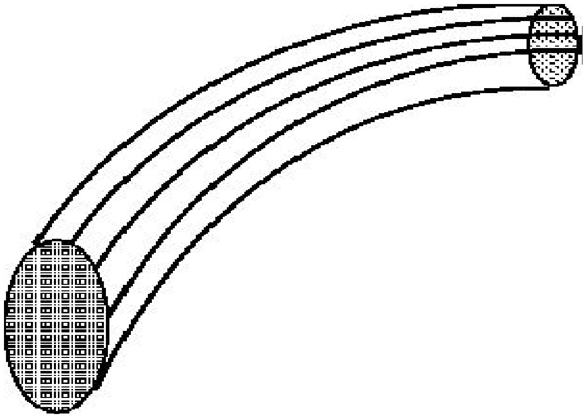


Figure 10 Stream tube

Mass flow rate

If we want to measure the rate at which water is flowing along a pipe. A very simple way of doing this is to catch all the water coming out of the pipe in a bucket over a fixed time period. Measuring the weight of the water in the bucket and dividing this by the time taken to collect this water gives a rate of accumulation of mass. This is known as the *mass flow rate.*

For example an empty bucket weighs 2.0kg. After 7 seconds of collecting water the bucket weighs 8.0kg, then:

$$Mass\ Flow\ Rate\ \ (m) = \frac{Mass\ \ colected}{Time\ taken} = \frac{8-2\ kg}{7\ sec} = 0.857\frac{kg}{sec}$$

Volume flow rate - Discharge.

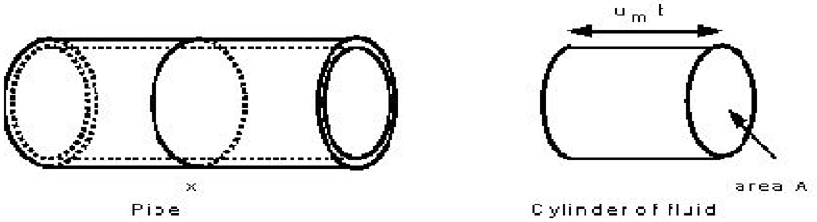
- More commonly we need to know the volume flow rate - this is more commonly know as *discharge.* (It is also commonly, but inaccurately, simply called flow rate). The symbol normally used for discharge is Q.
- The discharge is the volume of fluid flowing per unit time. Multiplying this by the density of the fluid gives us the mass flow rate. Consequently, if the density of the fluid in the above example is 850 kgm^{-3} then:

$$Dicharge\ (Q) = \frac{Volume\ of\ the\ fluid}{Time\ taken} = \frac{Mass\ \ of\ the\ fluid}{Density\ of\ the\ Fluid\ \ x\ Time\ taken} = \frac{Mass\ \ rate}{Density\ of\ the\ Fluid}$$

$$Dicharge\ (Q) = \frac{0.857\ kg/sec}{850\ kg/m^3} = 1.008x10^{-3}\ m^3/\text{ sec} \ \ = 1.008\ lier/sec$$

Discharge and mean velocity.

If we know the size of a pipe, and we know the discharge, we can deduce the mean velocity



(11) Discharge in a pipe

If the area of cross section of the pipe at point X is A, and the mean velocity here is u_m. During a time t, a cylinder of fluid will pass point X with a volume A×u_m×t. The volume per unit time (the discharge) will thus be

$$Q = \frac{Volume\ of\ the\ fluid}{Time\ taken} = \frac{Au_m t}{t} = Au_m$$

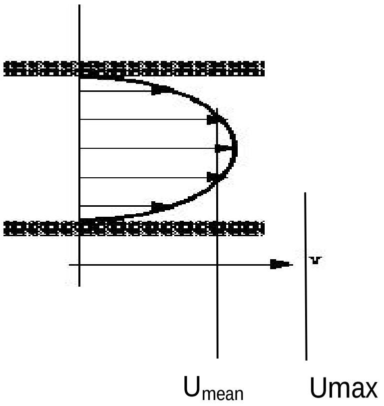
$$\therefore\ \ u_m = \frac{Q}{A}$$

So if the cross-section area, A, is 1.2×10^{-3} m^2 and the discharge, Q is 1.008 $lier/sec$, then the mean velocity, u_m, of the fluid is

$$u_m = \frac{1.008\ x\ 10^{-3}\ m^3/sec}{1.2\ 10^{-3}\ m^2} = 0.84\ m/sec$$

Note how carefully we have called this the *mean* velocity. This is because the velocity in the pipe is not constant across the cross section. Crossing the centre line of the pipe, the velocity is zero at the walls increasing to a maximum at the centre then decreasing symmetrically to the other wall.

This variation across the section is known as the velocity profile or distribution. A typical one is shown in the figure.



(11) A typical velocity profile across a pipe

Continuity

Matter cannot be created or destroyed - (it is simply changed in to a different form of matter). This principle is know as the *conservation of mass* and we use it in the analysis of flowing fluids.

The principle is applied to fixed volumes, known as control volumes (or surfaces), like that in the figure below:

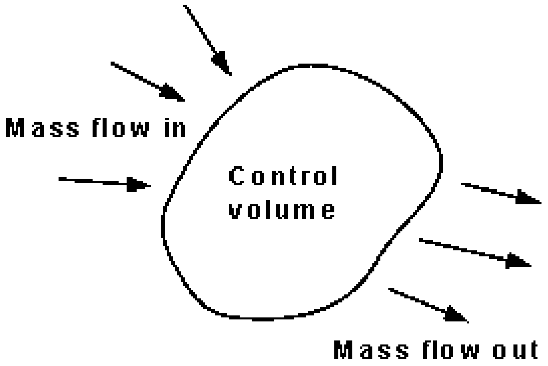
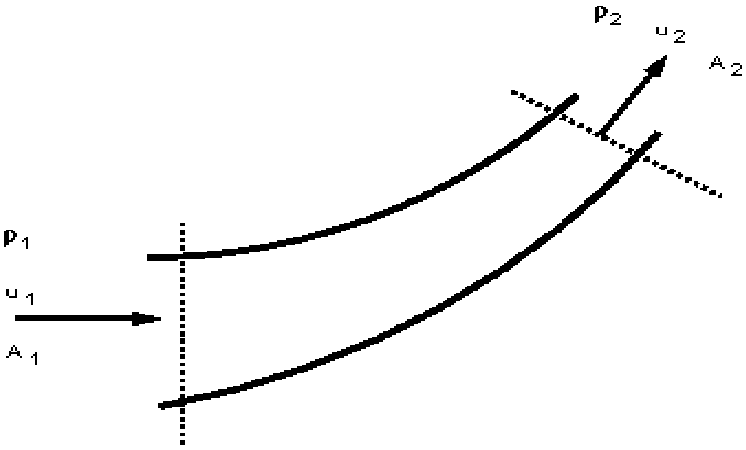


Figure 12

For any control volume the principle of *conservation of mass* says
Mass entering per unit time = Mass leaving per unit time + Increase of mass in the control volume per unit time
For **steady** flow there is no increase in the mass within the control volume, so

For steady flow **Mass entering per unit time = Mass leaving per unit time**

This can be applied to a streamtube such as that shown below. No fluid flows across the boundary made by the streamlines so mass only enters and leaves through the two ends of this streamtube section.



(13) A stream tube

We can then write
mass entering per unit time at end 1 = mass leaving per unit time at end 2

or $\rho_1 \delta A_1 u_1 = \rho_2 \delta A_2 u_2 = \text{Constant} = m$ **(26)**

Equation 16 is known as Equation of Continuity
The flow of fluid through a real pipe (or any other vessel) will vary due to the presence of a wall

- in this case we can use the *mean* velocity and write

or $\rho_1 \delta A_1 u_{m1} = \rho_2 \delta A_2 u_{m2} = \text{Constant} = m$ **(27)**

When the fluid can be considered incompressible, i.e. the density does not change, $\rho_1 = \rho_2 = \rho$ so

$A_1 u_{m1} = A_2 u_{m2} = \text{Constant} = Q$ **(28)**

This is the form of the continuity equation(18) most often used.

Some example applications

- We can apply the principle of continuity to pipes **with cross sections which change along their length.**

Consider the diagram below of a pipe with a contraction:

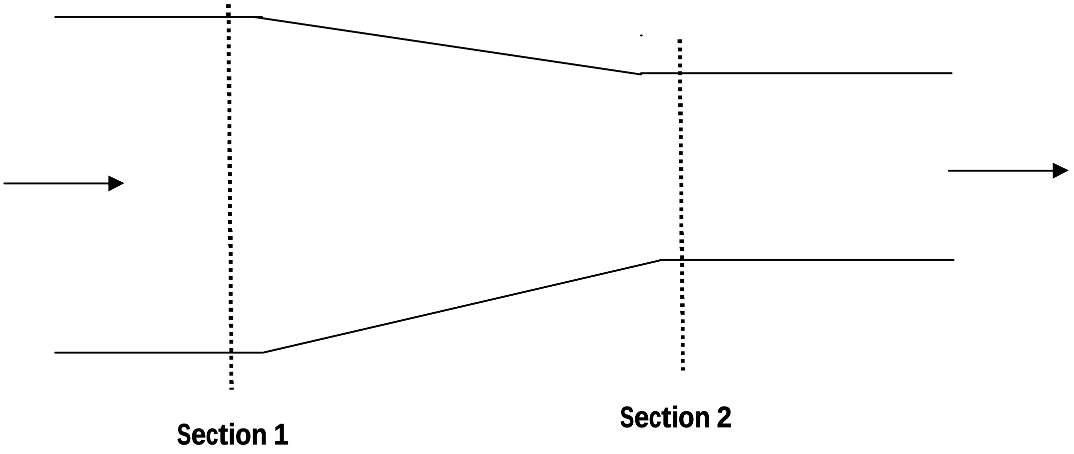


Figure 14

Applying Continuing equation for the incompressible flow (water) wose density does not change

$A_1 u_1 = A_2 u_2 = \text{Constant} = Q$

Example

Upstream : $A_1 = 10 \times 10^{-3}\ m^2$ $u_1 = 2.1$ m/sec
Down stream: $A_2 = 3 \times 10^{-3}\ m^2$ $u_2 = ?$
Here $u_2 = u_1 A_1 / A_2 = 2.1 \times 10 \times 10^{-3} / (3 \times 10^{-3}) = 7$ m/sec ANS

Above calculation also indicate that the downstream velocity only changes from the upstream by the ratio of the two areas of the pipe. As the area of the circular pipe is a function of the diameter we can reduce the calculation further,

$$u_2 = \frac{A_1}{A_2}u_1 = \frac{\pi d_1^2 / 4}{\pi d_2^2 / 4}u_1 = \frac{d_1^2}{d_2^2}u_1$$
$$= \left(\frac{d_1}{d_2}\right)^2 u_1$$

Another example of the use of the continuity principle is to determine the velocities in pipes coming from a junction.

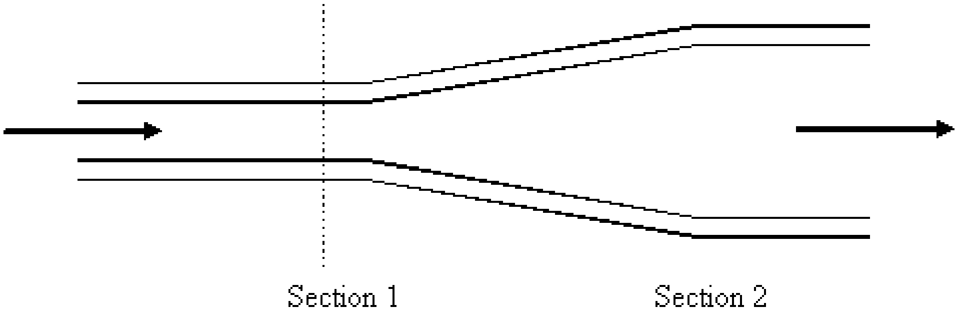


Figure 15

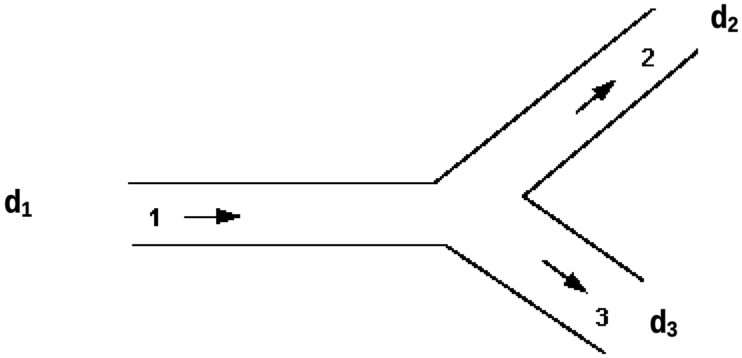
If the diameter at section 1 is d_1 =30 mm and at section 2 d_2 = 40 mm and the mean velocity at section 2 is u_2 = 3.0 m/sec

From Continuity equation 18 and 19 we have

$u_1 d_1^2 = u_2 d_2^2$

$\therefore u_1 = u_2 (d_2/d_1)^2 = 3.0(40/30)^2 = 5.33$ m/sec ANS

Another example of the use of the continuity principle is to determine the velocities in pipes coming from a junction.



Total mass flow into the junction = Total mass flow out of the junction

$$\rho_1 Q_1 = \rho_2 Q_2 + \rho_3 Q_3$$

When the flow is incompressible (e.g. if it is water) $\rho_1 = \rho_2 = \rho$

$$Q_1 = Q_2 + Q_3$$
$$A_1 u_1 = A_2 u_2 + A_3 u_3$$

If pipe 1 diameter = 50 mm, mean velocity 2m/s, pipe 2 diameter 40 mm takes 30% of total discharge and pipe 3 diameter 60 mm. What are the values of discharge and mean velocity in each pipe?

$Q_1 = Q_2 + Q_3$

$\mathbf{Q_1} = (\pi/4) d_1^2 \text{ x } u_1 = (\pi/4) \text{ x} (50 \text{ x} 10^{-3})^2 \text{ x } 2 = \mathbf{3.926 \text{ x } 10^{-3}\ m^3/sec}$

$\mathbf{Q_2} = 0.3 \text{ x } 3.926 \text{ x } 10^{-3} = \mathbf{1.178 \text{ x } 10^{-3}\ m^3/sec}$

$Q_2 = (\pi/4) d_2^2 \text{ x } u_2$

$\therefore\ \mathbf{u_2} = 4\, Q_2 / (\pi\, d_2^2) == 4 \text{ x } 1.178 \text{ x } 10^{-3} / (\pi \text{ x } 0.04^2) = \mathbf{0.931\ m/sec}$

$Q_3 = Q_1 - Q_2 = 3.926 \text{ x } 10^{-3} - 1.178 \text{ x } 10^{-3} = 2.748 \text{ x } 10^{-3}\ m^3/sec$

$\therefore\ \mathbf{u_3} = 4\, Q_3 / (\pi\, d_3^2) = 4 \text{x} 2.748 \text{ x } 10^{-3} / (\pi \text{ x } .06^2) = \mathbf{0.972\ m/sec}$ ANS

The Bernoulli Equation - Work and Energy

Work and energy

We know that if we drop a ball it accelerates downward with an acceleration $g = 9.81 m / s^2$ (neglecting the frictional resistance due to air). We can calculate the speed of the ball after falling a distance *h* by the formula

$$\mathbf{v_2^{\,2} = v_1^{\,2} + 2as\ (a = g \text{ and } s = h)} \qquad \mathbf{(29)}$$

The equation could be applied to a falling droplet of water as the same laws of motion apply

A more general approach to obtaining the parameters of motion (of both solids and fluids) is to apply the principle of ***conservation of energy***. When friction is negligible, **the sum of kinetic energy and gravitational potential energy is constant**.

$$Kinetic\ Energy = \frac{1}{2} m v^2$$

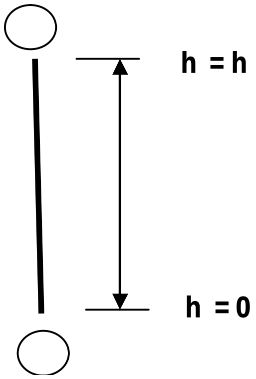
Gravitational potential energy = *mg h*

(*m* is the mass, *v* is the velocity and *h* is the height above the datum).

To apply this to a falling droplet we have an initial velocity of zero, and it falls through a height of h.

Initial kinetic energy = 0 as v =0

Initial potential energy = *mgh*



And

$Final\ Kinetic\ Energy \ = \dfrac{1}{2}mv^2$

Final potential energy = 0 h = 0

We know that

kinetic energy + potential energy = constant

so

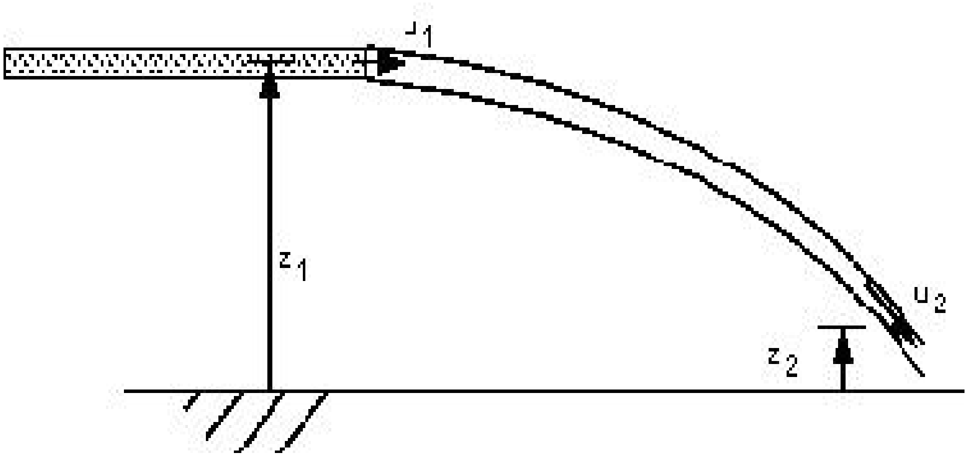
Initial kinetic energy + Initial potential energy = Final kinetic energy + Final potential energy

$$0 + mgh = \tfrac{1}{2}mv^2 + 0$$

$$\therefore \mathbf{mgh = \frac{1}{2}mv^2} \qquad \mathbf{(30)}$$

$$\therefore \mathbf{v = \sqrt{2gh}} \qquad \mathbf{(31)}$$

Although this is applied to a drop of liquid, a similar method can be applied to a **continuous jet** of liquid.



The Trajectory of a jet of water

We can consider the situation as in the figure above - a continuous jet of water coming from a pipe with velocity u_1. One particle of the liquid with mass *m* travels with the jet and falls from height z_1 to z_2. The velocity also changes from u_1 to u_2. The jet is travelling in air where the pressure is everywhere atmospheric so there is no force due to pressure acting on the fluid. The only force which is acting is that due to gravity. The sum of the kinetic and potential energies remains constant (as we neglect energy losses due to friction) so

Applying law of conservation of energy as above

We have

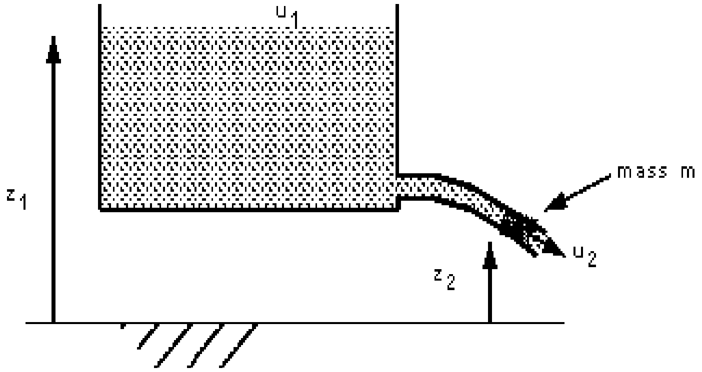
$$\frac{1}{2}mu_1^2 + mgz_1 = \frac{1}{2}mu_2^2 + mgz_2$$

As mass of the jet m is constant

$\frac{1}{2}\mathbf{u_1^2} + \mathbf{gz_1} = \frac{1}{2}\mathbf{u_2^2} + \mathbf{gz_2}$ $\quad(32)\quad$ note: jet does not break in to droplets

Flow from a reservoir

We can use a very similar application of the energy conservation concept to determine the velocity of flow along a pipe from a reservoir. Consider the idealized reservoir. in the figure below.



Idealized Reservoir

The Equation 22 in this case becomes

$$mgz_1 = \frac{1}{2}mu_2^2 + mgz_2$$

$$mg(z_1 - z_2) = \frac{1}{2}mu_2^2$$

$$\therefore \mathbf{u_2} = \sqrt{\mathbf{2g(z_1 - z_2)}} \qquad (33)$$

Example:

A reservoir of water has the surface at 310m above the outlet nozzle of a pipe with diameter 15mm. What is the a) velocity, b) the discharge out of the nozzle and c) mass flow rate. (Neglect all friction in the nozzle and the pipe).?

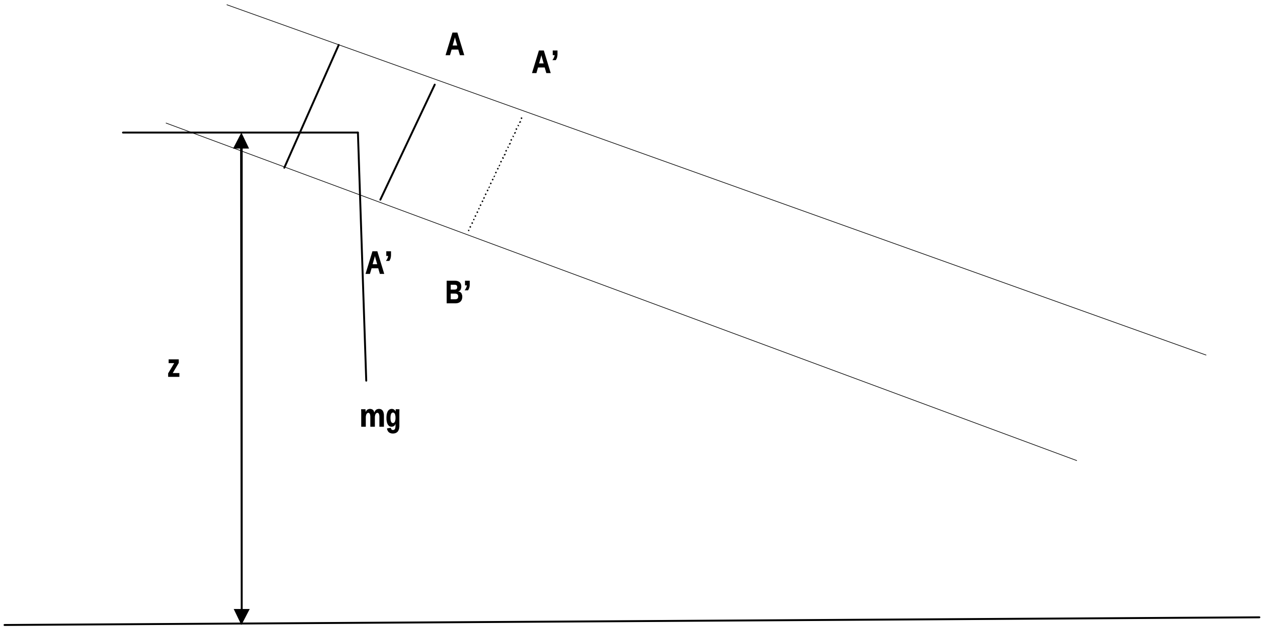
Applying equation 23

(a) $u_2 = \sqrt{2x\ 9.81(310 - 0)} = \mathbf{78.0\frac{m}{sec}}$ **ans a**

(b) Discharge $Q = Au_2 = (\pi/4)\, d^2 \times u_2 = (\pi/4)\,(15x10^{-3})^2 \times 78 =$ **.01378 m^3/sec ans b**

(c) Mass velocity $= Q \times \rho = 0.01378 \times 1000 =$ **13.78 kg/sec Ans**

Bernoulli's equation



With all above cases we can derive the Bernoulli's equation- a classical equation for fluid flow However it as has some restrictions in its applicability, they are:

- Flow is steady;
- Density is constant (which also means the fluid is incompressible);
- Friction losses are negligible.(it can also be incorporate at any stage of calculation.
- The equation relates the states at two points along a single streamline, (not conditions on two different streamlines).

All these conditions are impossible to satisfy at any instant in time! Fortunately for many real situations where the conditions are *approximately* satisfied, the equation gives very good results.

An element of fluid, as that in the figure above, has potential energy due to its height z above a datum and kinetic energy due to its velocity *u*. If the element has weight mg then

Potential Energy = mgz
Potential energy per unit weight = z

Kinetic energy $= \frac{1}{2}mu^2$

Kinetic energy per unit weight $= \frac{\mathbf{u^2}}{\mathbf{2g}}$

At any cross-section the pressure generates a force, the fluid will flow, moving the cross-section, so work will be done. If the pressure at cross section AB is *p* and the area of the cross-section is *a* then

force on AB = *pa*

when the mass *m* of fluid has passed AB, cross-section AB will have moved to A'B'

$$Volume\ of\ the\ fluid\ passing\ AB = \frac{m}{\rho}$$

$$\therefore The\ Distance\ \ move\ AA' = \frac{m}{\rho a}$$

$$\therefore work\ done\ \ = force\ x\ distance = pa\ x\ \frac{m}{\rho a}$$

$$\therefore \boldsymbol{work\ done\ \ per\ unit\ \ weight} = \frac{\boldsymbol{p}}{\boldsymbol{\rho g}}$$

This work done is known as Pressure energy of the flowing stream

Summing all of these energy terms gives

Total energy per unit weight =
Pressure energy per unit weight + Kinetic energy per unit weight +Potential energy per unit weight

OR $\frac{p}{\rho g} + \frac{u^2}{2g} + z = H \qquad (34)$

All the above terms have unit of length. Hence

$\frac{p}{\rho g}$ ***is known as pressure head in height of fluid***

$\frac{u^2}{2g}$ **is known as kinetic head in terms of height of fluid**

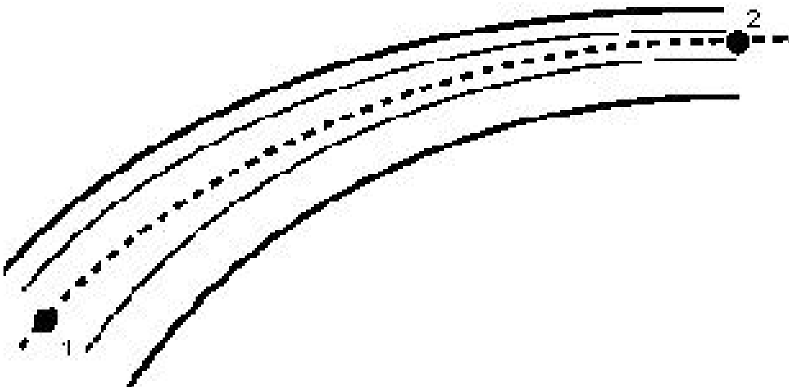
z is known as potential energy head in terms of height of fluid

H is known as total head in terms of height of fuid

By the principle of conservation of energy the total *energy* in the system does not change, Thus the total *head* does not change. So the **Bernoulli equation** can be written as

$$\frac{p}{\rho g} + \frac{u^2}{2g} + z = H = Constant \qquad (35)$$

As stated above, the Bernoulli equation applies to conditions along a streamline. We can apply it between two points, 1 and 2, on the streamline in the figure below



Stream line joining two points 1 and 2

total energy per unit weight at 1 = total energy per unit weight at 2

$$\frac{p_1}{\rho g} + \frac{u_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{u_2^2}{2g} + z_2 \qquad (36)$$

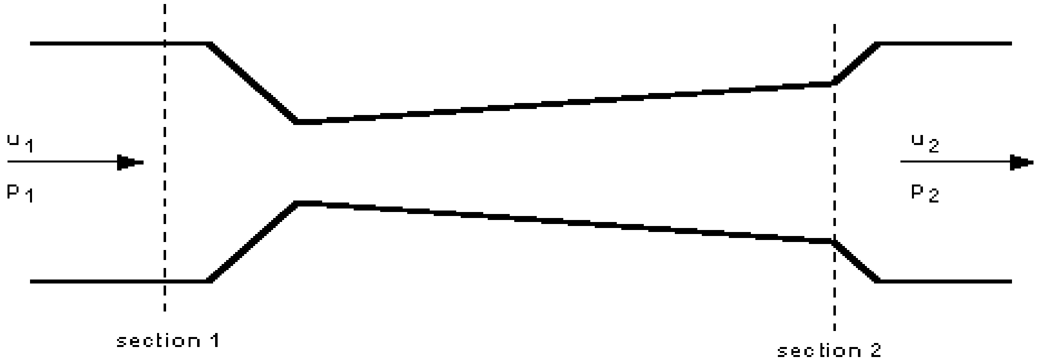
This equation assumes no energy losses (e.g. from friction) or energy gains (e.g. from a pump) along the streamline. It can be expanded to include these simply, by adding the appropriate energy terms:

$$\frac{p_1}{\rho g} + \frac{u_1^2}{2g} + z_1 + q = \frac{p_2}{\rho g} + \frac{u_2^2}{2g} + z_2 + h + w \qquad (37)$$

Where
q= Energy supplied to fluid
h = head loss e.g. frictional loss
w = work done by the fluid

Example

A fluid of constant density ρ = 960 *kg* /m^3 is flowing steadily through the tube shown bellow. . The diameters at the sections at 1 and 2 are 100 mm and = 80 mm respectively. . The gauge pressure at 1 is *p is* 200KN /m^2 and the velocity at this section is 5 m /sec . what is the gauge pressure at section 2. ?



We shall of course use the Bernoulli equation to do this and we apply it along a streamline joining section 1 with section 2.

The tube is horizontal, with $z_1 = z_2$ here h =q =w =0

Hence Bernoulli gives us the following equation for pressure at section 2:

$$p_2 = p_1 + \frac{\rho}{2}\left(u_1^2 - u_2^2\right)$$

We have p_1 = 200 kN/m^2 = 200 x 1000 kg-m/(sec^2 m^2)
u_1 = 5 /sec^2
u_2 = not known. Find by continuity equation
ρ =960 kg /m^3 d_1 = 100 mm d_2 =80 mm

by continuity equation $A_1 u_1 = A_2 u_2$
$d_1^2 u_1 = d_2^2 u_2$

Hence $u_2 = u_1(d_1/d_2)^2 = 5 \times (100/80)^2 = 7.8125$ m/sec

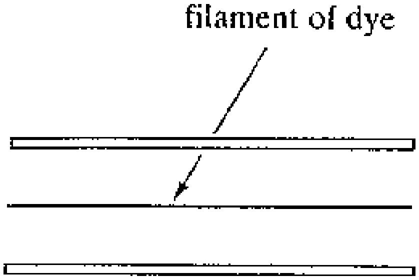
$$\boldsymbol{p_2} = 200\,x\,1000\,\frac{kg-m}{sec^2m^2} + \frac{960\,\frac{kg}{m^3}}{2}(5^2 - 7.8125^2)\,\frac{m^2}{sec^2} = \mathbf{182}.\frac{\boldsymbol{73KN}}{\boldsymbol{m^2}}\ \boldsymbol{ANS}.$$

Applications of Bernoulli's Equations.

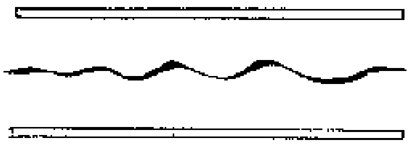
- Pumping fluid at height
- Emptying reservoir
- Flow measurement by pressure difference – Venturi meter, Pitot tube orifice meter etc
- Impact of Jet

Types of Flow

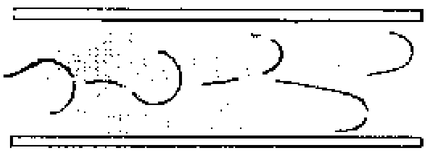
low velocities fluids tends to flow without lateral mixing, and adjacent layers solid past one another like playing cards. There are neither cross currents nor eddies. This regime is called Laminar Flow. At higher velocities turbulence appears and eddies form



Laminar (viscous)



Transitional



Turbulent

Prediction of Flow

The Flow laminar, transitional or turbulent can be predicted by a dimensionless number known as Reynolds's number (R_e) or (NR_e) and is given by

$$Re = \frac{Du\rho}{\mu}$$

Where where ρ = density, u = mean velocity, d = diameter and μ = viscosity

$Re < 2100$	Laminar
$Re > 4000$	Turbulent
$2100 < Re < 4000$	Transitional

- Transition Length

The length of the entrance region of the tube necessary for the boundary layer to reach the center of the tube and for fully developed flow to be established is called the Transition Length.

The approximate length of straight pipe necessary for completion of the final velocity distribution is.

i) For laminar Flow,

$$\frac{x_t}{D} = 0.05 N_{\text{Re}}$$

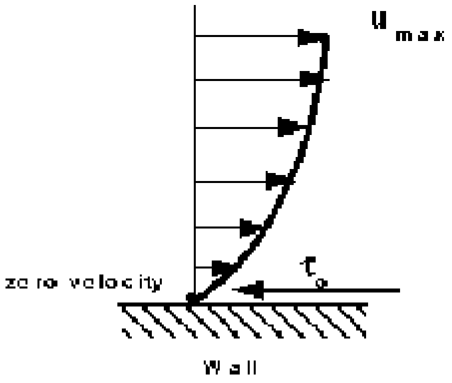
Where, x_t = Transition length

D = Diameter of pipe

ii) Turbulent flow, x_t as large as 100 pipe diameter is needed.

Boundary Layer

When a fluid flows over a stationary surface, e.g. the bed of a river, or the wall of a pipe, the fluid touching the surface is brought to rest by the shear stress t_o at the wall. The velocity increases from the wall to a maximum in the main stream of the flow.



Looking at this two-dimensionally we get the above velocity profile from the wall to the centre of the flow.

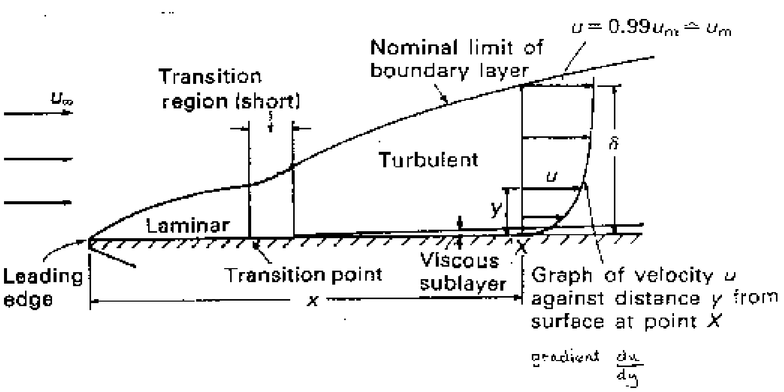
This profile doesn't just exit, it must build up gradually from the point where the fluid starts to flow past the surface - e.g. when it enters a pipe.

If we consider a flat plate in the middle of a fluid, we will look at the buildup of the velocity profile as the fluid moves over the plate.

Upstream the velocity profile is uniform, (free stream flow) a long way downstream we have the velocity profile we have talked about above. This is the known as fully developed flow. But how do we get to that state?

This region, where there is a velocity profile in the flow due to the shear stress at the wall, we call the boundary layer. The stages of the formation of the boundary layer are shown in the figure below:

BOUNDARY LAYER ON FLAT PLATE
(y scale greatly enlarged)



Pressure loss due to friction in a pipeline.

- Because fluids are viscous, energy is lost by flowing fluids due to friction which must be taken into account.
- The effect of the friction shows itself as a pressure (or head) loss.
- In a pipe with a real fluid flowing, at the wall there is a shearing stress retarding the flow, as shown below.
- as well as rough pipes as shown in figure 5.1. The data for the plot are taken over a wide range of each variable such as velocity, density, and pipe diameter etc. using liquids and gasses. This chart is also termed as the Friction factor-Reynolds numbers correlation chart.

Effect of Roughness:

- In turbulent flow, a rough pipe leads to a large friction factor than the strength pipe, for a given Reynolds number. If the rough pipe is smoothed, the friction factor is reduced and ultimately a stage will come when further smoothing of the pipe does not reduce the friction factor for a given Reynolds number. The pipe is then said to be hydraulically smooth.
- The roughness parameter (k) is a length representing the magnitude of surface roughness. The relative roughness is the ratio of roughness parameter to the diameter of the pipe i.e. k/D. The depending of friction factor on surface roughness is given through relative roughness. For low values of Reynolds number (NRe < 2100), the friction factor is independent of the surface-roughness. For large values of Reynolds number (NRe > 2500), the friction factor is also a function of surface roughness. At very large values of Reynolds number the friction factor is independent of NRe but is a function of surface roughness.

Friction Factor Chart:

- It is a logarithmic plot of friction factor as a function of Reynolds number over a wide range of Reynolds number for a flow in smooth pipe.

The friction factor is a function both Reynolds numbers & relative roughness.

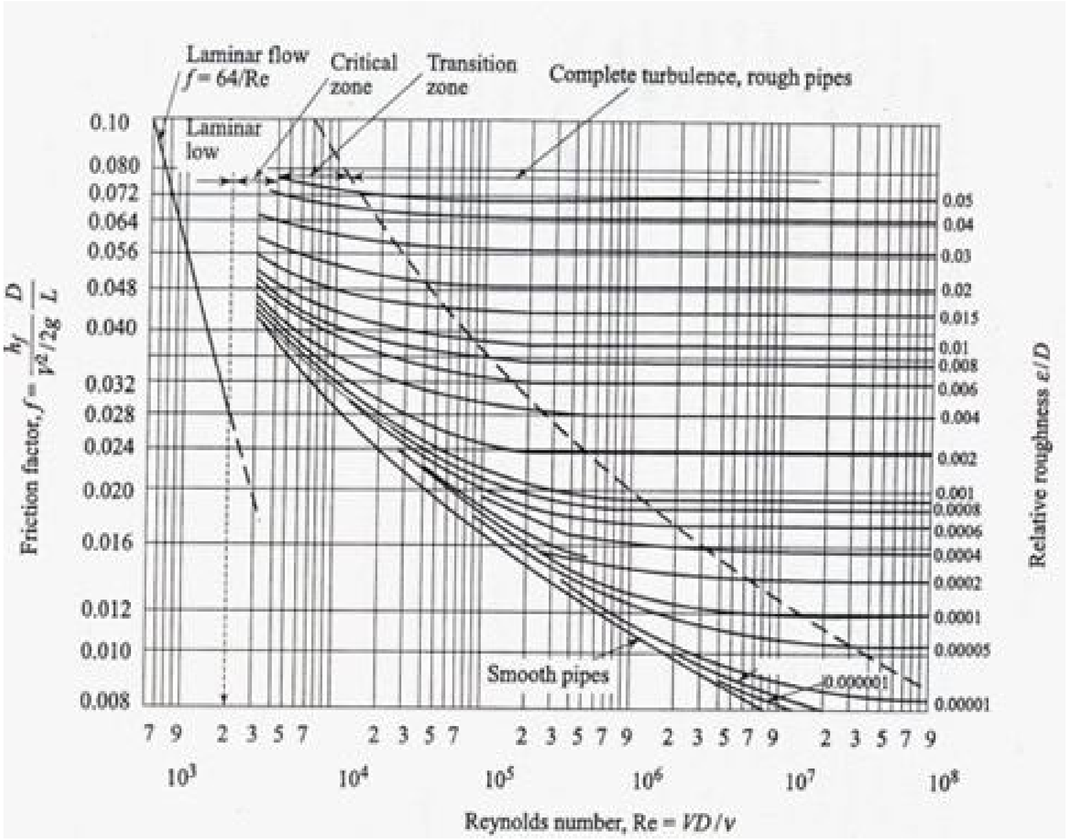
For laminar flow region,
for Reynolds number up to about 2100.

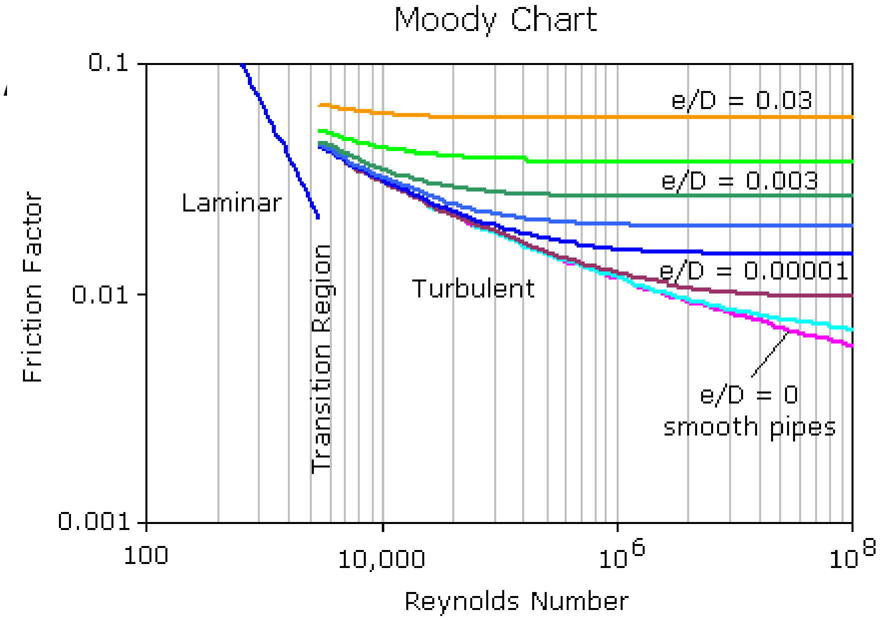
$$f = 64 / NRe$$

As ` f ' is also a function of relative roughness for turbulent flow, curves with different parameters of the dimensionless ratio k / D are presented in chart for $N_{Re} > 2100$, though the flow lies in transition region ($2100 < N_{Re} < 4000$) there is a doubt as to whether the flow is laminar, turbulent or combination of both.

For Nre > 2100 Friction factor is related to Reynolds number as:

$$f = 0.0014 + \frac{0.125}{NRe^{0.32}} \quad \text{OR} \quad f = \frac{0.078}{NRe^{0.25}}$$





From the knowledge of volumetric flow rate, density of fluid, viscosity, pipe diameter, the Reynolds number is calculated. The Reynolds number is used as the abscissa and friction factor is read as an ordinate. The friction factor is used in appropriate equation to calculate the head losses due to friction.

- **Hagen-Poiseuille Equation:**

$$\Delta P = \frac{32\Delta L\mu u}{g_c D^2}$$

ΔP – The pressure drop
ΔL – length of the pipe
μ – Viscosity of fluid

u – Velocity of fluid
D – Diameter of pipe

The Hagen-Poiseuille's equation is useful for measuring the viscosity of fluid by measuring the pressure drop and volumetric flow rate through a tube of given length and diameter.

Hydraulic radius and equivalent diameter: -

The friction in long straight channels of constant non-circular cross section can be estimated by using the equation for circular pipes if the diameter in the Reynolds number and in the definition of the friction factor is taken as on equivalent diameter. Equivalent diameter is four times the hydraulic radius.

The hydraulic radius is denoted by r_H and in turn defined as the ratio of the cross section area of the channels to the wetted perimeter of the channels.

$$r_H = \frac{S}{Lp}$$

Where
S = cross section area of channel
Lp = perimeter of channel in contact with fluid

For the special case of a circular tube, the hydraulic radius is

$$r_H = \frac{\frac{\pi}{4}D^2}{\pi D} = \frac{D}{4}$$

$\therefore$ Equivalent diameter is 4 r_H i.e. = D.

- In the case of annulus between concentric pipes,

$$r_H = \frac{\frac{\pi}{4}D_o^2 - \frac{\pi}{4}D_i^2}{\pi D_o + \pi D_i} = \frac{D_o - D_i}{4}$$

The equivalent diameter for annulus is simply difference between the two diameters.
Equivalent Diameter $=4r_H = D_o - D_i$

Friction loss in fittings & valves:-

Energy loss due to valves, fittings and bends is caused by some localized disruption of the flow. The dissipation of the lost energy occurs over a finite but not necessarily short section of the pipeline, however for hydraulic calculations it is accepted practice to consider the entire amount of this loss at the location of the device.

For pipe systems with relatively long pipes, it is often the case that fitting losses will be minor in relation to the overall pressure loss in the pipe. However some local losses such as those produced by a part open valve are often very significant and can never be termed a minor loss, and these must always be included.

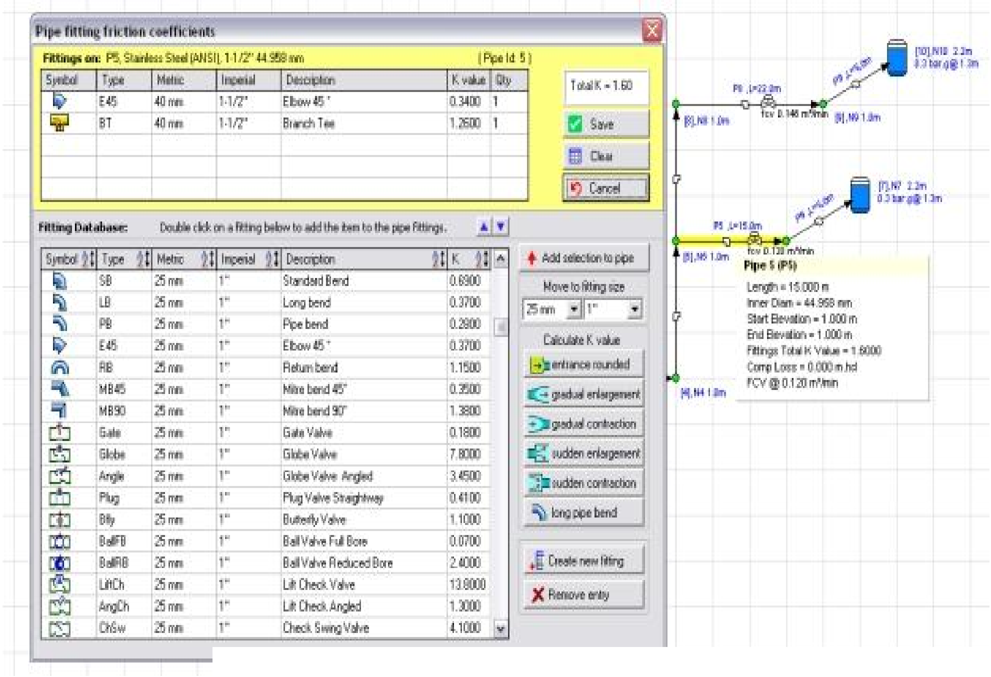
The loss that a specific pipe fitting introduces is measured using real world experimental data and this is then analyzed to determine a K factor (a local loss coefficient) that can be used to calculate the fitting loss as it varies with the velocity of the fluid passing through it.

$$\boldsymbol{h_f = k\frac{v^2}{2g_c}}$$

Where,
K = loss factor for fittings
V = average velocity

Another way to express the friction loss in fittings and valves is through equivalent length of fittings. The equivalent length is that length of straight pipe some normal size as that of fitting, which would cause friction loss equal to that caused by the fittings or valves.

The equivalent length is usually expressed not as actual meters of straight pipe but as a certain number of pipe diameters. Thus, if the bend has a equivalent length of X diameters and if the nominal pipe diameter is 5 cms the bend will cause a frictional loss equivalent to then caused by a straight pipe of length of 5X cms.



Fittings on: P5, Stainless Steel (ANSI), 1-1/2" 44.958 mm (Pipe Id: 5)

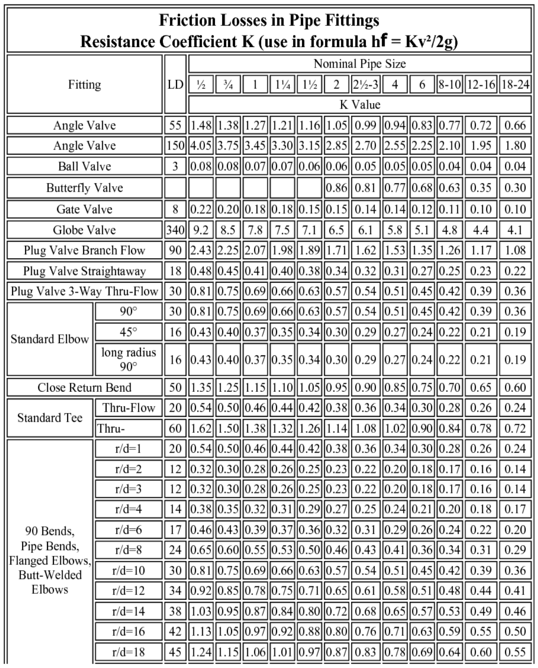
Symbol	Type	Metric	Imperial	Description	K value	Qty
	E45	40 mm	1-1/2"	Elbow 45 °	0.3400	1
	BT	40 mm	1-1/2"	Branch Tee	1.2600	1

Fitting Database: Double click on a fitting below to add the item to the pipe fittings.

Symbol	Type	Metric	Imperial	Description	K
	SB	25 mm	1"	Standard Bend	0.6900
	LB	25 mm	1"	Long bend	0.3700
	PB	25 mm	1"	Pipe bend	0.2900
	E45	25 mm	1"	Elbow 45 °	0.3700
	RB	25 mm	1"	Return bend	1.1500
	MB45	25 mm	1"	Mitre bend 45°	0.3500
	MB90	25 mm	1"	Mitre bend 90°	1.3800
	Gate	25 mm	1"	Gate Valve	0.1800
	Globe	25 mm	1"	Globe Valve	7.8000
	Angle	25 mm	1"	Globe Valve Angled	3.4500
	Plug	25 mm	1"	Plug Valve Straightway	0.4100
	Bfly	25 mm	1"	Butterfly Valve	1.1000
	BallFB	25 mm	1"	Ball Valve Full Bore	0.0700
	BallRB	25 mm	1"	Ball Valve Reduced Bore	2.4000
	LiftCh	25 mm	1"	Lift Check Valve	13.8000
	AngCh	25 mm	1"	Lift Check Angled	1.3000
	ChSw	25 mm	1"	Check Swing Valve	4.1000

Pipe 5 (P5)

Length = 15.000 m
Inner Diam = 44.958 mm
Start Elevation = 1.000 m
End Elevation = 1.000 m
Fittings Total K Value = 1.6000
Comp Loss = 0.000 m hd
FCV @ 0.120 m³/min



Friction Losses in Pipe Fittings
Resistance Coefficient K (use in formula $h_f = Kv^2/2g$)

Fitting		LD	Nominal Pipe Size											
			½	¾	1	1¼	1½	2	2½-3	4	6	8-10	12-16	18-24
			K Value											
Angle Valve		55	1.48	1.38	1.27	1.21	1.16	1.05	0.99	0.94	0.83	0.77	0.72	0.66
Angle Valve		150	4.05	3.75	3.45	3.30	3.15	2.85	2.70	2.55	2.25	2.10	1.95	1.80
Ball Valve		3	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04
Butterfly Valve								0.86	0.81	0.77	0.68	0.63	0.35	0.30
Gate Valve		8	0.22	0.20	0.18	0.18	0.15	0.15	0.14	0.14	0.12	0.11	0.10	0.10
Globe Valve		340	9.2	8.5	7.8	7.5	7.1	6.5	6.1	5.8	5.1	4.8	4.4	4.1
Plug Valve Branch Flow		90	2.43	2.25	2.07	1.98	1.89	1.71	1.62	1.53	1.35	1.26	1.17	1.08
Plug Valve Straightaway		18	0.48	0.45	0.41	0.40	0.38	0.34	0.32	0.31	0.27	0.25	0.23	0.22
Plug Valve 3-Way Thru-Flow		30	0.81	0.75	0.69	0.66	0.63	0.57	0.54	0.51	0.45	0.42	0.39	0.36
Standard Elbow	90°	30	0.81	0.75	0.69	0.66	0.63	0.57	0.54	0.51	0.45	0.42	0.39	0.36
	45°	16	0.43	0.40	0.37	0.35	0.34	0.30	0.29	0.27	0.24	0.22	0.21	0.19
	long radius 90°	16	0.43	0.40	0.37	0.35	0.34	0.30	0.29	0.27	0.24	0.22	0.21	0.19
Close Return Bend		50	1.35	1.25	1.15	1.10	1.05	0.95	0.90	0.85	0.75	0.70	0.65	0.60
Standard Tee	Thru-Flow	20	0.54	0.50	0.46	0.44	0.42	0.38	0.36	0.34	0.30	0.28	0.26	0.24
	Thru-	60	1.62	1.50	1.38	1.32	1.26	1.14	1.08	1.02	0.90	0.84	0.78	0.72
90 Bends, Pipe Bends, Flanged Elbows, Butt-Welded Elbows	r/d=1	20	0.54	0.50	0.46	0.44	0.42	0.38	0.36	0.34	0.30	0.28	0.26	0.24
	r/d=2	12	0.32	0.30	0.28	0.26	0.25	0.23	0.22	0.20	0.18	0.17	0.16	0.14
	r/d=3	12	0.32	0.30	0.28	0.26	0.25	0.23	0.22	0.20	0.18	0.17	0.16	0.14
	r/d=4	14	0.38	0.35	0.32	0.31	0.29	0.27	0.25	0.24	0.21	0.20	0.18	0.17
	r/d=6	17	0.46	0.43	0.39	0.37	0.36	0.32	0.31	0.29	0.26	0.24	0.22	0.20
	r/d=8	24	0.65	0.60	0.55	0.53	0.50	0.46	0.43	0.41	0.36	0.34	0.31	0.29
	r/d=10	30	0.81	0.75	0.69	0.66	0.63	0.57	0.54	0.51	0.45	0.42	0.39	0.36
	r/d=12	34	0.92	0.85	0.78	0.75	0.71	0.65	0.61	0.58	0.51	0.48	0.44	0.41
	r/d=14	38	1.03	0.95	0.87	0.84	0.80	0.72	0.68	0.65	0.57	0.53	0.49	0.46
	r/d=16	42	1.13	1.05	0.97	0.92	0.88	0.80	0.76	0.71	0.63	0.59	0.55	0.50
	r/d=18	45	1.24	1.15	1.06	1.01	0.97	0.87	0.83	0.78	0.69	0.64	0.60	0.55

Measurement of Flowing Fluids

Most meters operate on all the fluid in the pipe or channel and are known as Full-Bone meters. Others called Insertion meters measure the flow rate or more commonly the fluid velocity, at one point only.

(I) Full Bore Meters:

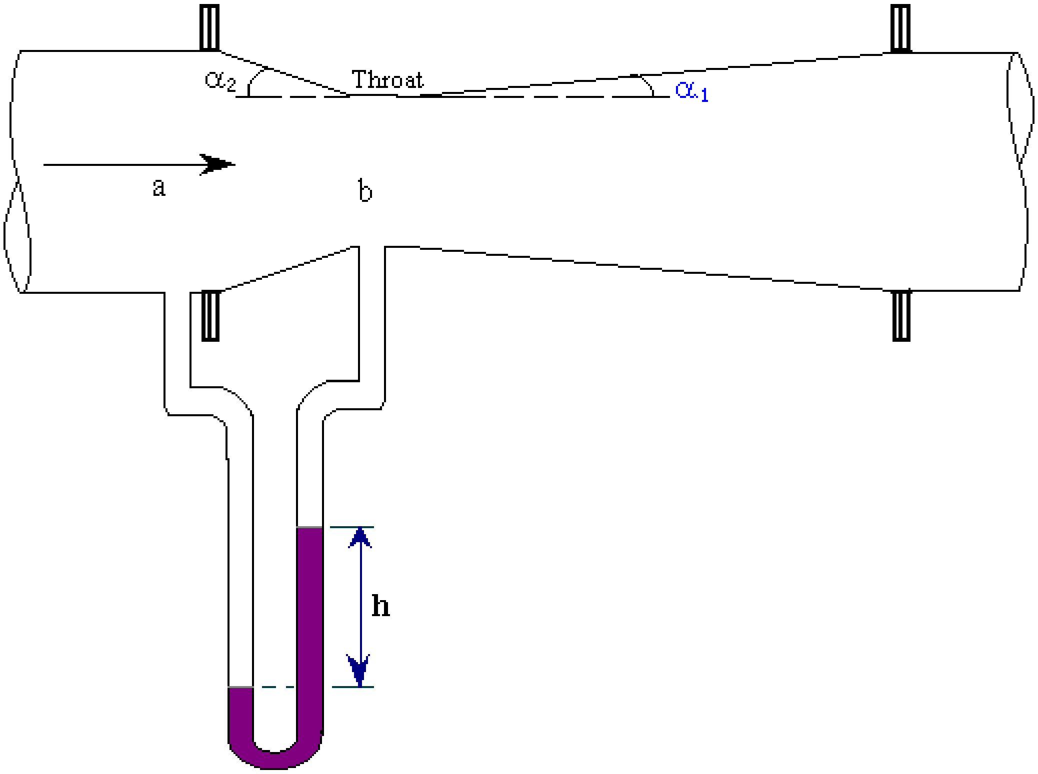
They include Variable Head Meters such as Venturi and Orifice Meters and Variable Area meters such as Rotameters.

A. Venturi Meter:

Venturi meter

Venturi meter is variable head meter. In this meter the fluid is accelerated by its passage through a converging cone of angle 15-20^{o}. The pressure difference between the upstream end of the cone and the throat is measured and provides the signal for the rate of flow. The fluid is then retarded in a cone of smaller angle (5-7^{o}) in which large proportion of kinetic energy is converted back to pressure energy. Because of the gradual reduction in the area there is no vena contracta and the flow area is a minimum at the throat so that the coefficient of contraction is unity.

The attraction of this meter lies in its high energy recovery so that it may be used where only a small pressure head is available, though its construction is expensive.



To make the pressure recovery large, the angle of downstream cone is small, so boundary layer separation is prevented and friction minimized. Since separation does not occur in a contracting cross section, the upstream cone can be made shorter than the downstream cone with but little friction, and space and material are thereby conserved.

Although venturi meters can be applied to the measurement of gas, they are most commonly used for liquids. The following treatment is limited to incompressible fluids.

The basic equation for the venturi meter is obtained by writing the Bernoulli equation for incompressible fluids between the two sections a and b. Friction is neglected, the meter is assumed to be horizontal.

If v_a and v_b are the average upstream and downstream velocities, respectively, and is the density of the fluid,

$$v_b^2 - v_a^2 = 2\frac{p_a - p_b}{\rho}$$

The continuity equation can be written as,

$$v_a = \left(\frac{D_b}{D_a}\right)^2 v_b = \beta^2 v_b$$

Where

D_a = diameter of pipe

D_b = diameter of throat (meter)

β = diameter ratio, D_b/D_a

If v_a is eliminated from equn.1 and 2, the result is

$$v_b = \frac{1}{\sqrt{1-\beta^4}}\sqrt{\frac{2(p_a - p_b)}{\rho}}$$

The Equation applies strictly to the frictionless flow of non-compressible fluids. To account for the small friction loss between locations a and b, equn.3 is corrected by introducing an empirical factor C_v. The coefficient C_v is determined experimentally. It is called the *venturi coefficient*,

The effect of the approach velocity v_a is accounted by the term $1/(1-\beta^4)^{0.5}$. When D_b is less than $D_a/4$, the approach velocity and the term β can be neglected, since the resulting error is less than 0.2 percent.

For a well designed venturi, the constant C_v is about 0.98 for pipe diameters of 2 to 8 inch and about 0.99 for larger sizes.

In a properly designed venturi meter, the permanent pressure loss is about 10% of the venturi differential (p_a - p_b), and 90% of differential is recovered.

Volumetric flow rate:

The velocity through the venturi throat v_b usually is not the quantity desired. The flow rates of practical interest are the mass and volumetric flow rates through the meter.

Volumetric flow rate is calculated from,

$Q = A_b v_b$ and mass flow rate from,

Mass flow rate = volumetric flow rate x density = $\rho A_b v_b$

Example :

A horizontal venturi meter having a throat diameter of 4 cm is set in a 10 cm I.D. pipeline. Water flows through the system and the pressure differential across the venturi meter is measured by means of a simple U-tube manometer filled with mercury. Estimate the flow rate when the manometer reading is 30 cm. Assume $C_v = 0.98$. If 10% of the pressure differential is permanently lost, calculate the power consumption of the meter.
Data:
Dia of pipe (D_a) = 10 cm = 0.1 m
Dia of throat (D_b) = 4 cm = 0.04 m
Manometer reading (h_m) = 30 cm of Hg
Venturi coefficient (C_v) = 0.98
Permanent pressure loss = 10 % of the pressure differential measured by the manometer.
$\rho_m = 13.6\ g/cc = 13.6 \times 10^3\ kg/m^3$
$\rho = 1\ g/cc = 1000\ kg/m^3$

Formulae:

Flow rate = Velocity at the throat x cross sectional area of throat

Velocity at the throat

$$v_b = \frac{1}{\sqrt{1-\beta^4}} \sqrt{\frac{2(p_a - p_b)}{\rho}}$$

Where $\beta = D_b / D_a$
The pressure difference measured by the manometer
$P_a - P_b = (\rho_m -)gh_m$

Power consumption of the meter = volumetric flow rate x permanent pressure loss

Calculations:
$P_a - P_b = (13600 - 1000) \times 9.812 \times 0.3 = 37089.4\ N/m^2$

$\beta = 0.04/0.1 = 0.4$

$V_b = (0.98/(1-0.4^4)^{0.5}) \times (2 \times 37089.4 / 1000)^{0.5} = 0.993 \times 8.613 =$ **8.553 m/sec**

Cross sectional area of throat = $\pi D_b^2/4 = \pi \times 0.04^2 / 4 = 0.00126\ m^2$

Volumetric flow rate = 8.553 x 0.00126 = 0.01078 m^3/sec = **10.78 lit/sec**

Permanent pressure loss = 0.1 x 37089.4 = 3708.94 N/m^2

Power consumption of the meter = 0.01078 x 3708.94 = **40 watt** (1w =1j/sec 1N =1j/M)

Advantages of Venturi Meter:

(1) Low permanent pressure loss
(2) High pressure recovery
(3) High accuracy over wick range
(4) For Compressible and Incompressible fluid it is used.

Disadvantages of Venturi Meter:

(1) Expensive and Bulky.
(2) Considerable Space is occupied.
(3) Relative complex construction.
(4) Ratio of throat to pipe diameter cannot be changed.
(5) Not suitable for highly viscous slurries.

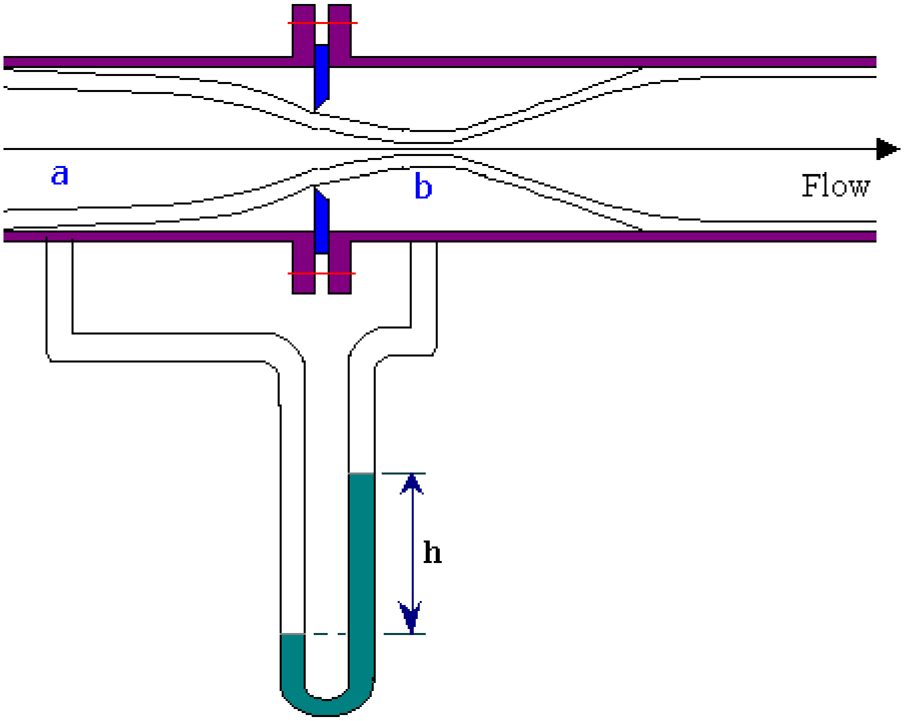
Orifice Meter

orifice meter is also variable head meter.

The Venturi meter has certain practical disadvantages for ordinary plant practice. It is expensive, it occupies considerable space, and its ratio of throat diameter cannot be changed. For a given meter and manometer system, the maximum measurable flow rate is fixed, so if the flow range is changed the throat diameter may be too large to give an accurate reading or too small to accommodate the next maximum flow rate. The Orifice meter meets these objectives to the Venturi but at the price of larger power consumption. A standard sharp-edged Orifice as in Figure.

The orifice meter consists of a flat orifice plate with a circular hole drilled in it. There is a pressure tap upstream from the orifice plate and another just downstream. There are three recognized methods of placing the taps. And the coefficient of the meter will depend upon the position of taps.

The principle of the orifice meter is identical with that of the venturi meter. The reduction of the cross section of the flowing stream in passing through the orifice increases the velocity head at the expense of the pressure head, and the reduction in pressure between the taps is measured by a manometer. Bernoulli's equation provides a basis for correlating the increase in velocity head with the decrease in pressure head.



It consists of an accurately machined and drilled plate mounted between two flanges with the hole concentric with the pipe in which it is mounted. Pressure taps, one above and one below the Orifice plate are installed and are connected to a manometer. Positions of the taps are arbitrary and the coefficient of the meter will depend upon the position of the taps.

- Types of Manometer tapping for Orifice Meter:
  - i. Vena Contracta
  - ii. Flanged Type Tappings
  - iii. Pipe type Tappings

$$v_b = \frac{Co}{\sqrt{1-\beta^4}}\sqrt{\frac{2(Pa-Pb)}{\rho}}$$

Where, V_b = Velocity through the orifice
β = Ratio of orifice diameter to pipe diameter = D_b/D_a
P_a and P_b = Pressures at stations a and b

The volumetric is given by
$Q = A_b v_b$

And Mass Flow rate $m = Q\rho$

Venturi meter - Orifice meter Comparison

In comparing the venturi meter with the orifice meter, both the cost of installation and the cost of operation must be considered.

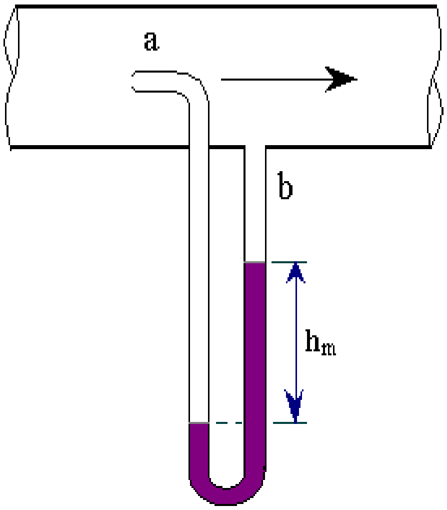
1. The orifice plate can easily be changed to accomodate widely different flow rates, whereas the throat diameter of a venturi is fixed, so that its range of flow rates is circumscribed by the practical limits of ⍰p.
2. The orifice meter has a large permanent loss of pressure because of the presence of eddies on the downstream side of the orifice-plate; the shape of the venturi meter prevents the formation os these eddies and greatly reduces the permanent loss.
3. The orifice is cheap and easy to install. The venturi meter is expensive, as it must be carefully proportioned and fabricated. A home made orifice is often entirely satisfactory, whereas a venturi meter is practically always purchased from an instrument dealer.
4. On the other hand, the head lost in the orifice for the same conditions as in the venturi is many times greater. The power lost is proportionally greater, and, when an orifice is inserted in a line carrying fluid continuously over long periods of time, the cost of the power may be out of all proportion to the saving in first cost. Orifices are therefore best used for testing purposes or other cases where the power lost is not a factor, as in steam lines.
5. However, in spite of considerations of power loss, orifices are widely used, partly because of their greater flexibility, because installing a new orifice plate with a different opening is a simpler matter. The venturi meter cannot be so altered. Venturi meters are used only for permanent installations.
6. Advantages of Orifice Meter:
    (1) Simple Construction
    (2) Can be installed and replaced easily
    (3) All different Pressure Permits.
    (4) Relatively Cheap
    (5) Ratio of throat diameter to pipe diameter can be changed.

7. Disadvantages of Orifice Meter:
    (1) Substantial loss in pressure
    (2) Higher Power Consumption
    (3) Can not be used for skimmed.
    (4) Should have straight pipe without fittings.

8. Pressure Recovery:

Because of the large friction losses from the eddies generated by the re expanding jet below the Vena Contracta, the pressure recovery in an Orifice meter is poor. The resulting power loss is one disadvantages of the Orifice meter.

Pitot tube



The pitot tube is a device to measure the local velocity along a streamline. The pitot tube has two tubes: one is static tube(b), and another is impact tube(a). The opening of the impact tube is perpendicular to the flow direction. The opening of the static tube is parallel to the direction of flow. The two legs are connected to the legs of a manometer or equivalent device for measuring small pressure differences. The static tube measures the static pressure, since there is no velocity component perpendicular to its opening. The impact tube measures both the static pressure and impact pressure (due to kinetic energy). In terms of heads the impact tube measures the static pressure head plus the velocity head.

The reading (h_m) of the manometer will therefore measure the velocity head, and

Pressure difference indicated by the manometer Δp is given by,

$\Delta p = h_m(\rho_m - \rho)g$

$$v = \sqrt{2\frac{h_m(\rho_m - \rho)g}{\rho}}$$

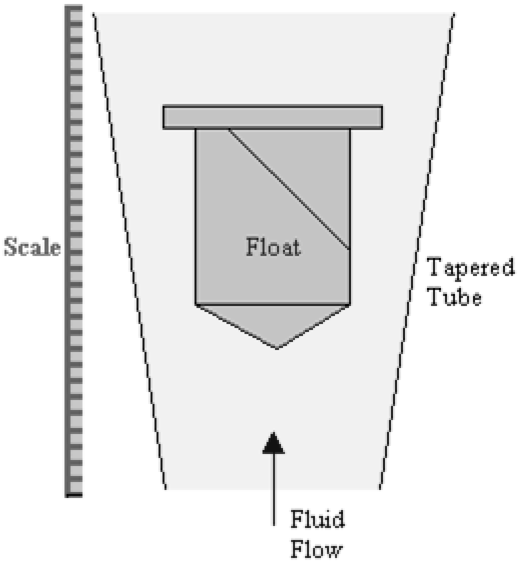
The Disadvantages of the Pitot tube are that,

1. Most designs do not give the average velocity directly.
2. That its readings for gases are extremely small when it is used for measuring low-pressure gases. Some form of multiplying gauge like that of inclined tube Manometer must also be used.

(II) Area Meters:

A. Rotameters:

In Orifice and Venturi the variation flow rate through a constant area generates a variable pressure drop, which, is related to the flow rate.



another class of meters called Area Meters consists of devices in which the pressure drop is constant or nearly so, and the area through which the fluid flow varies with flow rate. The area is related through proper calibration to the flow rate.

Rotameter is most important of them. It consists of a gradually tapered glass tube mounted vertically in a flame with the large end up. The fluid flows upward through the tapered tube and suspended freely a float (which actually does not float but is completely submerged in the fluid). The float is the indicating element, and greater the flow rate, the higher the float rides in the tube. The entire fluid stream must flow through the annular space between the float and tube wall. The tube is marked in proper dimensions and the reading of the mater is obtained from the scale reading at the reading edge of the float, which is taken at the largest cross section of the float.

Floats may be constructed of metals of various densities from lead to Aluminum or from glass or plastic. Stainless Steel floats are common. Float shapes and proportions are also varied for different applications. For a given flow rate, the equilibrium position of the float in a rotameter is established by a balance of three forces:

(1) The height of the float,
(2) The buoyancy force of the fluid on the float,
(3) The drag force on the float.

Rotameters can be used for either liquid or gas flow measurement.

Transportation of Fluids

What is the function of the pump?

A pump is a machine for raising a liquid - a relatively **incompressible** fluid - to a higher level of pressure or head. Pumps are used to transport fluids from one location to the other through pipelines.

- Pumps are essential to process facility operation
- Challenge: Process facilities rely heavily on pump operation. For example, a 250,000 barrel per day refinery likely has about 200 pumps in uses ranging from crude unit feed to downstream applications.
- Failures cause an estimated 0.2% production loss, and pump repairs consume 7% of the maintenance budget.
- Unanticipated pump failures cause facility slowdowns or shutdowns.

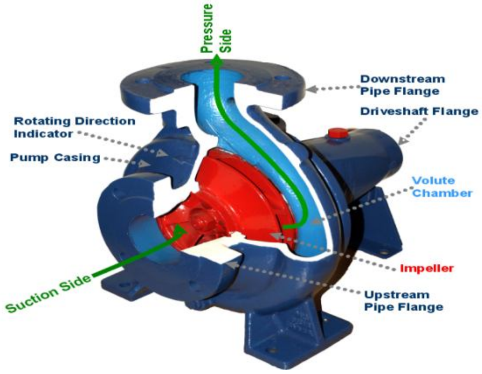
They can also lead to safety and environmental incidents or fires that bring negative publicity and more frequent agency audits as well as remediation costs and fines

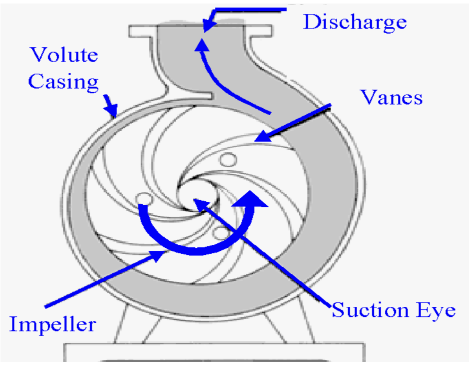
Centrifugal Pumps

Introduction

The operating manual of any centrifugal pump often starts with a general statement,

“Your centrifugal pump will give you completely trouble free and satisfactory service only on the condition that it is installed and operated with due care and is properly maintained”

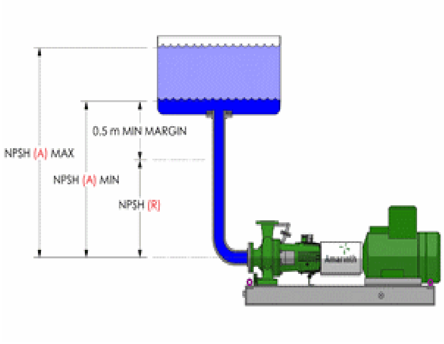




- A centrifugal pump is one of the simplest pieces of equipment in any process plant.
- Its purpose is to convert energy of a prime mover (a electric motor or turbine) first into velocity or kinetic energy and then into pressure energy of a fluid that is being pumped.
- The energy changes occur by virtue of two main parts of the pump, the impeller and the volute or diffuser.
- The impeller is the rotating part that converts driver energy into the kinetic energy.

- The volute or diffuser is the stationary part that converts the kinetic energy into pressure energy.

Note: All of the forms of energy involved in a liquid flow system are expressed in terms of feet(or Meter) of liquid i.e. head.



(NPSH (R) or NPSH required
The Net Positive Suction Head (NPSH) is the total head at the suction flange of the pump less the vapor pressure converted to fluid column height of the liquid.
(NPSH (R) *is a function of pump design*

Net Positive Suction Head available(NPSHa)
Net Positive Suction Head Available is a function of the system in which the pump operates. It is the excess pressure of the liquid in feet absolute over its vapor pressure as it arrives at the pump suction, to be sure that the pump selected does not cavitate. It is calculated based on system or process conditions
(NPSHa) > NPSHr

Pump Cavitation:

- Pump cavitation occurs when the pressure in the pump inlet drops below the vapor pressure of the liquid
- Cavitations' is the formation of vapour cavities in a liquid – i.e. small liquid-free zones ("bubbles" or "voids") – that are the consequence of forces acting upon the liquid. It usually occurs when a liquid is subjected to rapid changes of pressure that cause the formation of cavities where the pressure is relatively low. When subjected to higher pressure, the voids implode and can generate an intense shockwave.
- Cavitation is a significant cause of wear in some engineering contexts. Collapsing voids that implode near to a metal surface cause cyclic stress through repeated implosion. This results in surface fatigue of the metal causing a type of wear also called "cavitation". The most common examples of this kind of wear are to pump impellers, and bends where a sudden change in the direction of liquid occurs.
- Loud noise often described as a grinding or “marbles” in the pump

There three indicators for cavitaion.

- Noise,
- capacity loss, and
- Pitting

Direct measurement
not only helps to confirm your suspicions, but also let’s you know what your true NPSHA is.

- Install a compound gauge (one that measures both vacuum as well as light positive gauge pressures) *into the suction port of the pump (or as close as you can in the suction piping).*
- *When the pump is running, the reading from this gauge will be equal to your NPSHA,*

If after subtracting vapor pressure, this value is less than the pump's NPSHR, you have confirmed that this is a cavitation problem.

NPSH$_A$ Calculation:

The formula for calculating NPSHA:
NPSHA = HA ± HZ - HF + HV – HVP

Term Definition Notes

HA	The absolute pressure on the surface of the liquid in the supply tank	• Typically atmospheric pressure (vented supply tank), but can be different for closed tanks. • Don't forget that altitude affects atmospheric pressure • Always positive (may be low, but even vacuum vessels are at a positive absolute pressure)
HZ	The vertical distance between the surface of the liquid in the supply tank and the centerline of the pupm	• Can be positive when liquid level is above the centerline of the pump (called static head) • Can be negative when liquid level is below the centerline of the pump (called suction lift) • Always be sure to use the lowest liquid level allowed in the tank.
HF	Friction losses in the suction piping	• Piping and fittings act as a restriction, working against liquid as it flows towards the pump inlet.
HV	Velocity head at the pump suction port	Often not included as it's normally quite small.
HVP	Absolute vapor pressure of the liquid at the pumping temperature	• Must be subtracted in the end to make sure that the inlet pressure stays above the vapor pressure. • Remember, as temperature goes up, so does the vapor pressure

Energy useage:

The energy usage in a pumping installation is determined by the flow required, the height lifted and the length and friction characteristics of the pipeline. The power required to drive a pump (P_i), is defined simply using SI units by:

$$P_i = \frac{\rho \; g \; H \; Q}{\eta}$$

where:

P_i is the input power required (W)

ρ is the fluid density (kg/m^3)

g is the standard acceleration of gravity (9.80665 m/s^2)

H is the energy Head added to the flow (m)
Q is the flow rate (m^3/s)
η is the efficiency of the pump plant as a decimal

The head added by the pump (H) is a sum of the static lift, the head loss due to friction and any losses due to valves or pipe bends all expressed in metres of fluid. Power is more commonly expressed as kilowatts (10^3 W, kW) or horsepower (kW = hp*0.746). The value for the pump efficiency, η_{pump}, may be stated for the pump itself or as a combined efficiency of the pump and motor system.

energy usage is determined by multiplying the power requirement by the length of time the pump is operating

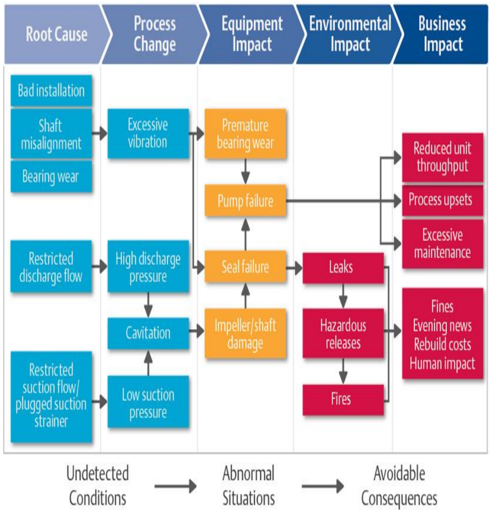
Trouble free Operations

- Two Basic Requirements for Trouble-Free Operation of Centrifugal Pumps requirements that have to be met at all the times for a trouble free operation and longer service life of centrifugal pumps.
- The first requirement is that no cavitation of the pump occurs throughout the broad operating range and
- the second requirement is that a certain minimum continuous flow is always maintained during operation

Difficulties with Centrifugal Pumps

These are some difficulties faced in centrifugal pumps:

- There are a number of unfavorable conditions which may occur separately or simultaneously when the pump is operated at reduced flows. Some include:
- Cases of heavy leakages from the casing, seal, and stuffing box
- Deflection and shearing of shafts
- Seizure of pump internals
- Close tolerances erosion
- Separation cavitation
- Product quality degradation
- Excessive hydraulic thrust
- Premature bearing failures

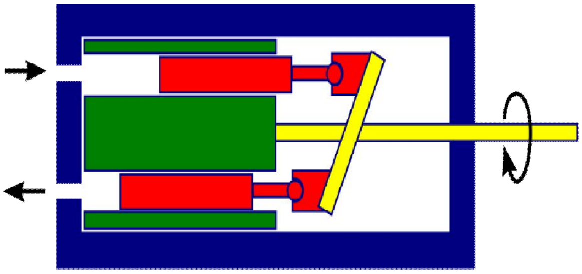


Reciprocating Pump:

A **reciprocating pump** is a positive plunger pump It is often used where relatively small quantity of liquid is to be handled and where delivery pressure is quite large.

Classification
Reciprocating pumps can be classified based on
1. Sides in contact with water
    a) Single acting Reciprocating pump
    b) Double acting reciprocating pump
2. Numbers of cylinder used
    a) Single cylinder pump
    b) Two cylinder pumps
    c) Multi-cylinder pumps

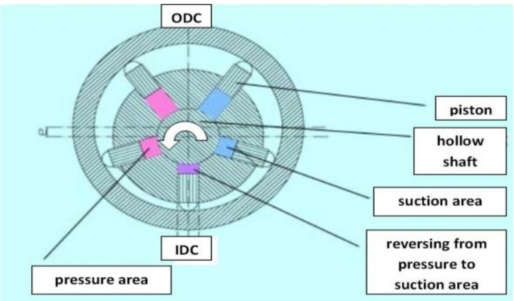
Axial Displacement Pump



An axial piston pump has a number of pistons (usually an odd number) arranged in a circular array within a *housing* which is commonly referred to as a *cylinder block*, *rotor* or *barrel*. This cylinder block is driven to rotate about its axis of symmetry by an integral shaft that is, more or less, aligned with the pumping pistons (usually parallel but not necessarily).

Radial Piston Pump

A **radial piston pump** is a form of hydraulic pump The working pistons extend in a radial direction symmetrically around the drive shaft, in contrast to the axial piston pump



The general mode of operation will be explained at the movement of one pumping piston by means of picture 1:
The outer ring for bracing of the pumping pistons is in eccentric position to the hollow shaft in the center. This eccentricity determines the stroke of the pumping piston.

The piston starts in the inner dead center (IDC) with suction process. After a rotation angle of 180° it is finished and the workspace of the piston is filled with the to moved medium. The piston is now in the outer dead center (ODC). From this point on the piston displaces the previously sucked medium in the pressure channel of the pump.

Industrial Fans And Blowers

Blowers

A blower is a machine for moving volumes of a gas with **moderate increase of pressure**.

Fans

A fan moves large amounts of gas with low increase in pressure.

Industrial fans and blowers are machines whose primary function is to provide a large flow of air or gas to various processes of many industries. This is achieved by rotating a number of blades, connected to a hub and shaft, and driven by a motor or turbine. The flow rates of these fans range from approximately 200 to 2,000,000 cubic feet (5.7 to 57000 cubic meters) per minute.

A **blower** is another name for a fan that operates where the resistance to the flow is primarily on the downstream side of the fan.

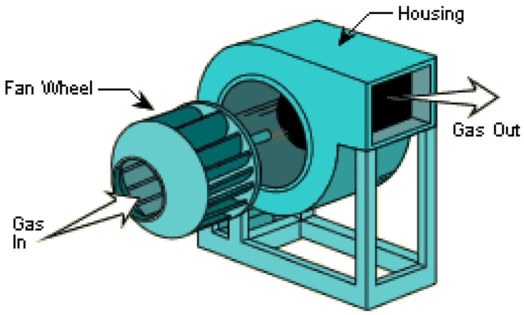
Function:

There are many uses for the continuous flow of air or gas that industrial fans generate, including combustion, ventilation, aeration, particulate transport, exhaust, cooling, air-cleaning, and drying, to name a few. The industries served include electrical power production, pollution control, metal manufacturing and processing, cement production, mining, petrochemical, food processing, cryogenics, and clean rooms.

Centrifugal and Axial Fans :

Most industrial fans may be categorized into one of two general types: centrifugal fans and axial fans.

Centrifugal Fans:



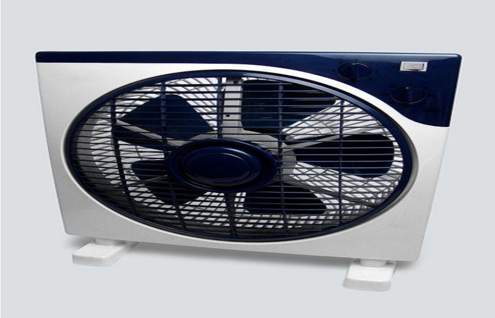
The centrifugal design uses the centrifugal force generated by a rotating disk, with blades mounted at right angles to the disk, to impart movement to the air or gas and increase its pressure.

The assembly of the hub, disk and blades is known as the fan wheel, and often includes other components with aerodynamic or structural functions.

The centrifugal fan wheel is typically contained within a scroll-shaped fan housing, resembling the shell of the nautilus sea creature with a central hole. The air or gas inside the spinning fan is thrown off the outside of the wheel, to an outlet at the housing's largest diameter. This simultaneously draws more air or gas into the wheel through the central hole. Inlet and outlet ducting are often attached to the fan's housing, to supply and/or exhaust the air or gas to the industry's requirements.

There are many varieties of centrifugal fans, which may have fan wheels that range from less than a foot (0.3 meters) to over 16 feet (5 m) in diameter.

Axial fans



The axial design uses axial forces to achieve the movement of the air or gas, spinning a central hub with blades extending radially from its outer diameter. The fluid is moved parallel to the fan wheel's shaft, or axis of rotation. The axial fan wheel is often contained within a short section of cylindrical ductwork, to which inlet and outlet ducting can be connected.

Axial fan types have fan wheels with diameters that usually range from less than a foot (0.3 meters) to over 30 feet (9 m), although axial cooling tower fan wheels may exceed 82 feet (25 m) in diameter.

In general, axial fans are used where the principal requirement is for a large volume of flow, and the centrifugal design where both flow and higher pressures are required.

Compressors

A compressor is a machine for raising a gas - a **compressible** fluid - to a higher level of pressure.

The three basic types of air compressors are

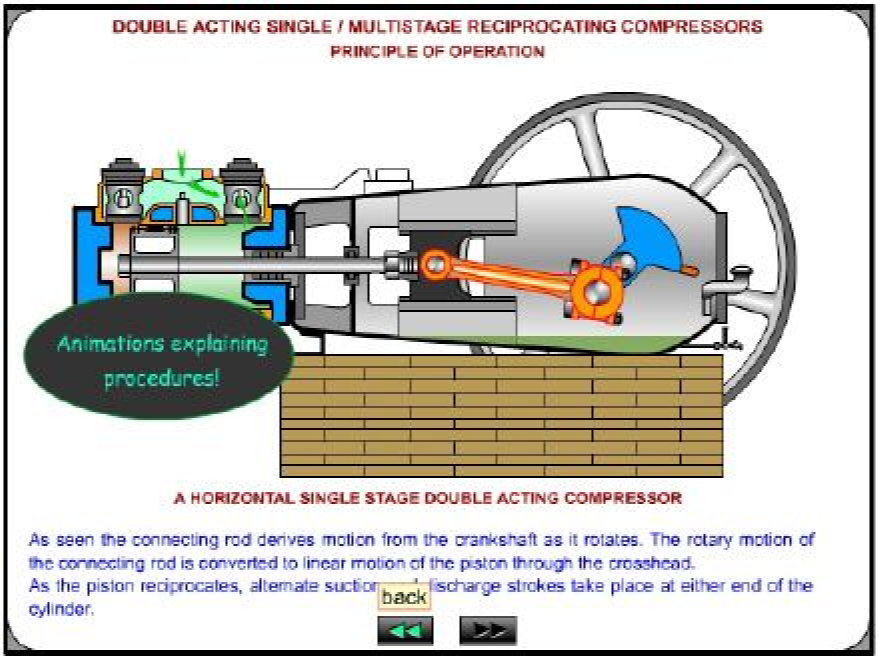
- reciprocating
- rotary screw
- rotary centrifugal

These types are further specified by:

- the number of compression stages
- cooling method (air, water, oil)
- drive method (motor, engine, steam, other)
- lubrication (oil, Oil-Free where Oil Free means no lubricating oil contacts the compressed air)
- packaged or custom-built

Reciprocating Air Compressors

Reciprocating air compressors are positive displacement machines, meaning that they increase the pressure of the air by reducing its volume. This means they are taking in successive volumes of air which is confined within a closed space and elevating this air to a higher pressure. The reciprocating air compressor accomplishes this by a piston within a cylinder as the compressing and displacing element.



DOUBLE ACTING SINGLE / MULTISTAGE RECIPROCATING COMPRESSORS
PRINCIPLE OF OPERATION

A HORIZONTAL SINGLE STAGE DOUBLE ACTING COMPRESSOR

As seen the connecting rod derives motion from the crankshaft as it rotates. The rotary motion of the connecting rod is converted to linear motion of the piston through the crosshead.
As the piston reciprocates, alternate suctio [illegible] ischarge strokes take place at either end of the cylinder.

Single-stage and two-stage reciprocating compressors are commercially available.

- Single-stage compressors are generally used for pressures in the range of *70 psig to 100 psig*.
- Two-stage compressors are generally used for higher pressures in the range of *100 psig to 250 psig.*

Note that *1 HP ~ 4 CFM at 100 psi* and that *1 to 50 HP* are typically for reciprocating units. Compressors *100 hp* and above are typically Rotary Screw or Centrifugal Compressors.

The reciprocating air compressor is **single acting** when the compressing is accomplished using only one side of the piston. A compressor using both sides of the piston is considered **double acting**.

Load reduction is achieved by unloading individual cylinders. Typically this is accomplished by throttling the suction pressure to the cylinder or bypassing air either within or outside the compressor. Capacity control is achieved by varying speed in engine-driven units through fuel flow control.

Reciprocating air compressors are available either as air-cooled or water-cooled in lubricated and non-lubricated configurations and provide a wide range of pressure and capacity selections.

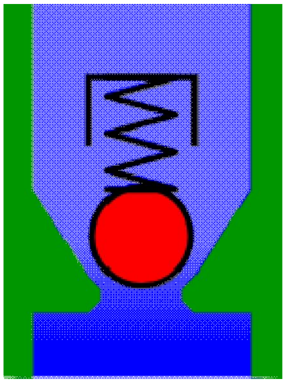
Reciprocating air compressors are available either as air-cooled or water-cooled in lubricated and non-lubricated configurations and provide a wide range of pressure and capacity selections.

Valves

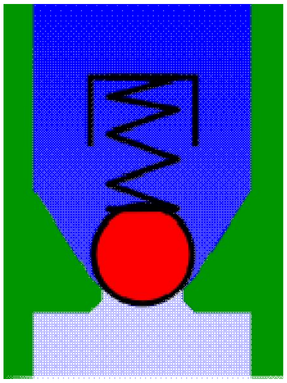
Valves can be categorized into the following basic Types

- Ball valve, for on/off control without pressure drop, and ideal for quick shut-off, since a 90° turn offers complete shut-off angle, compared to multiple turns required on most manual valves.
- Butterfly valve for flow regulation in large pipe diameters.
- Ceramic Disc valve used mainly in high duty cycle applications or on abrasive fluids. Ceramic disc can also provide Class IV seat leakage
- Check valve or non-return valve, allows the fluid to pass in one direction only.
- Choke valve, a valve that raises or lowers a solid cylinder which is placed around or inside another cylinder which has holes or slots. Used for high pressure drops found in oil and gas wellheads.
- Diaphragm valve, which controls flow by a movement of a diaphragm. Upstream pressure, downstream pressure, or an external source (e.g., pneumatic, hydraulic, etc.) can be used to change the position of the diaphragm.
- Gate valve, mainly for on/off control, with low pressure drop.
- Globe valve, good for regulating flow.
- Knife valve, similar to a gate valve, but usually more compact. Often used for slurries or powders on/off control.
- Needle valve for accurate flow control.
- Pinch valve, for slurry flow regulation.
- Piston valve, for regulating fluids that carry solids in suspension.
- Plug valve, slim valve for on/off control but with some pressure drop.
- Spool valve for hydraulic control
- Thermal expansion valve, used in refrigeration and air conditioning systems.
- Pressure Reducing Valve
- Sampling valves
- Safety valve

Check Valve:



Open position



Close Position

A **check valve**, **clack valve**, **non-return valve** or **one-way valve** is a valve that normally allows fluid (liquid or gas) to flow through it in only one direction.

Check valves are two-port valves, meaning they have two openings in the body, one for fluid to enter and the other for fluid to leave. There are various types of check valves used in a wide variety of applications.

Check valves work automatically and most are not controlled by a person or any external control; accordingly, most do not have any valve handle or stem. The bodies (external shells) of most check valves are made of plastic or metal.

An important concept in check valves is the **cracking pressure** which is the minimum upstream pressure at which the valve will operate. Typically the check valve is designed for and can therefore be specified for a specific cracking pressure.

Some of the Types of check Valves:

- Diaphragm Check Valve
- Swing or tilting Disc Check Valve
- Stop Check Valve
- Lift Check Valve

Applications:

Pumps:

Check valves are often used with some types of pumps. Piston-driven and diaphragm pumps such as metering pumps and pumps for chromatography commonly use inlet and outlet ball check valves. These valves often look like small cylinders attached to the pump head on the inlet and outlet lines. Many similar pump-like mechanisms for moving volumes of fluids around use check valves such as ball check valves. The feed pumps or injectors which supply water to steam boilers are fitted with check valves to prevent back-flow.

Industrial processes

Check valves are used in many fluid systems such as those in chemical and power plants, and in many other industrial processes.

Check valves are also often used when multiple gases are mixed into one gas stream. A check valve is installed on each of the individual gas streams to prevent mixing of the gases in the original source. For example, if a fuel and an oxidizer are to be mixed, then check valves will normally be used on both the fuel and oxidizer sources to ensure that the original gas cylinders remain pure and therefore nonflammable.

Needle Valve:

A **needle valve** is a type of valve having a small port and a threaded, needle-shaped plunger. It allows precise regulation of flow, although it is generally only capable of relatively low flow rates.

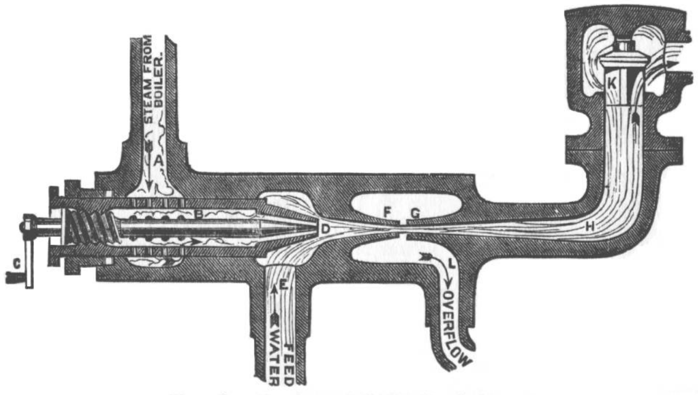


FIG. 6.— *Section of Giffard's Injector.*

A -
B -
C - Steam needle valve handle
D - Steam and water combine here
E Water feed pipe
F - Combining cone
G - Delivery nozzle & cone
H - delivery chamber & pipe
K - Check valve
L - overflow

Needle valves are usually used in flow metering applications, especially when a constant, calibrated, low flow rate must be maintained for some time, such as the idle fuel flow in a carburetor

Since flow rates are low and many turns of the valve stem are required to completely open or close, needle valves are not used for simple shutoff applications.

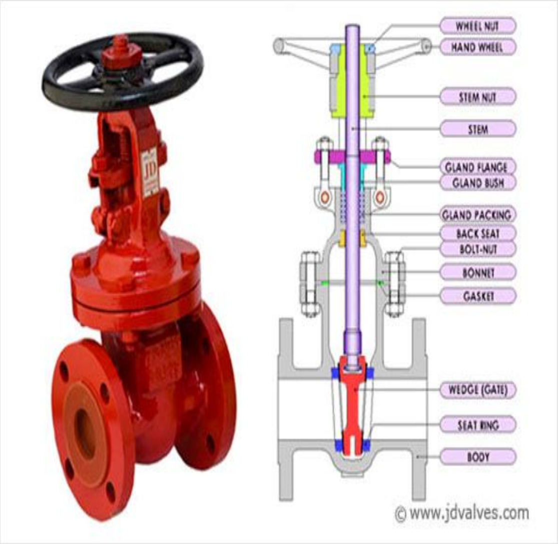
Since the orifice is small and the force advantage of the fine-threaded stem is high, needle valves are usually easy to shut off completely, with merely "finger tight" pressure. The spindle and/or seat of a needle valve, especially one made from brass are easily damaged by excessive turning force when shutting off the flow.

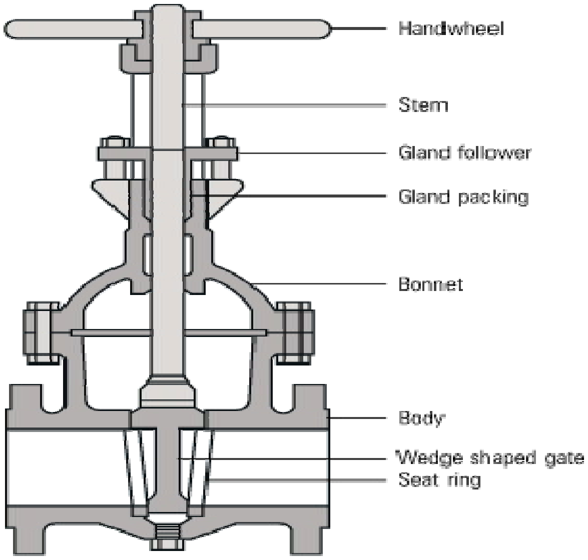
Small, simple needle valves are often used as bleed valves in hot water heating applications.

Unlike a ball valve or valves with a rising stem, it is not easy to tell from examining the handle position whether the valve is open or closed

Gate valve:

The **gate valve**, also known as a **sluice valve**, is a valve that opens by lifting a round or rectangular gate/wedge out of the path of the fluid. The distinct feature of a gate valve is the sealing surfaces between the gate and seats are planar, so gate valves are often used when a straight-line flow of fluid and minimum restriction is desired.





The gate faces can form a wedge shape or they can be parallel. Gate valves are primarily used to permit or prevent the flow of liquids, but typical gate valves shouldn't be used for regulating flow, unless they are specifically designed for that purpose. Because of their ability to cut through liquids, gate valves are often used in the petroleum industry. For extremely thick fluids, a specialty valve often known as a **knife valve** is used to cut through the liquid.

On opening the gate valve, the flow path is enlarged in a highly nonlinear manner with respect to percent of opening. This means that flow rate does not change evenly with stem travel. Also, a partially open gate disk tends to vibrate from the fluid flow. Most of the flow change occurs near shutoff with a relatively high fluid velocity causing disk and seat wear and eventual leakage if used to regulate flow.

Typical gate valves are designed to be fully opened or closed. When fully open, the typical gate valve has no obstruction in the flow path, resulting in very low friction loss.

Gate valves are characterized as having either a rising or a nonrising stem.

Rising stems provide a visual indication of valve position because the stem is attached to the gate such that the gate and stem rise and lower together as the valve is operated.

Nonrising stem valves may have a pointer threaded onto the upper end of the stem to indicate valve position, since the gate travels up or down the stem on the threads without raising or lowering the stem. Nonrising stems are used underground or where vertical space is limited.

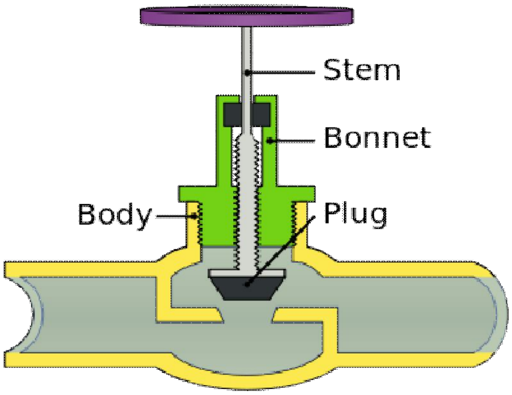
Bonnets provide leak proof closure for the valve body. Gate valves may have a screw-in, union, or bolted bonnet. Screw-in bonnet is the simplest, offering a durable, pressure-tight seal. Union bonnet is suitable for applications requiring frequent inspection and cleaning. It also gives the body added strength. Bolted bonnet is used for larger valves and higher pressure applications.

Another type of bonnet construction in a gate valve is **pressure seal bonnet**. This construction is adopted for valves for high pressure service, typically in excess of 15 MPa (2250 psi). The unique feature about the pressure seal bonnet is that the body - bonnet joints seals improves as the internal pressure in the valve increases, compared to other constructions where the increase in internal pressure tends to create leaks in the body-bonnet joint.

Gate valves may have flanged ends which are drilled according to pipeline compatible flange dimensional standards.

Gate valves are typically constructed from cast iron ductile iron, cast carbon steel, gun metal, stainless steel, alloy steels, and forged steels.

Globe Valve



A **globe valve**, different from ball valve is a type of valve used for regulating flow in a pipeline consisting of a movable disk-type element and a stationary ring seat in a generally spherical body.[

Globe valves are named for their spherical body shape with the two halves of the *body* being separated by an internal baffle This has an opening that forms a *seat* onto which a movable *plug* can be screwed in to close (or shut) the valve. The plug is also called a *disc* or *disk*. In globe valves, the plug is connected to a *stem* which is operated by screw action using a hand wheel in manual valves. Typically, automated globe valves use smooth stems rather than threaded and are opened and closed by an actuator assembly.

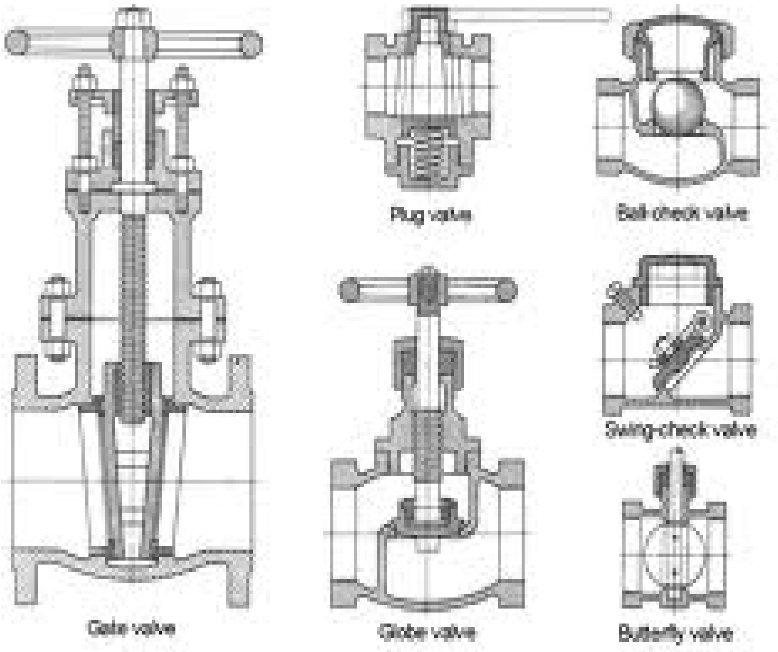


FIG. 10 Valves. The sectional drawings show their construction.

1. INTRODUCTION

In chemical engineering and related fields, a **unit operation** is a basic step in a process. The different chemical industries were regarded as different industrial processes and with different principles. Arthur Dehon Little proposed the concept of "unit operations" to explain industrial chemistry processes in 1916. In 1923, William H.Walker, Warren K. Lewis and William H. McAdams wrote the book *The Principles of Chemical Engineering* and explained the variety of chemical industries have processes which follow the same physical laws. They summed-up these similar processes into unit operations. Each unit operation follows the same physical laws and may be used in all chemical industries. The unit operations form the fundamental principles of chemical engineering.

Chemical engineering unit operations consist of mainly five classes:

Fluid flow operations- like fluids transportation and solids fluidization

Heat transfer operations - like evaporation and condensation

Mass transfer operations -like gas absorption, distillation, extraction, adsorption, drying

Thermodynamic operations -like gas liquefaction and refrigeration

Mechanical operations - like solids transportation, crushing and pulverization, screening and sieving, filtration

Introduction of Mechanical – Physical Separation

- These mechanical- physical forces will be acting on particle, liquids or mixtures of particles and liquids themselves and not necessarily on the individual molecules.
- The mechanical-physical forces include
  - Gravitational force
  - Centrifugal force

  - actual mechanical and kinetic forces arising from flow.

Classification of Mechanical-Physical separation process

- Size Reduction
- Screening
- Size Enlargement
- Filtration
- Sedimentation

Industrial Application: Mechanical-Physical process

- Cement Industries : Size Reduction, Screening, Sedimentation
- Pharma Industries : Size Enlargement, Filtration, Agitation and mixing
- Paints, Dyes and Intermediates : Agitation and mixing Size Reduction, Filtration
- Coal Mines : Jigging, Screening, Size Reduction
- Food and Food Processing : Size Reduction,Enlargement,
- Plastic and Rubber Industries: Size Reduction, Pneumatic
- conveying, Screening, Agitation and Mixing
- Sugar and Starch Industries: Size Reduction, Filtration, Sedimentation, Screening
- Fertilizer Industries: Filtration, Size Reduction ,Storage and Conveying of Solid

Solid- Solid Separeation: Screening Operations

Screening is used for a variety of operations including cleaning, and removal of solids from liquids. This topic discusses screening from the viewpoint of the separation of solids with a variety of sizes into two or more fractions each with less size variation.

- **Screening terminology**

(a) Undersize : fines or minus (-) material, material passing through a given screen

(b) Oversize : tails or plus (+) material, material retained on a given screen

(c) Screen aperture : the space between two nearest parallel wires of a screen mesh.

(d) Mesh Number : Screens are denoted by mesh number . It is number of square opening per linear inch.

(e) Screen interval : It is relationship between successively decreasing openings in a standard screen series. In the **Tyler Standard** the ratio between screen apertures in successive screens is $2^{0.5}$, though at finer sizes a screen interval of $2^{0.25}$ is used. In **British Standards** and **American Society for Testing Materials**, the screen interval is $2^{0.25}$.

(f) Diameter of a sieve fraction : It is average diameter of the fraction passing one screen, but retained on the next larger screen. This is normally taken as the arithmetic average of the two screen apertures.

(g) Diameter of solid particles : It is defined as the particle dimension controlling its retention on a particular sized screen. Since particles are usually irregularly shaped, so an average diameter is used. A number of methods of measurement may be used. In practice, average particle diameter is often determined by sieve analysis, with a spherical shape assumed for the sake of calculation.

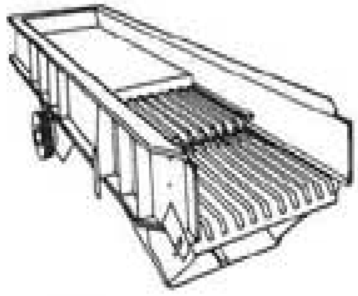
Method of Particle Size Measurement

Sieves or screens are used on a large scale for the separation of particles according to their sizes, and on a small scale for the production of closely graded materials in carrying out size analyses. The method is applicable for particles of a size as small as about 50 μm, but not for very fine materials because of the difficulty of producing accurately woven fine gauze of sufficient strength, and the fact that the screens become clogged. Woven wire cloth is generally used for fine sizes and perforated plates for the larger meshes. Some large industrial screens are formed either from a series of parallel rods or from H-shaped links bolted together, though square or circular openings are more usual.

Screens may be operated on both a wet or a dry basis. With coarse solids the screen surface may be continuously washed by means of a flowing stream of water which tends to keep the particles apart, to remove the finer particles from the surface of larger particles and to keep the screen free of adhering materials. Fine screens are normally operated wet, with the solids fed continuously as a suspension. Concentrated suspensions, particularly when flocculated, have high effective viscosities and frequently exhibit shear-thinning non-Newtonian characteristics. By maintaining a high cross-flow velocity over the surface of the screen, or by rapid vibration, the apparent viscosity of the suspension may be reduced and the screening rate substantially increased.

Types of Industrial Screen

(a) **Grizzlies or bar screens:** A Grizzly is a grid of parallel metal bars set in an inclined stationary frame, with a slope of 30-50^{0}.Consist of a set of parallel metal bars. The material of construction of the bars is manganese steel.It is Used for screening larger particles - greater than 25 mm. The bars are often wedge shaped to minimise clogging. They may be shaken mechanically or electromagnetically.



Grizzly Screen

Stationary Grizzlies: It is simplest type of grizzlies require less maintenance. It can handle dry material of ≥ 50 mm sizes. It is not suitable for moist or sticky material

Vibrating Grizzlies: are use an eccentric arrangement to impact length wise reciprocal movement which permit easy flow of material and prevent clogging.

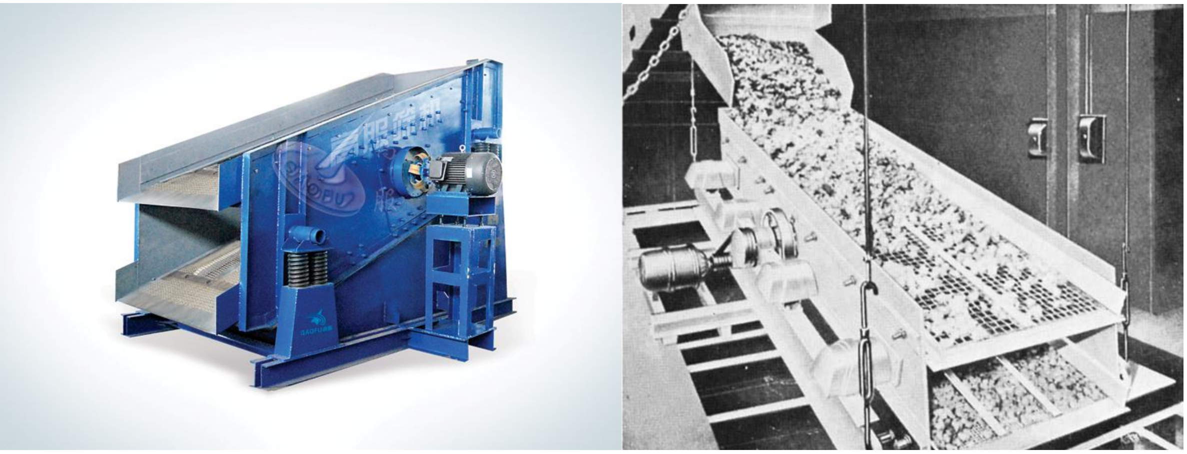
Flat Grizzllies are used above feed bins of coal and ores or below the unloading supports to retain large lumps.

Inclined Grizzlies maintain a slope of 20-50^0 with the horizontal

Chain grizzlies : the metal bars are replaced with endless chain passing over pully are used for handling sticky or clay-like material.

(b) Vibrating Screen

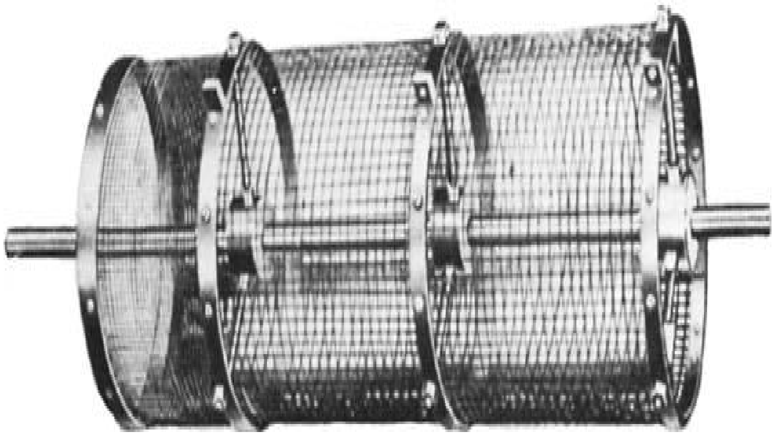
It is one of the most popular screen used in Chemical Process Industries (CPI) . It can handle large tonnage of material, posses high efficiency , provide good accuracy of sizing, require less maintainance per ton of material and also provide saving in space and weight. It can be mechanically vibrated using an eccentric which give a circular motion in the vertical plane and applicable for wide verity of material starting from 4 mesh to 325 mesh screen.



(c) Revolving Screen or Trommels

Trommels are revolving screens usually cylindrical or conical in shape,open at both ends and are mormally inclined at 5-10^0 with the horizontal .Trommels are rotated about their axis at around

15-20 rpm. It has relatively low capacity and low efficiency because at any time less surface area is used for screening operation. The material to be screened is fed in at the top and gradually moves down the screen and passes over apertures of gradually increasing size, with the result that all the material has to pass over the finest screen. Therefore there is a tendency for blockage of the apertures by the large material and for oversize particles to be forced through. Further, the relatively fragile fine screen is subjected to the abrasive action of the large particles. These difficulties are obviated to some extent by arranging the screens in the form of concentric cylinders, with the coarsest in the centre. The disadvantage of all screens of this type is that only a small fraction of the screening area is in use at any one time. The speed of rotation of the trommel should not be so high that the material is carried completely round in contact with the screening surface. The lowest speed at which this occurs is known as the critical speed and is analogous to the critical speed of the ball mill. Speeds of between one-third and a half of the critical speed are usually recommended. In a modified form of the trommel, the screen surfaces are in the form of truncated cones. Such screens are mounted with their axes horizontal and the material always flows away from the apex of the cone.



(d) Reciprocating Screen

It is used in CPI for handling materials down upto 325 mesh.They are driven by essentric under the screen at the feed end.The motion varies from gyratory at the feed end to reciprocating at the discharge end.The speed varies from 500-600 RPM.They are generally kept inclined at around 5^0

with the horizontal.It is Used for handling dry chemicals, light metal powders, powder food and granular materials but not suitable for handling heavy rock or gravel.

(e) Oscillating Screens

Oscillating screens are characterized by relatively low speed oscillations (300 to 400 per minute) in a plane parallel to the screen cloth. It is one of the cheapest type of industrial screen . It is widely used for batch screning of coarse material of 5 to 15 mm and fine , light , free flowing materials.

(f) Gyratory Screen

Gyratory screens are box like machines either square or round with series of screen clothes nested one upon the other.Eccentric impart oscillations in circular motion.

Factors affecting the efficiency of a screening system

(i) **Rate of feeding:** If feed rate is too high, there is insufficient residence time. The screen becomes overloaded, and some "fines" leave with the oversize.

(ii) **Particle size:** Large particles can impede the path of smaller ones, and a preliminary separation may be required if a high proportion of larger particles are present

(iii) **Moisture:** Moisture can cause adhesion of small particles to larger ones, so some undersize leave with the oversize

(iv) **Worn or damaged screens:** Oversize may fall through damaged areas

(v) **Blinding (clogging) of screens:** Particularly likely when the size of particles is very close to the screen aperture. Result can be undersize leaving with oversize.

Comparison of Ideal and Actual Screen

- An ideal screen would sharply separate the feed mixture in such a way that the smallest particle in the overflow would be just larger than the largest particle in the under flow.

- The ideal separation defines a cut diameter Dpc which makes the point of seperation between the undrsize and oversize fractions and is nearly equal to the opening of the screen
- Ideal screen yield sharp separation,whereas actual screen does not give sharp separation)
- Efficiency of the screen 100%(In reality it is less than 100%)
- Such screen do not found in practice

Size Reduction

- The method in which particles of solid are cut or broken into smaller pieces.
- Reduction of size of the solid from large size to coarse, fine , very fine or ultrafine particles depending upon the end applications
- It is required to
  - Increase the surface area of the solid and ultimately reactivity of the solid
  - Permits separation of unwanted ingredients by mechanical methods.
  - Reduces the bulk of fibrous materials for easy handling.

Mechanism of Size Reduction

(a) Compression: Particle disintegration by two rigid force.
Ex. Jaw Crusher, Nut Cracker

(b) Impact : Particle size reduced by a single rigid force. Ex. Hammer Mill, hammer

(c) Attrition : Arising from particles scraping against one another or against a rigid surface. Ex. Ball Mill, File

(d) Cutting: To give definite shape and size, Ex. Knife and Knife Cutter,

Energy Requirement for SR

- The energy consumed in SR equipment at much higher rate than would be predicted from the new surface area created, by a factor of about 1000.
- This lost energy is consumed in
  - Deforming the particle to its elastic limit
  - Compacting particles after fracture
  - Overcoming friction between particles
  - Elastically deforming milling surface
  - Deformation of fractured particles.
- This energy is dissipated as heat. There are also significant mechanical losses in the milling equipments.

Nature of Material to be crushed

The choice of a machine for a given crushing operation is influenced by the nature of the product required and the quantity and size of material to be handled. The more important properties of the feed apart from its size are as follows:

(a) Hardness.

- The hardness of the material affects the power consumption and the wear on the machine. With hard and abrasive materials it is necessary to use a low-speed machine and to protect the bearings from the abrasive dusts that are produced. Materials are arranged in order of increasing hardness in the *Mohr* scale in which the first four items rank as soft and the remainder as hard. The Mohr Scale of Hardness is:
- 1. Talc 2. Rock salt or gypsum 3. Calcite 4. Fluorspar (Soft material)
- 5. Apatite 6. Felspar 7. Quartz (Intermediate)
- 8. Topaz9. Carborundum10. Diamond (Hard)

(b) ***Structure***. Normal granular materials such as coal, ores and rocks can be effectively crushed employing the normal forces of compression, impact, and so on. With fibrous materials a tearing action is required.

(c) ***Moisture content***. It is found that materials do not flow well if they contain between about 5 and 50 per cent of moisture. Under these conditions the material tends to cake together in the form of balls. In general, grinding can be carried out satisfactorily outside these limits.

(d) ***Crushing strength***. The power required for crushing is almost directly proportional to the crushing strength of the material.

(e) ***Friability*****.** The friability of the material is its tendency to fracture during normal handling. In general, a crystalline material will break along well-defined planes and the power required for crushing will increase as the particle size is reduced.

(f) ***Stickiness*****:** A sticky material will tend to clog the grinding equipment and it should therefore be ground in a plant that can be cleaned easily.

(g) Explosive materials must be ground wet or in the presence of an inert atmosphere.

(h) Materials yielding dusts that are harmful to the health must be ground under conditions where the dust is not allowed to escape.

Methods of operating crushers

There are two distinct methods of feeding material to a crusher.

The first, known as ***free crushing***, involves feeding the material at a comparatively low rate so that the product can readily escape. Its residence time in the machine is therefore short and the production of appreciable quantities of undersize material is avoided.

The second method is known as ***choke feeding***. In this case, the machine is kept full of material and discharge of the product is impeded so that the material remains in the crusher for a longer period.This results in a higher degree of crushing, although the capacity of the machine is reduced and energy consumption is high because of the accumulated product. This method is therefore used only when a comparatively small amount of materials is to be crushed and when it is desired to complete the whole of the size reduction in one operation.

Open and Closed Circuit Grinding

If the plant is operated such a way that the material is passed only once through the equipment, the process is known as *open circuit grinding*.

If, on the other hand, the product contains material which is insufficiently crushed, it may be necessary to separate the product and return the oversize material for a second crushing. This system which is generally to be preferred, is known as *closed circuit grinding*.

Wet and Dry Grinding

- Grinding may be carried out either wet or dry, although wet grinding is generally applicable only with low speed mills.
- The advantages of wet grinding are:
  - (a) The power consumption is reduced by about 20–30 %.
  - (b) The capacity of the plant is increased.
  - (c) The amount of fines is reduced.
  - (d) Dust formation is eliminated.
  - (e) The solids are more easily handled.
- Against this, it may be necessary to dry the product.

Classification of SR Equipments

(a) Crusher (Coarse and fine) : Jaw Crusher, Gyratory Crusher, Crushing Rolls

(b) Grinders (Intermediate and fines)

- Hammer mill, Attrition Mill,
- Rolling Compression Mill
    - Bowl mill and Roller Mill
- Tumbling Mill
    - Rod Mill
    - Ball Mill : Pebble Mill
    - Tube Mill : Compartment Mill

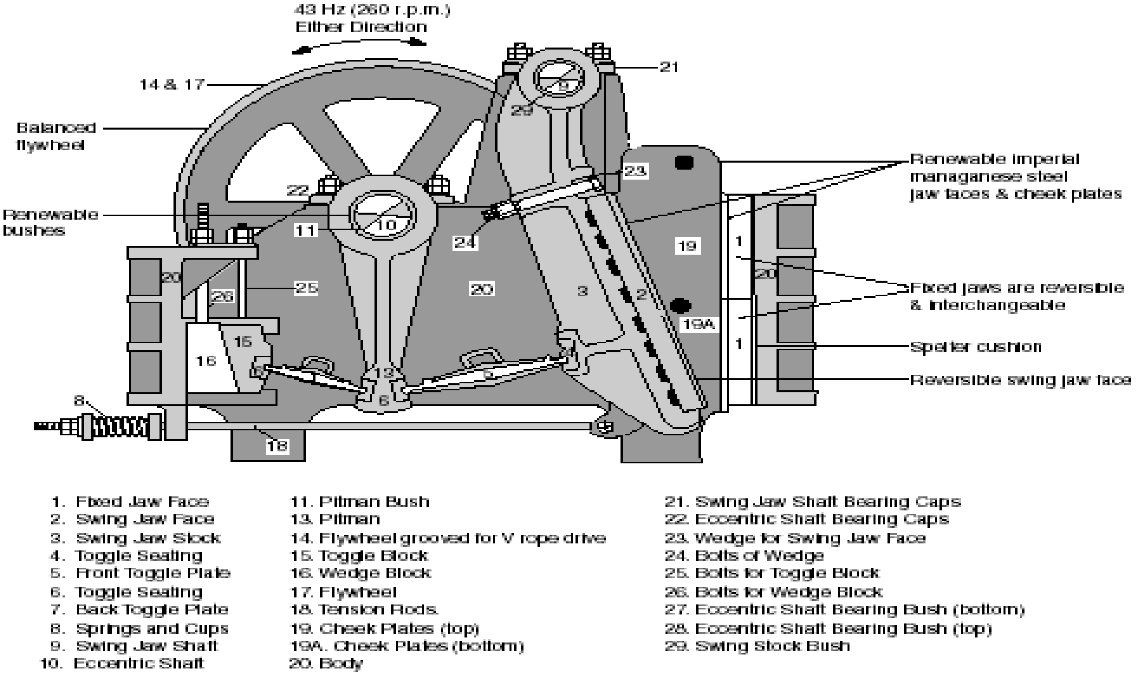
(c) Ultrafine Grinders

- Hammer Mill with Internal Classification
- Fluid Energy Mill
- Agitated Mill

(d) Cutting Machines

- Knife Cutters, Dicers, Slitters

- **Stage Jaw Crusher**



- The Stag jaw crusher shown in Figure, has a fixed jaw and a moving jaw pivoted at the top with the crushing faces formed of manganese steel.

- Since the maximum movement of the jaw is at the bottom, there is little tendency for the machine to clog, though some uncrushed material may fall through and have to be returned to the crusher. The maximum pressure is exerted on the large material which is introduced at the top.

- The machine is usually protected so that it is not damaged if lumps of metal enter, by making one of the toggle plates in the driving mechanism relatively weak so that, if any large stresses are set up, this is the first part to fail. Easy renewal of the damaged part is then possible.

- Stag crushers are made with jaw widths varying from about 150 mm to 1.0 m and the running speed is about 240 rpm with the smaller machines running at the higher speeds.

- The speed of operation should not be so high that a large quantity of fines is produced as a result of material being repeatedly crushed because it cannot escape sufficiently quickly.
- The angle of nip, the angle between the jaws, is usually about 30°.
- Because the crushing action is intermittent, the loading on the machine is uneven and the crusher therefore incorporates a heavy flywheel. The power requirements of the crusher depend upon size and capacity and vary from 7 to about 70 kW, the latter figure corresponding to a feed rate of 10 kg/s.

The Dodge jaw crusher

- In the Dodge crusher, the moving jaw is pivoted at the bottom.
- The minimum movement is thus at the bottom and a more uniform product is obtained, although the crusher is less widely used because of its tendency to choke.
- The large opening at the top enables it to take very large feed and to effect a large size reduction.

This crusher is usually made in smaller sizes than the Stag crusher, because of the high fluctuating stresses that are produced in the parts of the machine.

The gyratory crusher

- The gyratory crusher shown in Figure ,employs a crushing head, in the form of a truncated cone, mounted on a shaft, the upper end of which is held in a flexible bearing, whilst the lower end is driven eccentrically so as to describe a circle.
- The crushing action takes place round the whole of the cone and, since the maximum movement is at the bottom, the characteristics of the machine are similar to those of the Stag crusher.

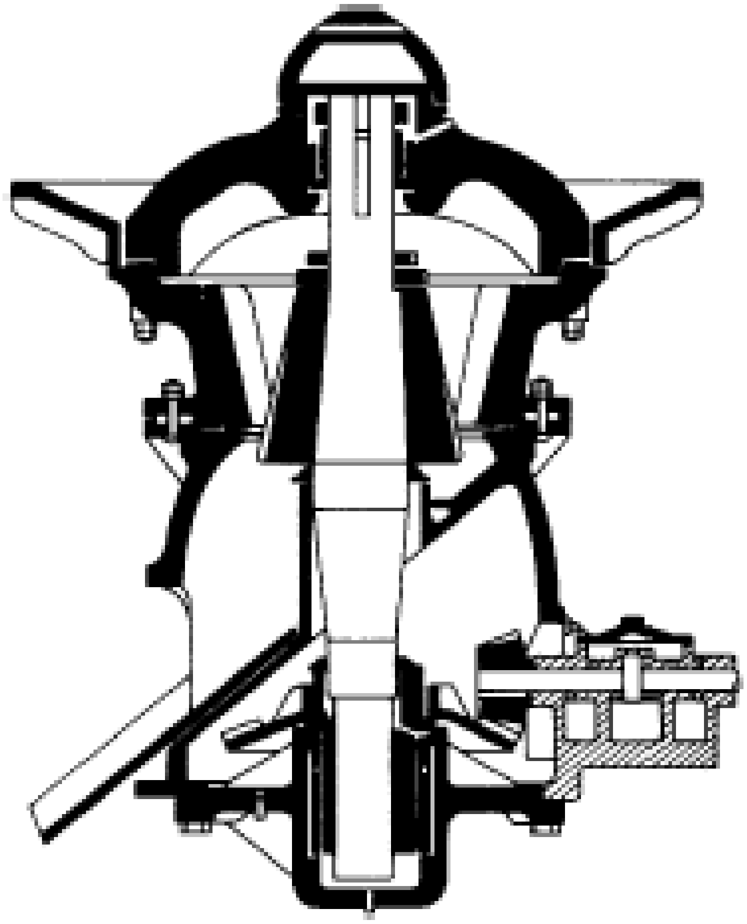


Figure 2.6. Gyratory crusher

- As the crusher is continuous in action, the fluctuations in the stresses are smaller than in jaw crushers and the power consumption is lower.
- This unit has a large capacity per unit area of grinding surface, particularly if it is used to produce a small size reduction.
- It does not, however, take such a large size of feed as a jaw crusher, although it gives a rather finer and more uniform product.

- Because the capital cost is high, the crusher is suitable only where large quantities of material are to be handled.

Intermediate Crusher

The edge runner mill

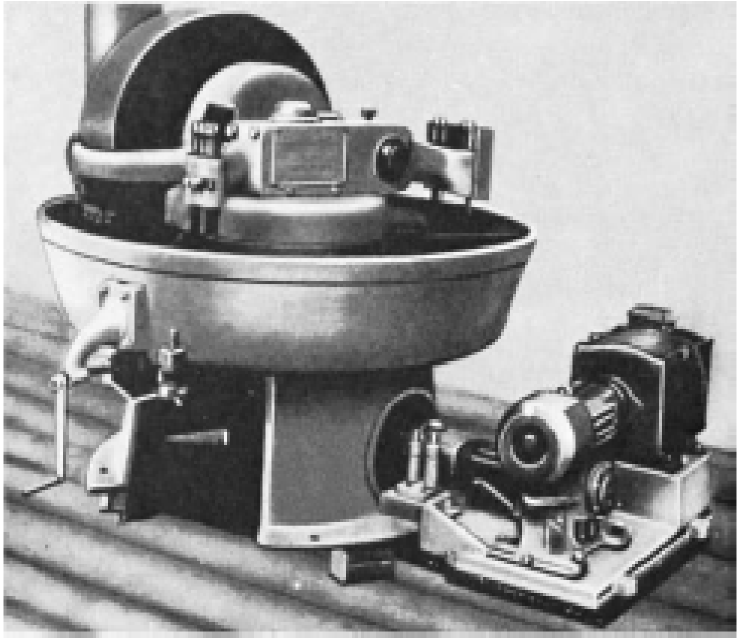


Figure 2.8. Edge runner mill

In the edge runner mill shown in Figure , a heavy cast iron or granite wheel, or *muller* as it is called, is mounted on a horizontal shaft which is rotated in a horizontal plane in a heavy pan. Alternatively, the muller remains stationary and the pan is rotated, and in some cases the mill incorporates two mullers.

Material is fed to the centre of the pan and is worked outwards by the action of the muller, whilst a scraper continuously removes material that has adhered to the sides of the pan, and returns it to the crushing zone.

In many models the outer rim of the bottom of the pan is perforated, so that the product may be removed continuously as soon as its size has been sufficiently reduced. The mill may be operated wet or dry and it is used extensively for the grinding of paints, clays and sticky materials.

Hammer mill

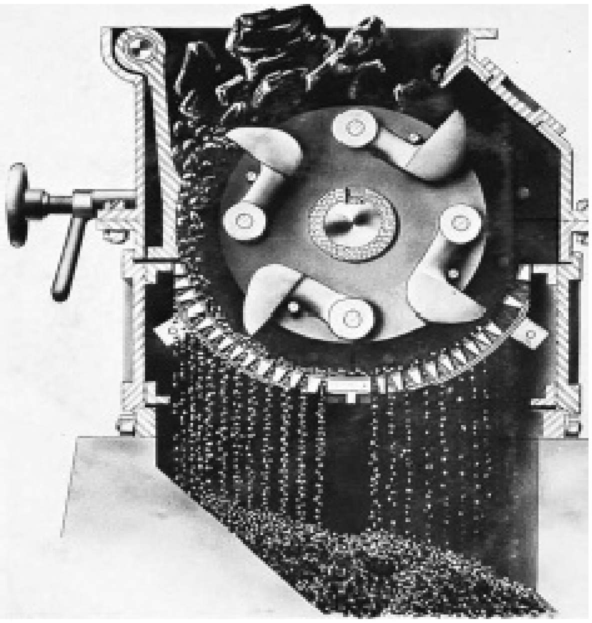


Figure 2.9. Swing claw hammer mill

The hammer mill is an impact mill employing a high speed rotating disc, to which are fixed a number of hammer bars which are swung outwards by centrifugal force. An industrial model is illustrated in Figure 2.9 .Material is fed in, either at the top or at the centre, and it is thrown out centrifugally and crushed by being beaten between the hammer bars, or against breaker plates fixed around the periphery of the cylindrical casing. The material is crushed until it is small enough to fall through the screen which forms the lower portion of the casing. Since the hammer bars are flexible, the presence of any hard material does not cause damage to the equipment. The bars are readily replaced when they are worn out. The machine is suitable for the crushing of both brittle and fibrous materials, and, in the latter case, it is usual to employ a screen with cutting edges.The size of the product is regulated by the size of the screen and the speed of rotation.

Single roll crusher

The single roll crusher shown in Figure 2.13 consists of a toothed crushing roll which rotates close to a breaker plate. The material is crushed by compression and shearing between the two surfaces. It is used extensively for crushing coal.

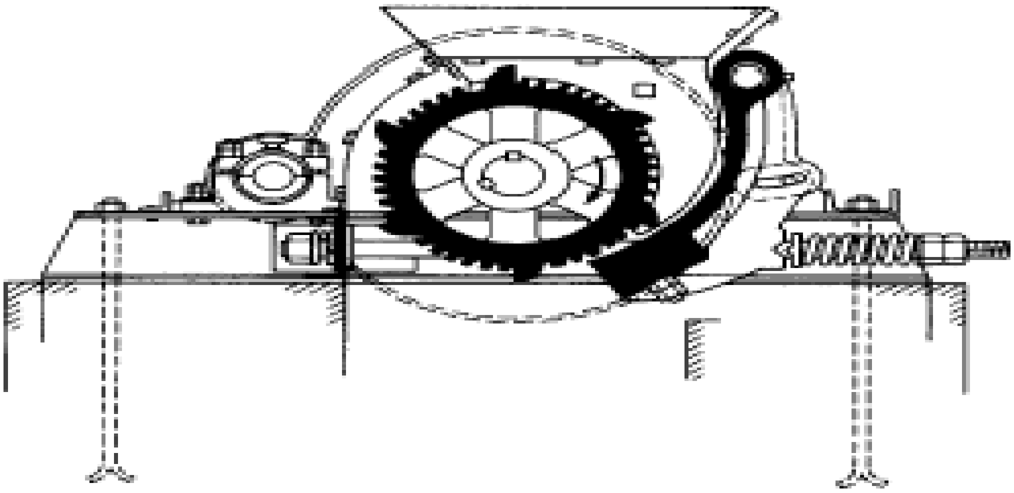


Figure 2.13. Single roll crusher

Crushing rolls

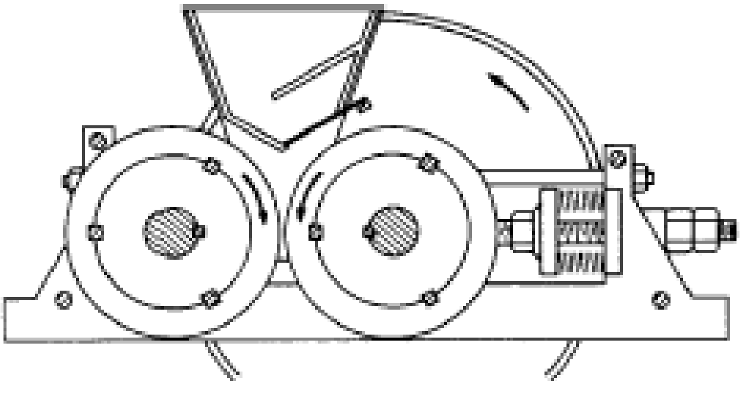


Figure 2.15. Crushing rolls

- Two rolls, one in adjustable bearings, rotate in opposite directions as shown in Figure and the clearance between them can be adjusted according to the size of feed and the required size of product.
- The machine is protected, by spring loading, against damage from very hard material. Both rolls may be driven, or one directly and the other by friction with the solids. The crushing rolls, which may vary from a few centimetres up to about 1.2 m in diameter, are suitable for effecting a small size reduction ratio, 4 : 1 in a single operation, and it is therefore common to employ a number of pairs of rolls in series, one above the other.
- Roll shells with either smooth or ridged surfaces are held in place by keys to the main shaft. The capacity is usually between one-tenth and one-third of that calculated on the assumption that a continuous ribbon of the material forms between the rolls.

Fine Crushers

- ***The ball mill***
- In its simplest form, the ball mill consists of a rotating hollow cylinder, partially filled with balls, with its axis either horizontal or at a small angle to the horizontal.
- The material to be ground may be fed in through a hollow trunnion at one end and the product leaves through a similar trunnion at the other end. The outlet is normally covered with a coarse screen to prevent the escape of the balls.
- The balls are therefore carried further in contact with the cylinder and thus drop on to the feed from a greater height. In some cases, lifter bars are fitted to the inside of the cylinder.
- The ball mill is used for the grinding of a wide range of materials, including coal, pigments, and felspar for pottery, and it copes with feed up to about 50 mm in size.
- The efficiency of grinding increases with the hold-up in the mill, until the voids between the balls are filled. Further increase in the quantity then lowers the efficiency.

- The balls are usually made of flint or steel and occupy between 30 and 50 per cent of the volume of the mill. The diameter of ball used will vary between 12 mm and 125 mm and the optimum diameter is approximately proportional to the square root of the size of the feed, with the proportionality constant being a function of the nature of the material.
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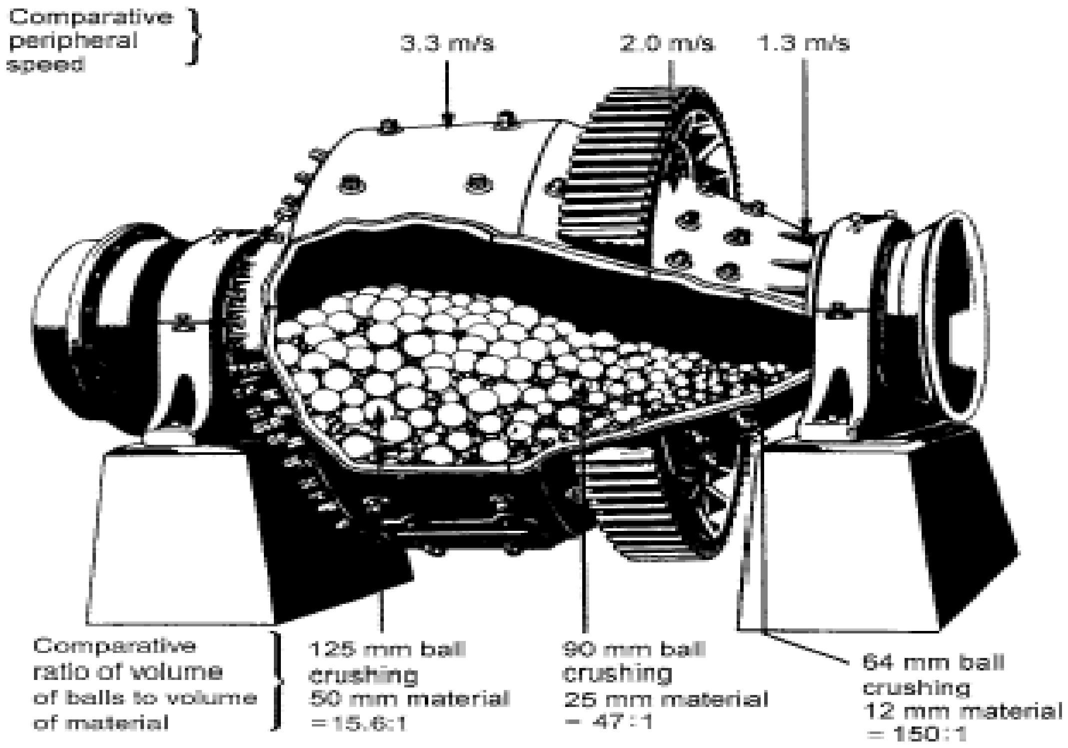


27. Cut-away view of the Hardinge conical ball mill showing how energy is proportioned to the work required

-
- In the compound mill, the cylinder is divided into a number of compartments by vertical perforated plates.
- The material flows axially along the mill and can pass from one compartment to the next only when its size has been reduced to less than that of the perforations in the plate.
- Each compartment is supplied with balls of a different size. The large balls are at the entry end and thus operate on the feed material, whilst the small balls come into contact

with the material immediately before it is discharged. This results in economical operation and the formation of a uniform product. It also gives an improved residence time distribution for the material.

Advantages of the ball mill

The mill may be used wet or dry although wet grinding facilitates the removal of the product.

(ii) The costs of installation and power are low.

(iii) The ball mill may be used with an inert atmosphere and therefore can be used for the grinding of explosive materials.

(iv) The grinding medium is cheap.

(v) The mill is suitable for materials of all degrees of hardness.

(vi) It may be used for batch or continuous operation.

(vii) It may be used for open or closed circuit grinding. With open circuit grinding, a wide range of particle sizes is obtained in the product. With closed circuit grinding, the use of an external separator can be obviated by continuous removal of the product by means of a current of air or through a screen,

Factors influencing the size of the product

(a) The rate of feed. With high rates of feed, less size reduction is effected since the material is in the mill for a shorter time.

(b) *The properties of the feed material*. The larger the feed the larger is the product under given operating conditions.

(c) *Weight of balls*. A heavy charge of balls produces a fine product. Since optimum grinding conditions are usually obtained when the bulk volume of the balls is equal to 50 per cent of the volume of the mill.

(d) The diameter of the balls. Small balls facilitate the production of fine material although they do not deal so effectively with the larger particles in the feed. The limiting size reduction obtained with a given size of balls is known as the free grinding limit. For most economical operation, the smallest possible balls should be used.

(e) *The slope of the mill.* An increase in the slope of the mill increases the capacity of the plant because the retention time is reduced, although a coarser product is obtained.

(f) *Discharge freedom*. Increasing the freedom of discharge of the product has the same effect as increasing the slope.

(g) *The speed of rotation of the mill*.

At low speeds of rotation, the balls simply roll over one another and little crushing action is obtained.

At slightly higher speeds, the balls are projected short distances across the mill, and at still higher speeds they are thrown greater distances.

At very high speeds, the balls are carried right round in contact with the sides of the mill and little relative movement or grinding takes place again.

The minimum speed at which the balls are carried round in this manner is called the critical speed of the mill and, under these conditions, there will be no resultant force acting on the ball when it is situated in contact with the lining of the mill in the uppermost position, that is the centrifugal force will be exactly equal to the weight of the ball.

Objective of Size Enlargement

- Production of useful structural forms, as in pressing of intricate shapes in powder metallurgy.
- Provision of a defined quantity to facilite dispensing and metering, as in agricultural chemical granules or pharmaceutical tablets.

- Elimination of dust-handling hazards or losses, as in briquetting of waste fines.
- Improved product appearance, or product renewal.
- Reduced caking and lump formation, as in granulation of fertilizer.
- Improved flow properties, generally defined as enhanced flow rates with improved flow rate uniformity, as in granulation of pharmaceuticals for tableting or ceramics for pressing.
- Increased bulk density for storage and tableting feeds.
- Creation of nonsegregating blends of powder ingredients with ideally uniform distribution of key ingredients, as in sintering of fines for steel or agricultural chemical or pharmaceutical granules.
- Control of solubility, as in instant food products.
- Control of porosity and surface-to-volume ratio, as with catalyst supports.
- Improvement of heat-transfer characteristics, as in ores or glass for furnace feed.
- Remove of particles from liquid, as with polymer additives, which induce clay flocculation.

FILTRATION

Filtration is the removal of solid particles from a fluid by passing the fluid through a filtering medium or septum on which the solids are deposited using normal or applied pressure. The solid deposited on the filter media is known as filter cake. The clear liquid which is almost free from solid is known as filtrate.

Filter Media

- The filter media must meet these requirement.

- It must retain the solid to be filtered, giving reasonably clear liquid
- It must not plug or blind.
- It must be resistant chemically and strong enough physically to withstand the process condition.
- It must permit the cake formed to discharge cleanly and completely.
- It should be cheaper and easily available.

- Most widely used filter media in CPI is Canvas Cloth.Corrosive liquid require the use of special type of filter media like woolen cloth, monel or stainless steel , glass cloth and paper.
- Synthetic fabrics like nylon, polypropylene, Dacron are highly used because of higher resistant towards chemical attack.

Factors Afecting on Filtration

(a) Cake Compressibility : If the cake is rigid and incompressible as observed with hard granular particles, the compressibility coefficient is zero. The rate of filtration is directly proportional to the pressure of filtration and square of the filtration surface. The rate of filtration is inversely proportional to the viscosity of the filtrate and amount of cake. If the cake is extremely soft or compressible, compressibility coefficient is one. For this condition, the rate of filtration is independent of pressure of filtration.

(b) Effect of Pressure : Increase in Pressure always brings about a nearly proportionate increase in the rate of filtration. However, for cake composed of flocculent or slimy substances, rate of filtration increases only slightly with the increase of pressure.

(c) Cake Thickness : In the early stage of filtration, it has not significant effect on rate of filtration, but as the time increases, the thickness of the cake is also increases. It reduce the rate of filtration.

(d) Effect of Viscosity : The rate of filtration is inversely proportional to the viscosity of filtrate.

(e) Effect of Temperature: As increase in temperature reduce the viscosity of solution, the rate of filtration is increase.

Classification of filters

(a) ***By Driving force:***

- Either gravitational or centrifugal force
- Super atmospheric pressure applied on upstream side (Pressure filter) or sub atmospheric pressure on downstream side (Vacuum filter)

(b) ***By Operation Cycle :***

- Filtration may be batch or continuous operation
- Batch filtration may be either constant rate or constant pressure or combination of both

(c) ***By Filtration mechanism :***

(i) Solid deposited on the filter media layer by layer and form cake, they do not penetrate beyond the filter surface.

(ii) The suspended solids of the charge get arrested within the pores or body of the filter medium – a process known as filter medium filtration

(d) ***By Function :*** Whether the cake is the product of value or filtrate is the product or both

(e) ***By Nature of Solid :*** Filter cake may be compressible or substantially incompressible depending upon the nature of solid suspended in the feed slurry are deformable or rigid.

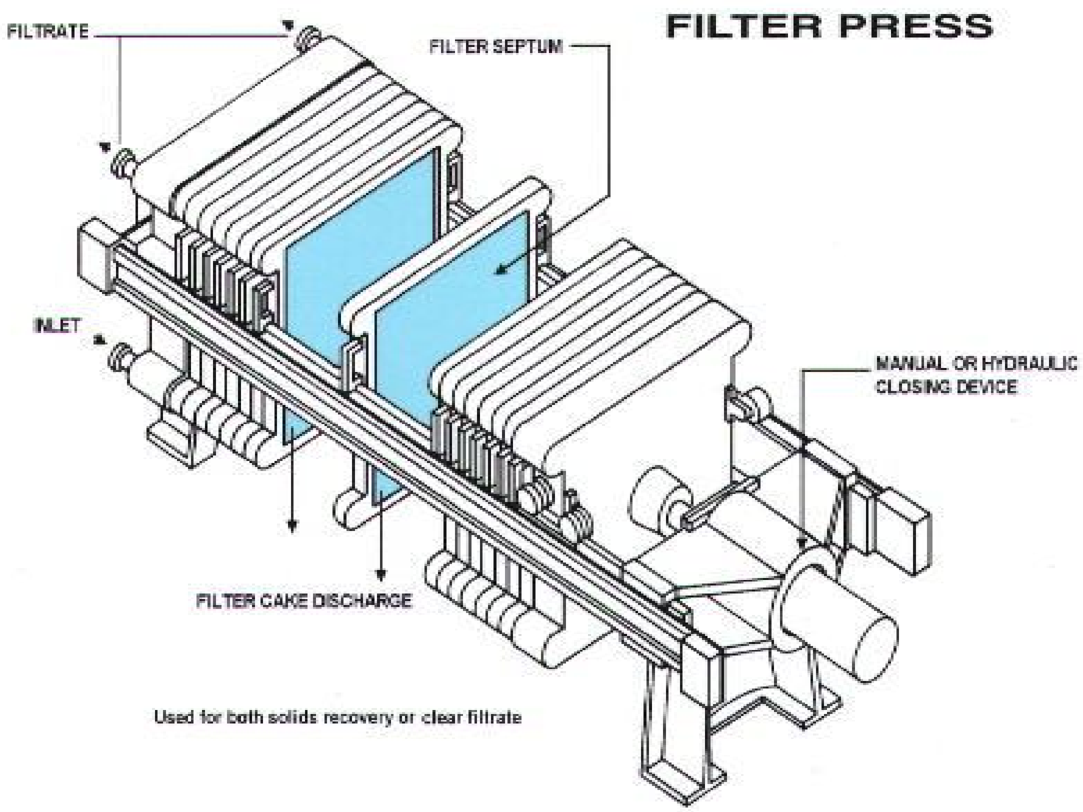
Factors to be considered when selecting filtration equipments

- The nature of the slurry & cake formed
- The solid concentration in the feed
- The through out required
- The nature & physical properties of the liquid e.g. viscosity , flammability , toxicity, corrosiveness
- Whether cake washing is required
- The cake dryness required
- Whether contains of the solid by a filter aid is acceptable
- Whether the valuable product is the solid or the liquid or both.

Plate and Frame Filter (Filter Press)

- A filter press contains a set of plate design to provide a series of chambers or compartments in which solids may collects. The plated are covered with a filter medium such as canvas. The plates of a filter place may be square or circulars / vertical- horizontal line made of from either polypropylene or steel as per requirement.

- Plates and frames are sit vertically or horizontally in a metal rake and are squeezed tightly together by a screw or a hydraulic ram.
- The slurry enters at one end of plate and frame filters. It passes through a channel running length wise through one corner of the assembly. Auxiliary channels carries slurry from the main inlet channel in to each frame and Liquor passes through the cloth. Down/ grooves or corrugations in the plate faces and out of the press.
- Filtration is continued until liquor no longer flows out the discharge or the filtration pressure suddenly rises. These occurs when the frames are full of solids and no more slurry can enters is known as JAMMED. Wash liquid may then be admitted to remove soluble impurities from the solids. After which the cake may be blown with steam or air to displace as much residual liquid as possible. The solids are deposited on the cloth cover faces of the plates
- The press is then open and the cake of solids is removed from the filter medium. And dropped to a conveyor or storage bin.



<u>Rotary Drum Filters :</u>

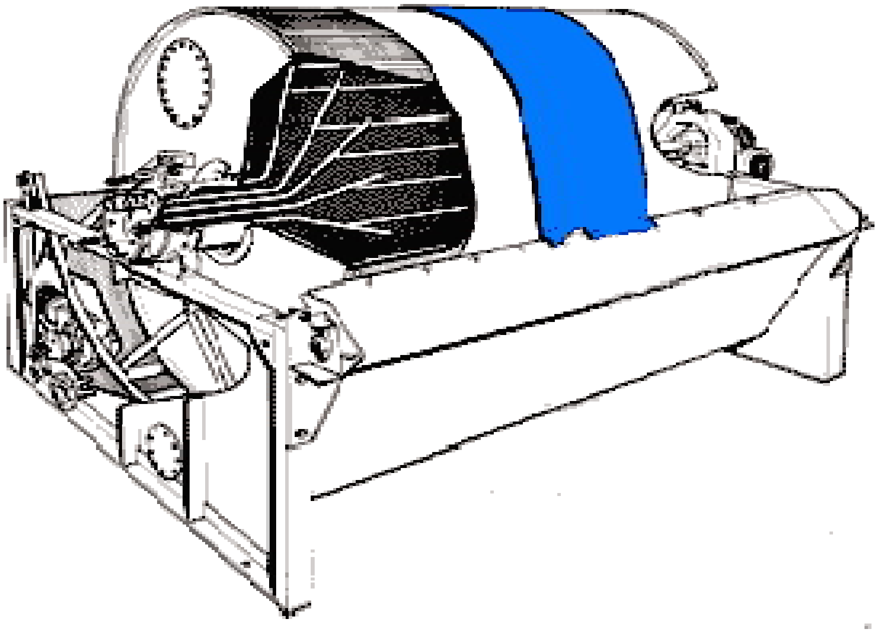
These filters work in industries more than 50 years because of good flexibility, easy to handling feed slurry and lowest cost of filtration per unit area.

The drum surface is divided in to a number of sections which are parallel to the drum axis. Division strips are utilized to separate the sections. Drum submergence can range from 35 to 50%. Each section is also connected by its own piping system to the rotating portion of the filter valve. Each section can be shut off from vacuum directed to different filtrate receivers as demand.

A controlled quantity of air can be admitted through one set of piping to purge the filtrate in to other set of piping to remove the filtrate efficiently from the drainage deck and piping system. For example, on the rising side of drum, air would be purged through the lead piping to force filtrate out through the trail piping. Diameter of Drum may be from 1.22 meter to 3.66 meters

Drum as large as 7.32 meters have been constructed. Mild steel , various grade of stainless steel , rubber covered mild steel , titanium for the more corrosive slurries, molded plastic filters of the thermo plastic type, polyethylene, polypropylene & fluro carbons.

Panel is enter in the slurry as deep under the surface of liquid. The vacuum is applied through the Rotary valve. A layer of solid builds up on the surface of the filter medium & Filtrate of the filter is drawn through the filter medium in to the compartment, through the lead and collect in collecting tank. As the panel leaves the slurry and enters the washing & drying zone, vacuum is applies to a panel from a separate system.After the cake of solids on the surface of the panel has been sucked as dry as possible. The panel leaves the drying zone, vacuum is cut off and the cake is removed by scraping. Once the cake is removed the panels reenters the slurry and cycle is repeated . Cake formed may be 3 to 40 mm thick



Agitation and Mixing

"Many processing operations depend for their success on the effective agitation & mixing of fluids" ……McCabe

Mixing and agitation is the heart of the chemical industry. Almost all process equipments need some type of mixing or agitation. Uniformity of composition and desired flow pattern depends upon the type of agitator and the speed of agitation. It is also necessary to control the quality of the product, specifically where there is evaluation of heat and the temperature has to be maintained constant.

Agitation

- It is an induced motion of a material in a specified way.
- The pattern is normally circulatory.
- It is normally taken place inside a container.

Mixing

- Random distribution, into & through one another of two or more initially separate phases

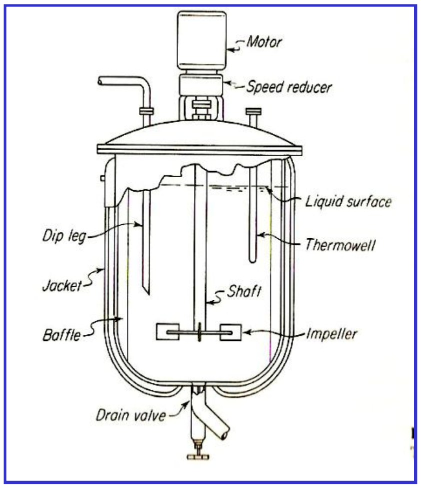


Fig. 1 Agitated Vessel

- Liquids are agitated in a tank
- Bottom of the tank is rounded
- Impeller creates a flow pattern.
- Small scale tank (less than 10 litres) is constructed using Pyrex glass.
- For larger reactors/tank, stainless steel is used.
- Speed reduction devices are used to control the agitation speed.
- Mixing Flow : 3 patterns (axial, radial, tangential flow)

Different types of operations:

1. Blending of miscible liquids
2. Gas absorption
3. Gas dispersion
4. Dissolution
5. Crystallization
6. Heat transfer
7. Chemical Reaction
8. Extraction etc.

A good mixing should achieve the following:

1. Minimum power requirement.
2. Efficient mixing in optimum time.
3. Best possible economy.
4. Minimum maintenance, durable and trouble free operation.
5. Compactness.

Important consideration in the designing are:

- Determination of amount of energy required or power required for satisfactory performance of mixing operation.
- Process has to be well defined e.g. a mixing system is to be designed to make up and hold in uniform suspension a 15% slurry.
- Description of the components to be mixed. Their properties at initial stage, final stage, overall specific gravity, initial and final viscosity, concentration etc.
- Details of the tank geometry.
- Outline of the mixing cycle: It depends upon the nature of the operation. Decide whether the process is a batch, semi-continuous or continuous etc.

Factors affecting the designing of the agitator:

- Type of vessel
- Circulation pattern.
- Location of the agitator
- Shape and size of the vessel
- Diameter and width of the agitator
- Method of baffling
- Power required
- Shaft overhang
- Type of stuffing box or seal, bearing, drive system etc.

Mixing Flow patterns (3 types):

(i) **Axial flow.**

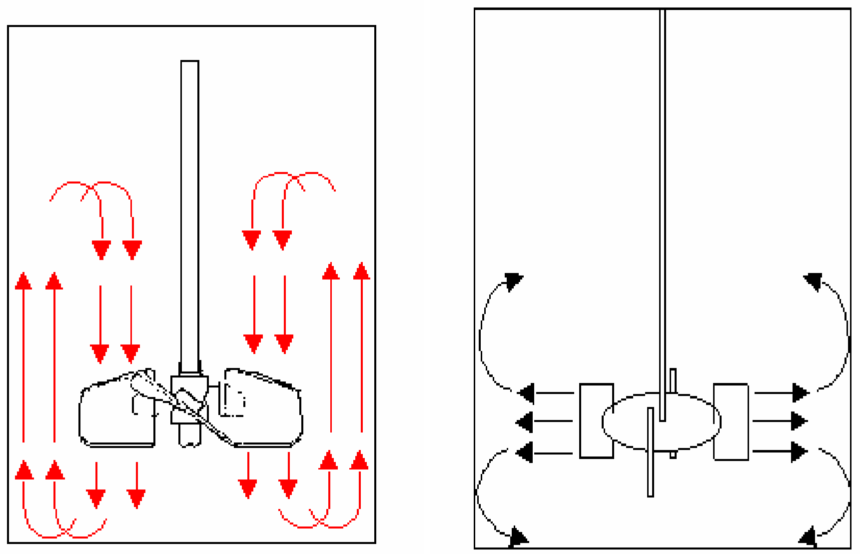
- Impeller makes an angle of less than 90^o with the plane of rotation thus resultant flow pattern towards the base of the tank (i.e. marine impellers).
- More energy efficient than radial flow mixing.
- More effective at lifting solids from the base of the tank.

(ii) **Radial flow.**

- Impellers are parallel to the axis of the drive shaft.
- The currents travel outward to the vessel wall & then either upward or downward.
- Higher energy is required compared to axial flow impellers.

(ii) **Tangential flow.**

- The currents acts in the direction tangent to the circular path around the shaft.
- Usually, it produce vortex (disadvantageous) & swirling the liquid.



With axial impellers, the liquid is pushed in a downward direction; that is, along the axis of the reactor.

With radial flow impellers, the liquid is pushed towards the wall of the tank; that is, along the radius of the reactor

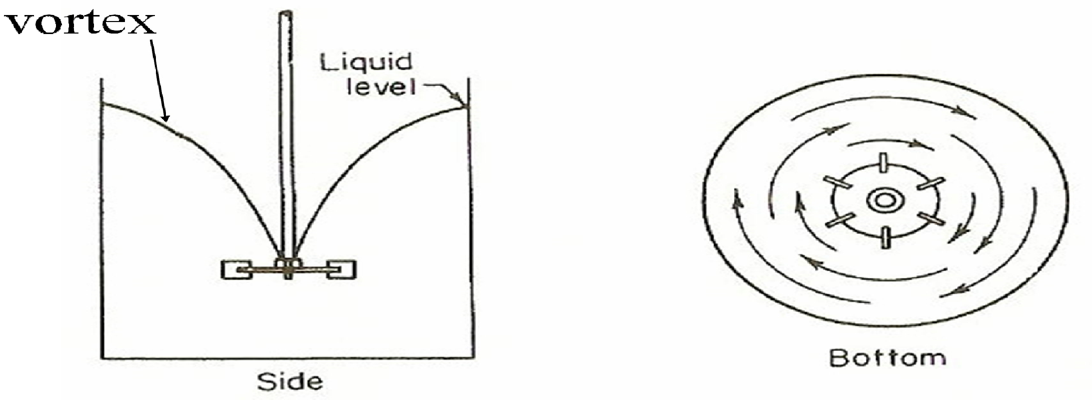


Fig. 2 (i) Axial Mixing (ii) Radial Mixing (iii) Tangential Mixing

Vortex

- If solid particles present within tank; it tends to throw the particles to the outside by centrifugal force.
- Power absorbed by liquid is limited.
- At high impeller speeds, the vortex may be so deep that it reaches the impeller.
- Method of preventing vortex
  - baffles
  - impeller in an angular off-center position

Preventing vortex

(i) Baffles on the tank walls

(ii) Impeller in an angular off-center position

(i) Baffles

Baffles are vertical plates (typically about 10% of the tank diameter) that stick out radially from the tank wall

- If simple swirling motion is required no baffling is necessary.
- Generally 4 baffles are used located 90° apart.
- Baffle width is 10-12% tower diameter
- Baffle height 2 times impeller height
- With coils in the tank, baffles are placed inside the coil.

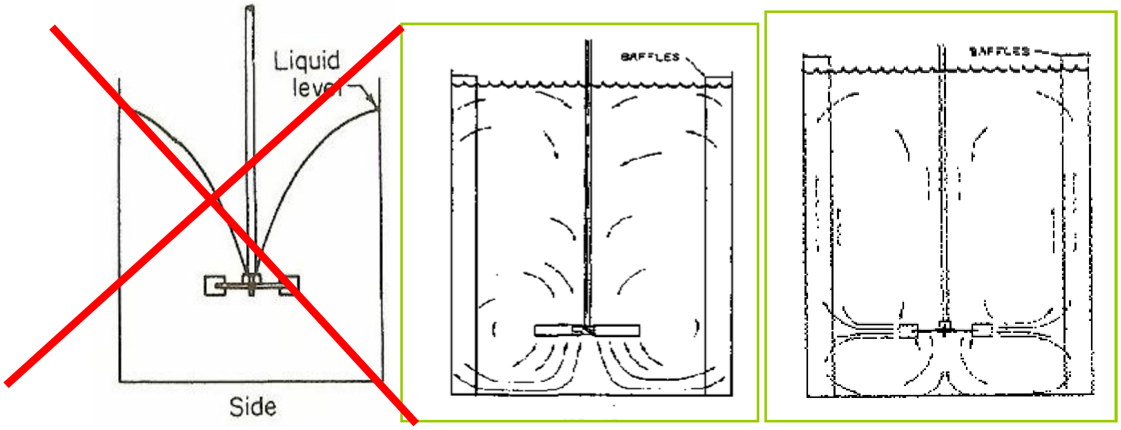


Fig. 3 Flow Pattern in presence of baffles (i) Vertex (ii) Axial Flow turbine (iii) Radial Flow Turbine

- Without baffles, the tangential flow (swirling) occurred in a mixing tank causes the entire fluid mass to spin (more like a centrifuge than a mixer).
- With baffles, most impellers show their true flow characteristics.
- Most common baffles are straight flat plates of metal (standard baffles).
- Most vessels will have at least 3 baffles. 4 is most common and is often referred to as the "fully baffled" condition.

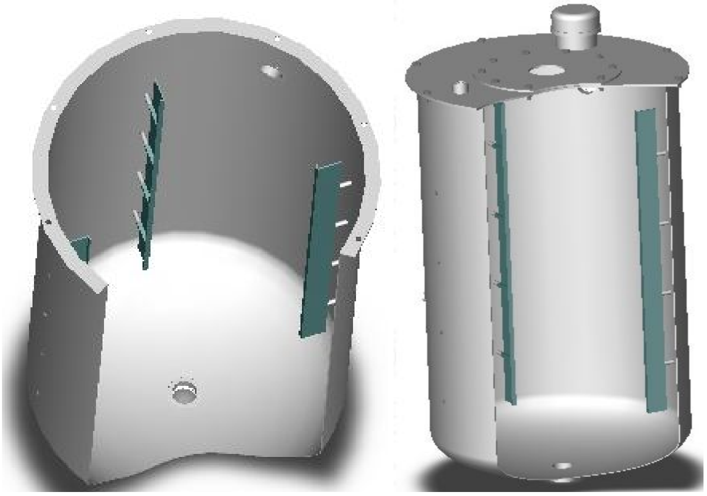


Fig 4. Baffled Vessel

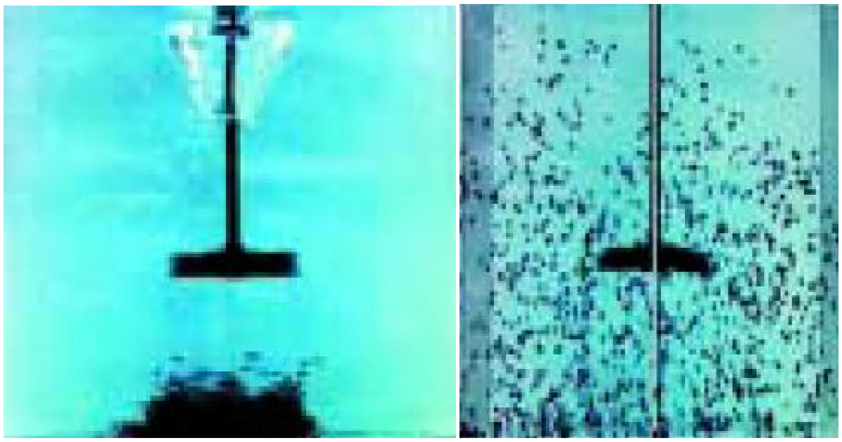


Fig. 5. Agitation with and without baffles

(ii) Impeller in an angular off-center position

Mount the impeller away from the center of the vessel & tilted in the direction perpendicular to the direction of flow.

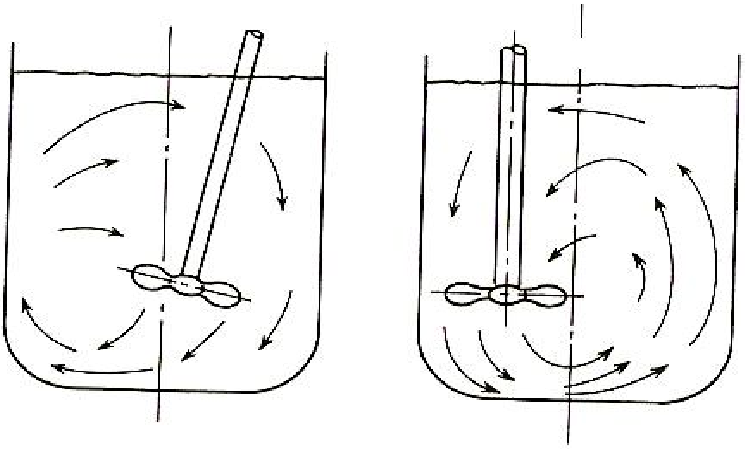
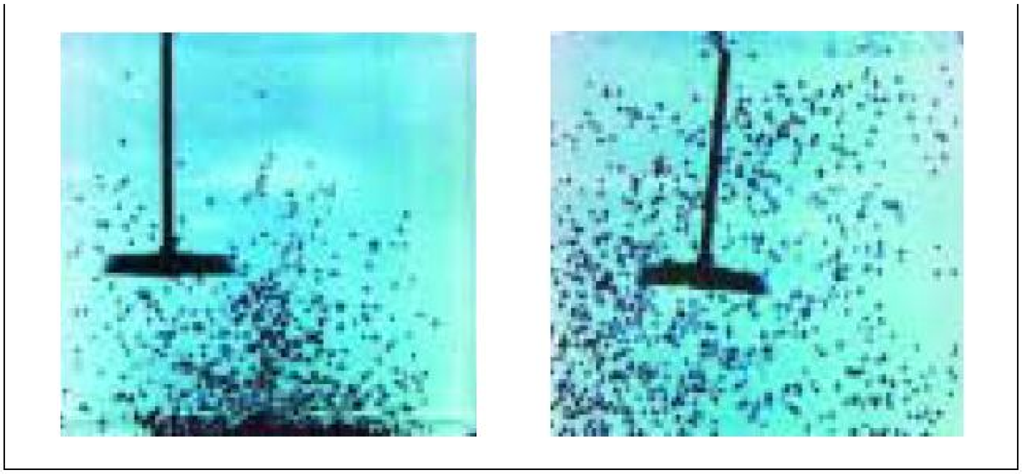


Fig. 6 Flow pattern for off mounted impeller



■ Figure 5. Off-center agitator mounting (left) reduces swirl in unbaffled vessels, while angled, off-center mounting (right) approximates the flow in fully-baffled vessels.

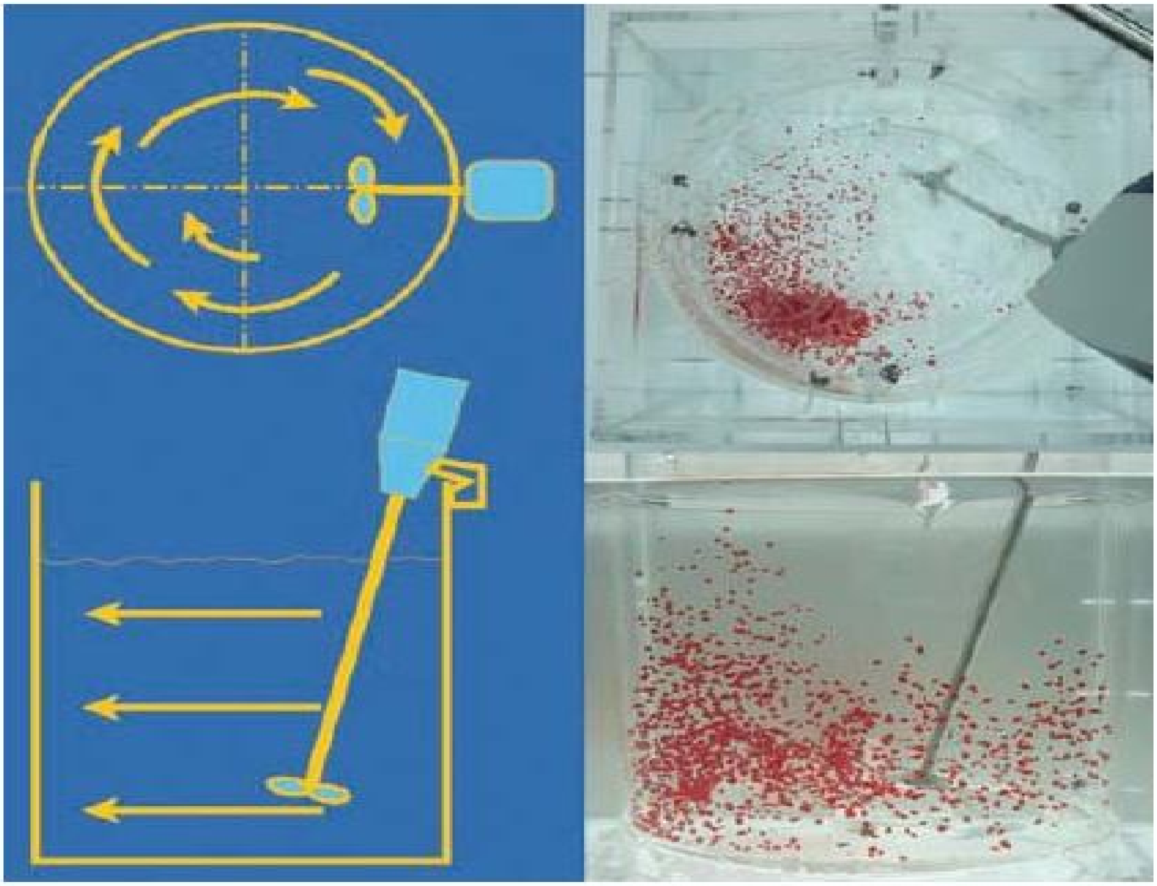


Fig. 7 (i) Side Mounted Impeller (ii) Angle Mounted Impeller

Types of impeller:

1. Paddle
2. Anchor
3. Propeller
4. Turbine
5. Beater
6. Gate Type
7. Helical
8. Ribbon
9. Toothed
10. Marine
11. Plate Type

Paddle type agitator

- Speed range 5-300rpm
- Used for large size vessels
- Agitator size almost touching vessel wall
- Normally used for reaction vessel having jacket by providing good heat transfer area
- Doesn't allow solid buildup at the wall

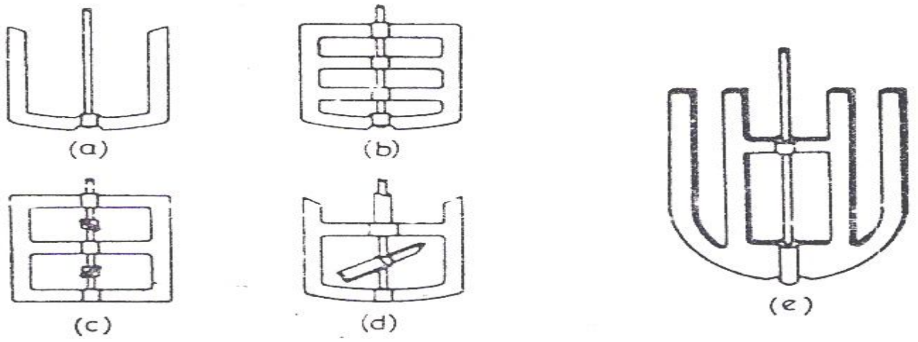


Fig. 14.1 **Paddle Agitators: (a) Anchor, (b) Gate, (c) Gate with pitched cross arms, (d) Anchor with pitched cross arms, (e) Combined anchor and gate**

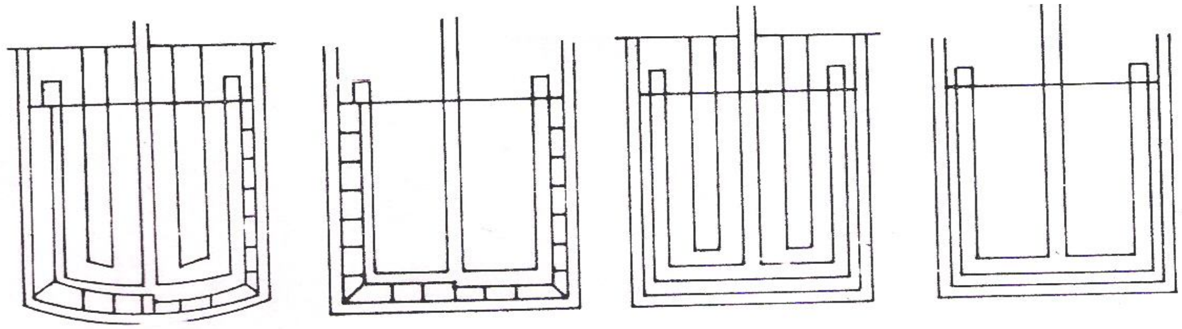


Fig. 4.1 Types of Anchor Agitator

Fig. 8 Paddle and Anchor Type Agitators

Propeller type agitator

- Axial flow impellers
- Maximum flow is achieved at axis of agitator
- Maximum vessel size is 1m^3
- Maximum speed is 415 r/minute
- Diameter of propeller is 15-30% of vessel diameter

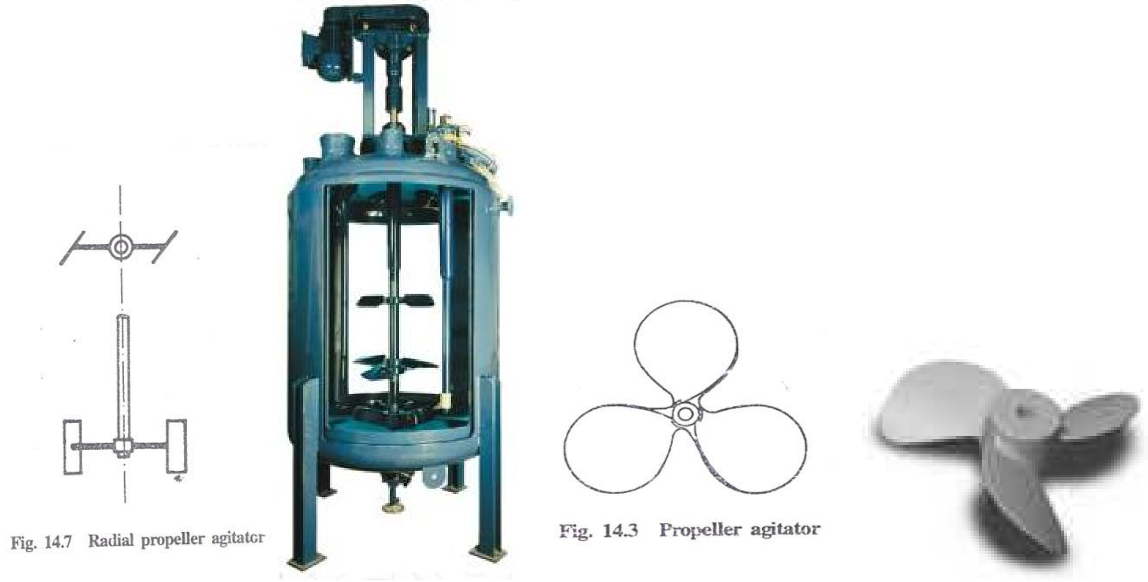


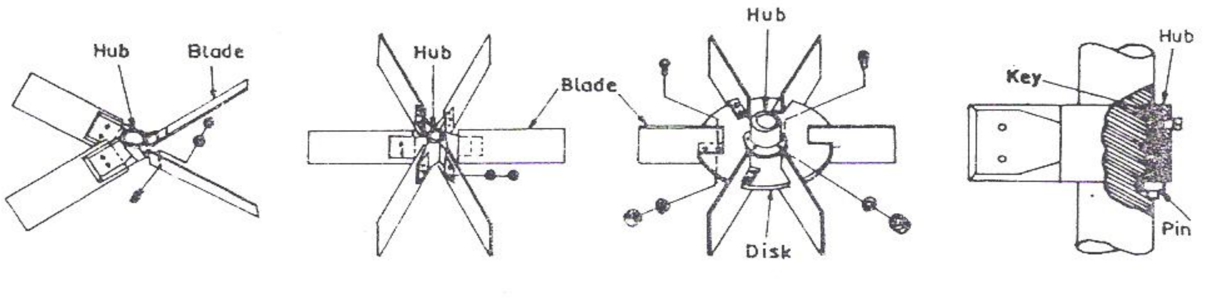
Fig. 14.7 Radial propeller agitator

Fig. 14.3 Propeller agitator

Fig. 9 Propeller Type Agitator

Turbine type agitator

- Motion is achieved due to rotary action of impeller
- Two types are available
    - Axial flow turbine
    - Radial flow turbine
      flat bladed
      pitched bladed
      curved bladed



(1) Pitched blade impeller

(2) Flat blade impeller

(3) Flat impeller with center disk

(4) Impeller hub

Fig. 4.8 Types of turbine impeller

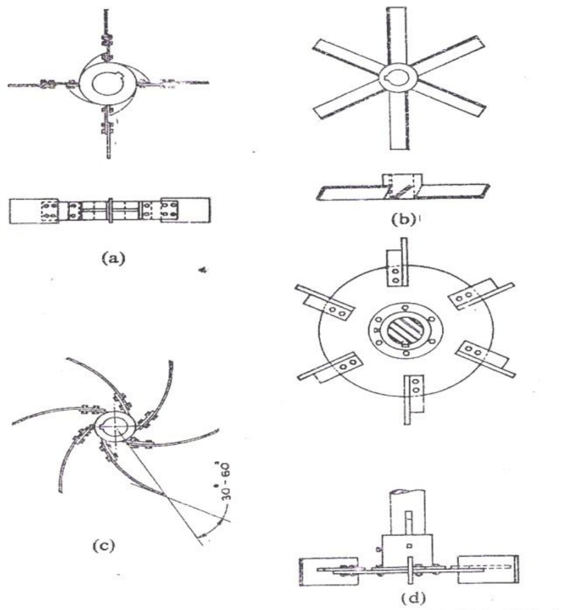
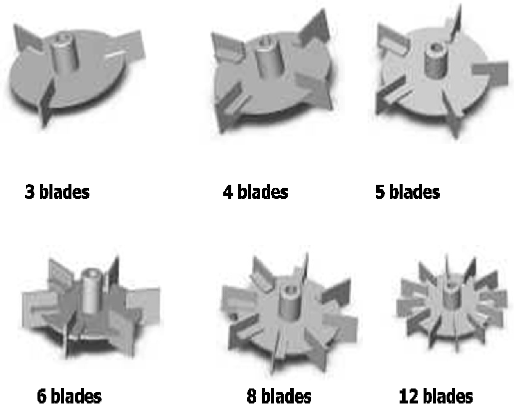


Fig. 14.2 Turbine Agitators: (a) Straight flat blade, (b) Pitched blade, (c) Curved back-sloped, (d) Straight blades attached to disc



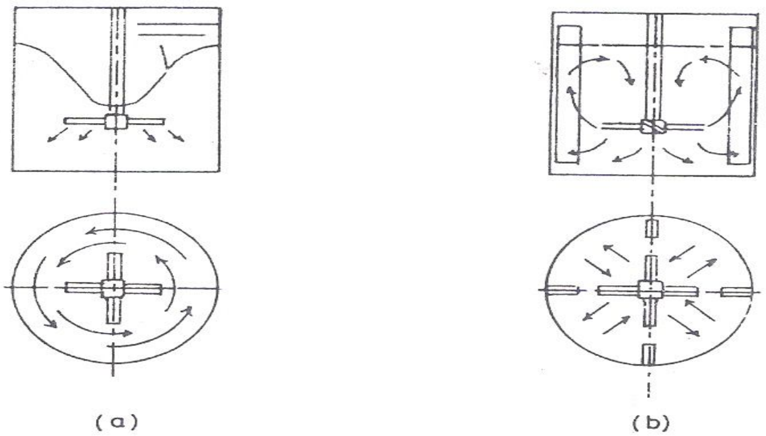


Fig. 14.9 Shows the Flow Pattern Generated by a Turbine: (a) Agitator without baffles, (b) With baffles

Fig. 10 Different arrangement in Turbine Type agitator and flow pattern in turbine type agitator

Helical or ribbon type agitator

- 4 types are available in market
  - Single helical
  - Double helical
  - Helical screw
  - Ribbon type
- Good for top to bottom liquid circulation
- Used for blending for pseudo plastic materials
- High power requirement

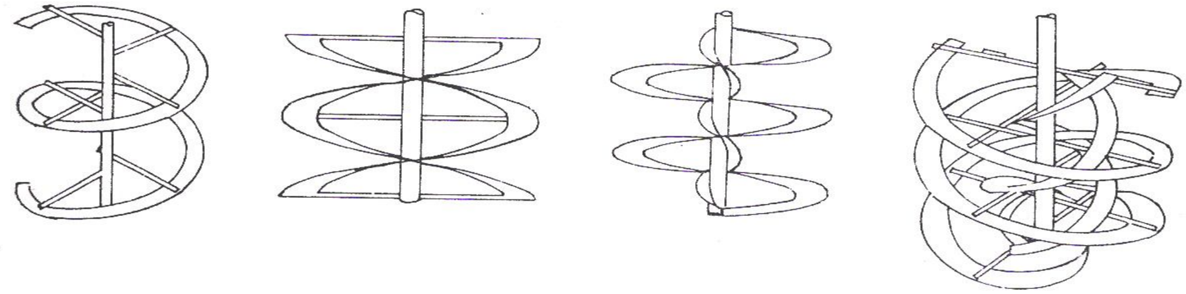


Fig. 4.2 Types of helical ribbon agitator

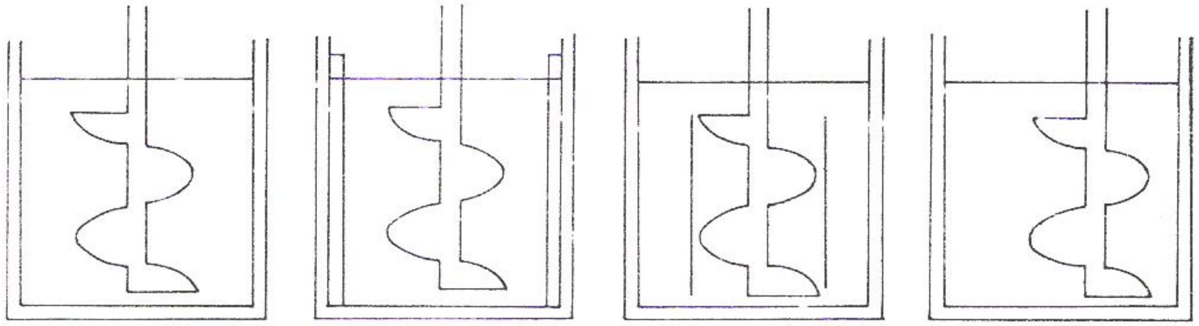


Fig. 11. Helical Ribbon Type Agitators

Specially designed Agitators

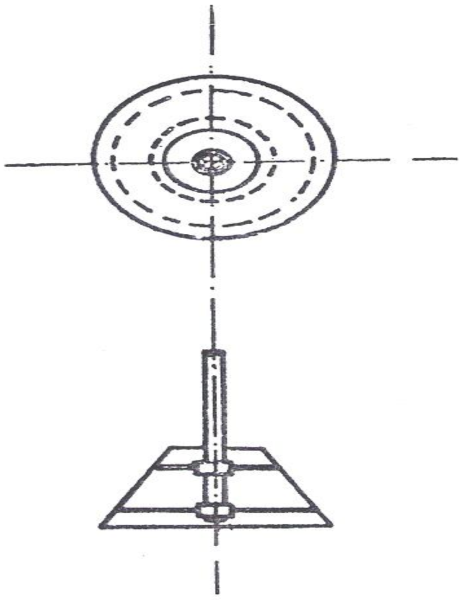


Fig. 14.5 Cone type agitator

- Cone type agitator is used for handling fibrous and dense slurries.
- Speeds are similar to turbine type

- Speed provides sufficient centrifugal force through surface friction to generate flow.
- Produces high shear and helps disintegration of low density fibrous solids

Fig. 14.8 High speed disc agitator

Selection of the agitator depends upon the viscosity of the fluid to be agitated.

When the blade area is small it can rotate at very high speed. For such cases the propeller and turbine type agitators are preferred. (μ = 1000 to 50000cps)

When the blade area is larger it will rotate at the slow speed. For such cases the anchor bolts and helical screw type agitators are used. (μ >> 50000cps)

Mounting of the agitators are done in mainly two ways:

- Top entering agitators ➔ Used in large units
- Side entering agitators ➔ Used in small units and economical

$$\text{Number of agitators} = \frac{\text{Maximum liquid height} * \text{average specific gravity}}{\text{tank diameter}}$$

Distance between two agitators is 1 to 15agitator diameter.

Agitator Drive system

- Electric motor supplies the power.
- IF rpm of motor shaft and agitator shaft is similar then gear box is not required.
- Gear box transmits power of electric motor shaft to agitator shaft directly or sometimes to the other shaft which is attached to agitator shaft.
- Coupling is used to connect two shafts.

Shaft seals

- During the process, liquid vapors or gases should not leak through agitator shaft nozzle.
- There should not be any exchange either from inside to outside or vise versa.
- Like in case of vacuum reaction
- Most common method for sealing shaft is with stuffing box and gland.

Stuffing box

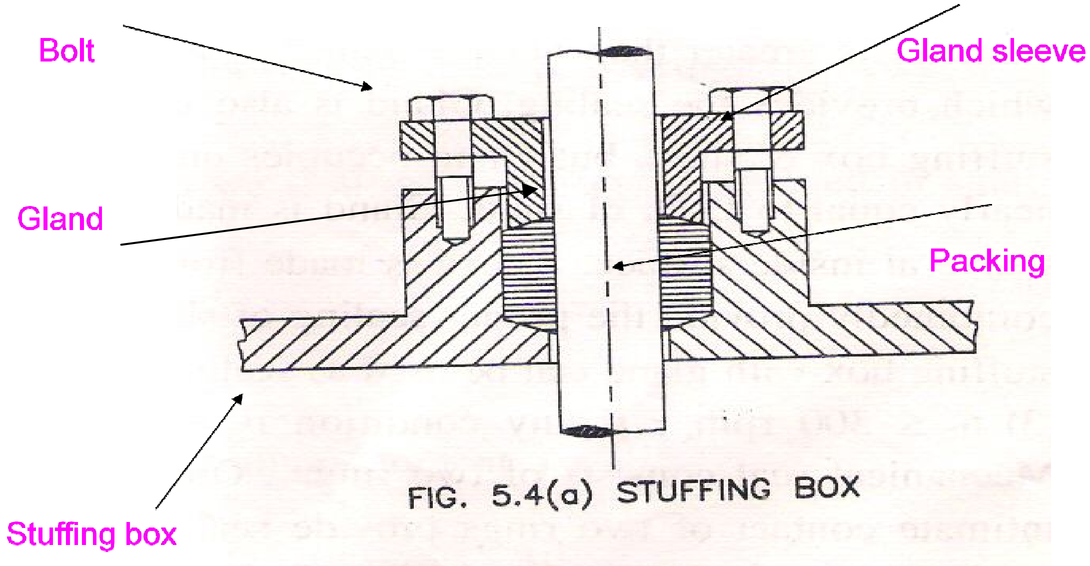
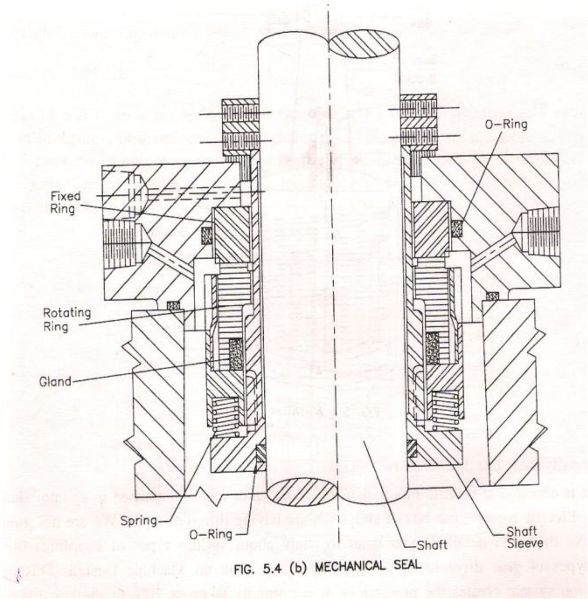
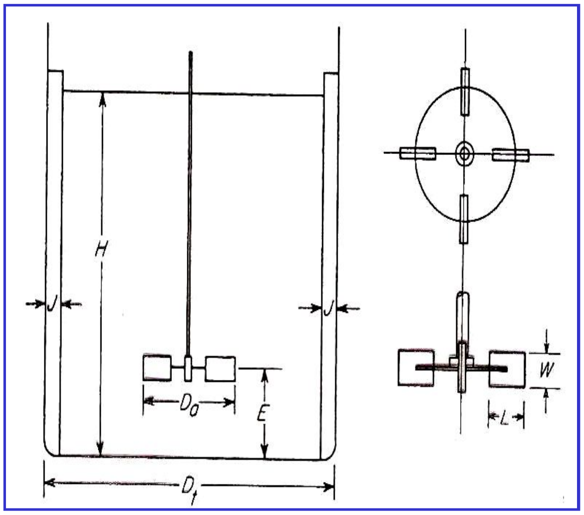


Fig. 12 Stuffing Box

Mechanical Seal



- Stuffing box is having cylindrical shape, placed around the shaft.
- Inside diameter is greater than outside diameter of shaft, having packing material in between for sealing.
- Gland has ID nearly equal to OD of shaft.
- Gland is made of hard metals having sleevs attached to it made of soft metals.
- Glands is bolted to stuffing box using bolts.
- Used only when, P ≤ 10kg, T≤ 120C and N ≤ 300rpm.
- If any of these conditions are not satisfied then better replace stuffing box with mechanical seals.



$$\frac{D_a}{D_t}=\frac{1}{3} \qquad \frac{H}{D_t}=1 \qquad \frac{J}{D_t}=\frac{1}{12}$$

$$\frac{E}{D_t}=\frac{1}{3} \qquad \frac{W}{D_a}=\frac{1}{5} \qquad \frac{L}{D_a}=\frac{1}{4}$$

Fig. 13. Standard Turbine Design

Draft tubes

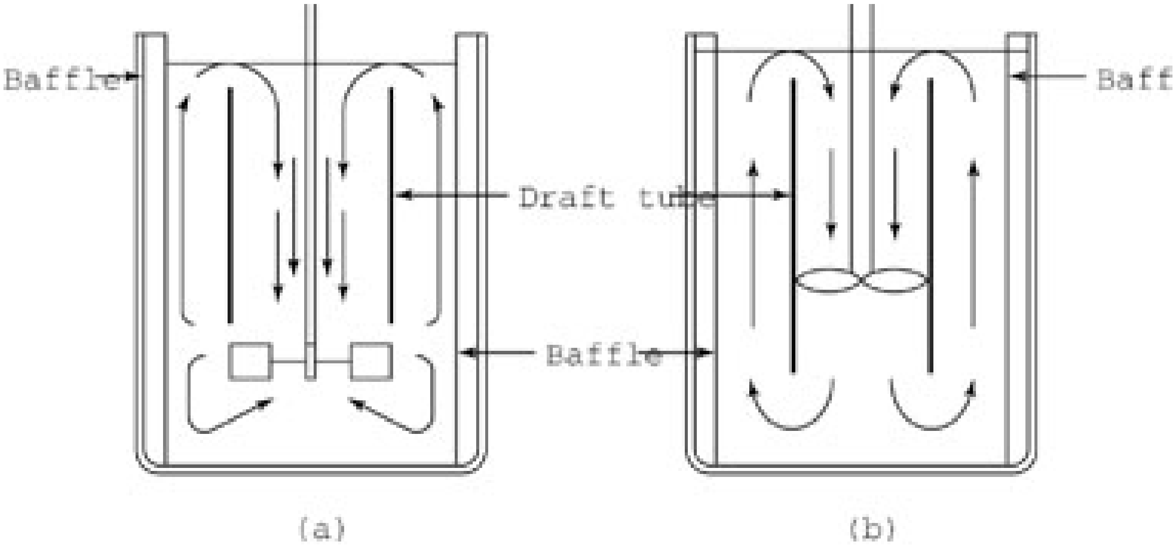


Fig. 14 Draft Tube arrangement

Circulation and Velocity in Agitated Vessels

- Volume of fluid circulated by impeller must be sufficient to sweep out entire vessel in reasonable time
- Velocity of stream leaving impeller must be sufficient to carry current to remotest parts of tank
- In mixing, also need turbulence
  - Results from properly directed currents and large velocity gradients in liquid
- Circulation and generation of turbulence both consume energy
- Large impeller + medium speed = flow
- Small impeller + high speed = turbulence

Mixing Types

- Laminar
- Turbulent

Mixing Mechanism

- Dispersion or Diffusion is the act of spreading out
- Molecular diffusion is diffusion caused by molecular motion and characterized by molecular diffusivity DAB.
- Eddy Diffusion or Turbulent Diffusion is dispersion in turbulent flows caused by motion of large groups of molecules called eddies; this motion is measured as the turbulent velocity fluctuations.
- Convection or bulk diffusion is dispersion caused by bulk motion.
- Taylor dispersion is a special case of convection, where dispersion is caused by mean velocity gradient. This is the case of Laminar flow conditions.

Scale of Mixing

- Macro mixing is mixing driven by largest scale of motion in the fluid. Characterized by mixing time or blend time in a batch system.
- Mesomixing is mixing on a scale smaller than the bulk circulation (tank diameter) but larger than the micromixing scales, where molecular and viscous diffusion become important. It is an evident of feed pipe scale of semibatch reactors.
- Micromixing is mixing on the smallest scales of motion and at the final scale of molecular diffusivity. It is usually limiting step in progress of fast reactions. It is more or less fixed value.

Measures of Mixedness

- Scale of segregation is a measure of the large scale break up process without the action of diffusion. (Fig.a)
- Intensity of segregation is a measure of difference in concentration between the purest concentration of B and the purest concentration of A in the surrounding fluid. (Fig. b)
- Molecular diffusion is needed to reduce the intensity of segregation.
- Even smallest eddy have a very large diameter relative to the size of molecule, turbulence may not be needed for reduction in intensity of segregation but it can definitely increase the rate of reduction.

Intensity and scale of segregation

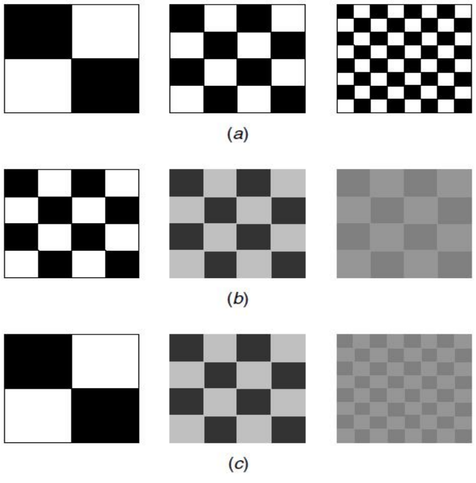


Fig. 15. (a) Reduction in scale of segregation (b) Reduction in intensity of segregation (c) simultaneous reduction in scale and intensity of segregation

Turbulence Vs. Laminar

- The Concept was developed by Prandtl.
- Also called Prandtl mixing length.
- The Design and operation of mixing process in these two flow regime is quit different, the reason for this is
  - Reynolds number
  - Low Reynolds number – Laminar Flow – Viscosity Dominant – Infinitesimal disturbances are damped out.
  - Higher Reynolds number – Turbulent flow – Interfacial force Dominates - No viscosity effect on process

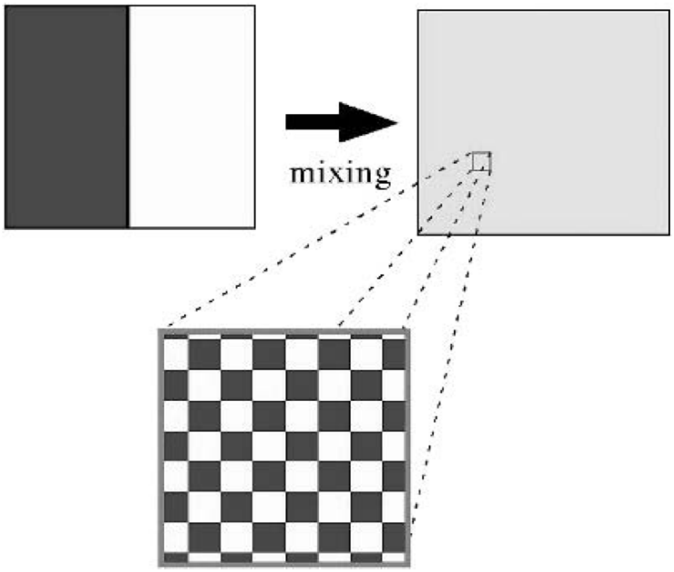


Fig. 16. Evaluating Mixing Performance

Heat and Mass Transfer

In figure 17 both materials are available in equal amount 50%. However, the internal contact area between the two constituent is higher in case (b). The parameter affecting mass transfer, the area available for transport and the diffusion distance, are both affected by the topology of mixture. The area available for transport is greater and diffusion distance is shorter in case (b). if this were a reactive mixture, these difference would result in a faster overall reaction rate in case (b). similar situation occurs in industrial mixture also.

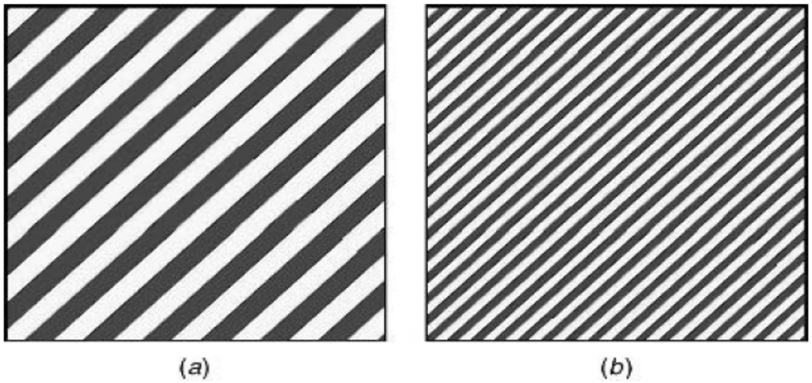


Fig. 17 Interfacial area available

POWER REQUIREMENT

- For an effective mixing, the volume of fluid circulated in a vessel via an impeller must be sufficient to sweep out the entire vessel in a reasonable time.
- Stream velocity leaving the impeller must be sufficient to carry currents to the remotest part of the vessel.

FACTORS AFFECTING THE POWER REQUIREMENT:

- Properties of fluid to be agitated
- Height of the liquid
- Tank size and dimensions
- Agitator type and size
- Speed of agitator

Terminology in Power Calculation

(i) Flow Number

$$q \propto n D_a^{3} \qquad \boxed{N_Q = \frac{q}{nD_a^3}}$$

- Where q is the volumetric flow rate, measured at the tip of the blades, n is the rotational speed (rpm), Da is the impeller diameter
- Total flow was shown to be→ $\boxed{q_T = 0.92 n D_a^3 \left(\frac{D_t}{D_a}\right)}$
- N_Q is constant for each type of impeller. For flat-blade turbine (FBT), in a baffled vessel, N_Q may be taken as 1.3; For marine propellers (Square pitch), $N_Q = 0.5$; For four blade 45^o turbine, $N_Q = 0.87$;
- For HE impeller- N_Q=0.47

(ii) The Reynolds number, N_{Re}

$$\boxed{N_{RE} = \frac{D_a^2 n\rho}{\mu}}$$

(iii) The Froude number, N_{Fr}

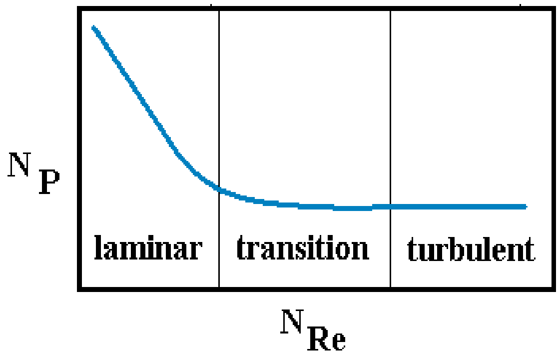
$$\boxed{N_{Fr} = \frac{n^2 D_a}{g}}$$

- Froude No. is a measure of the ratio of the inertial stress to the gravitational force per unit area acting on the fluid. It appears in the dynamic situations where there is significant wave motion on a liquid surface. Important in ship design. Unimportant when baffles are not used or Re< 300

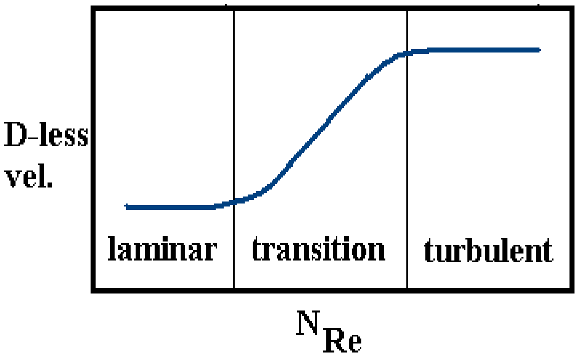
Why Dimensionless Numbers?

- Empirical correlations to estimate the power required to rotate a given impeller at a give speed, with respect to other variables in system
  - Measurements of tank and impeller
  - Distance of impeller from tank floor
  - Liquid depth
  - Dimensions of baffles
  - Viscosity, density, speed

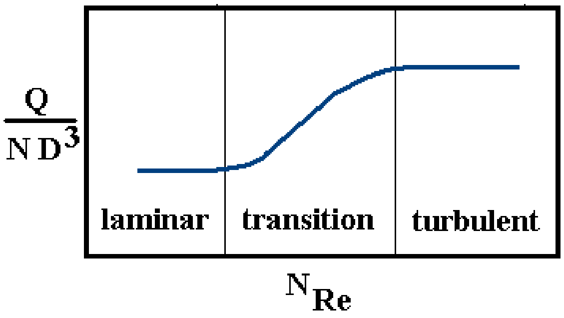
Dimensionless Correlations



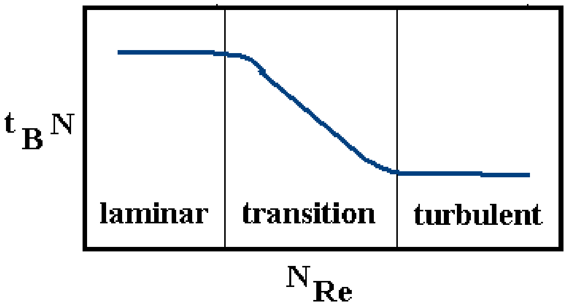
Power versus Reynolds



Velocity versus Reynolds



Pumping number versus Reynolds



Blend time versus Reynolds

Not a predefined empirical equation to find out the power requirement it will depend upon all factors described above some unexpected problems.

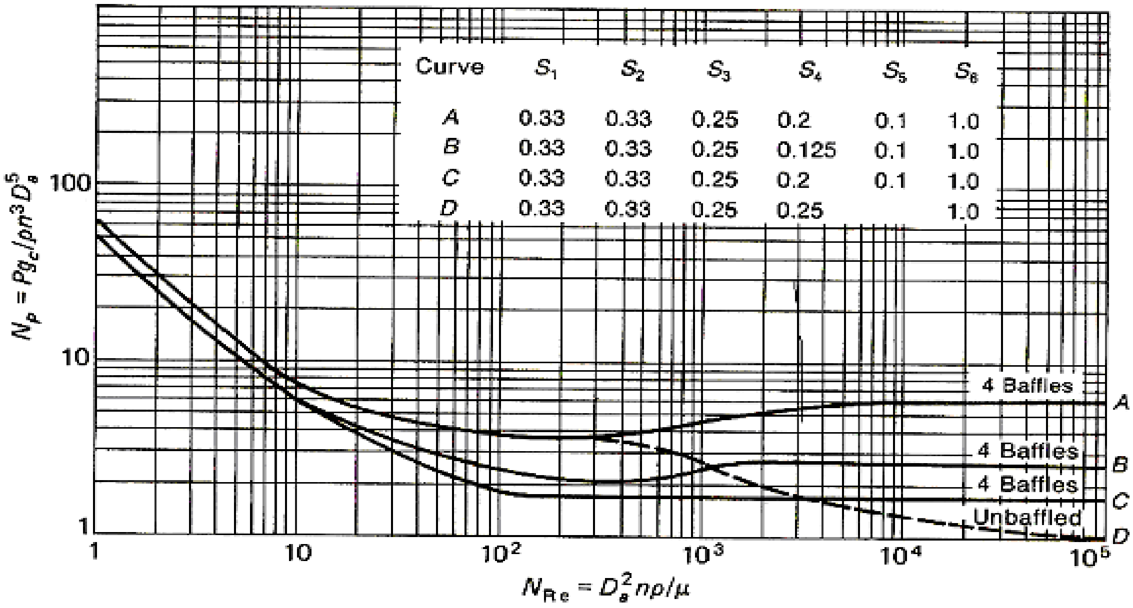
In the power curve:

Region A : Viscous range

Region B : Transition range

Region C : Turbulent region

The curve is drawn for 6flat bladed turbine with height of the liquid is equal to diameter of the vessel and vessel is having 4 baffles.



Power number N_P versus N_{Re} for six-blade turbines. With the dashed portion of curve D, the value of N_P read from the figure must be multiplied by N_{Fr}^m.

Fig. 18. Power Curve for Turbine Type agitator

Curve A = vertical blades, $W/D_a = 0.2$

Curve B = vertical blades, $W/D_a = 0.125$

Curve C = pitched blade

Curve D = unbaffled tank

The power number is calculated as:

$$\phi = N_p = \frac{Pg_c}{8N^3D_a^5} \qquad \text{and} \qquad N_{\mathrm{Re}} = \frac{\rho N D_a^2}{\mu}$$

where N_p = power number

P = power requirement, kg.m

g_c = gravitational acceleration, m/sec^2

ρ = density of the fluid, kg/m^3

μ = viscosity of the fluid, kg/m sec

D_a = Diameter of the vessel

For unbaffled vessel:

$$\phi = N_p = \frac{Pg_c}{\rho N^3 D_a}$$ for $N_{Re} <= 300$

$$\phi = N_p = \frac{\alpha - \log_{10} N_{Re}}{N_{Fr}\beta}$$ For $N_{Re} > 300$

$$N_{Fr} = \frac{N^2 D_a}{g}$$ Fraud Number

Here the values of α & β are given as the function of Diameter of the agitator:

Diameter Da	Da/D	α	β
10	0.3	1.0	4.0
15	0.33	1.0	4.0

If the configuration changes the graph will be changed and the also the values.

After calculating the power requirement from the above calculations the losses of power we have to consider because equation gives the actual values not the losses.

Losses due to the fittings and other attachments.

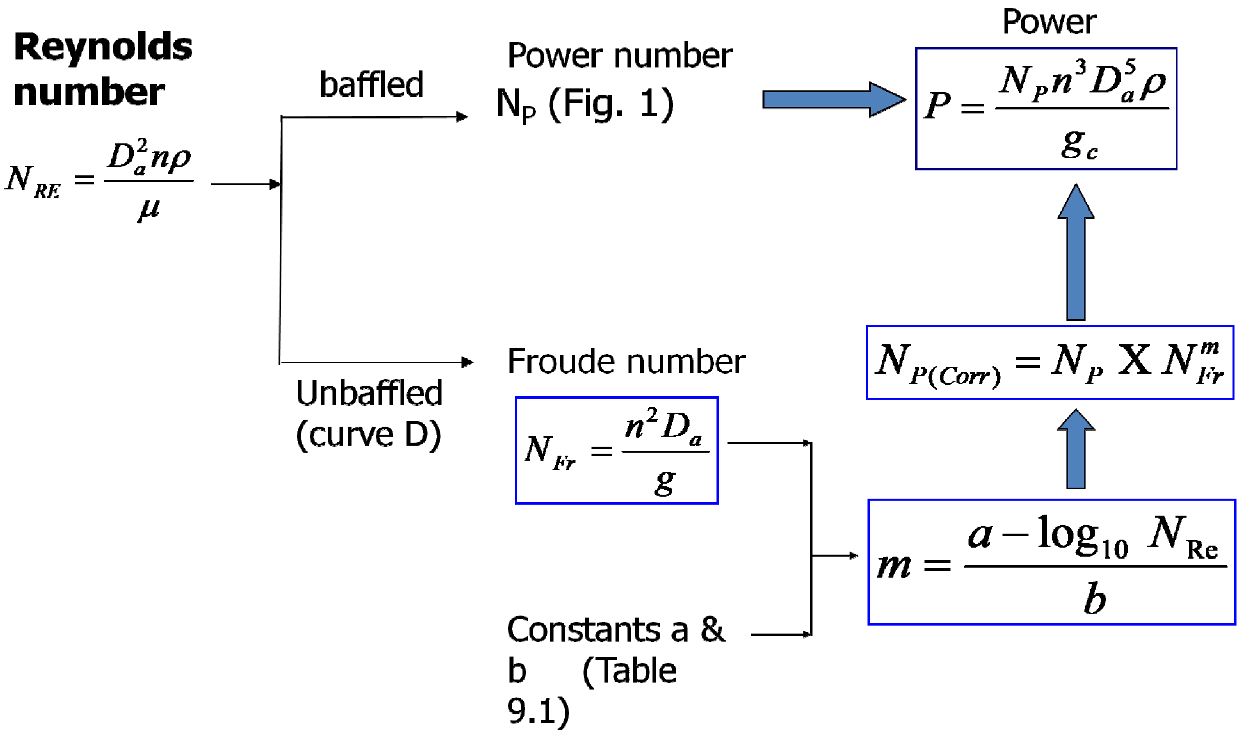
Losses due to transmission and glands (0.5 – 5.0hP or 10 – 20% of maximum requirement)

Basic quantities

Characteristic length:	Impeller diameter	D (m)
Characteristic time:	Inverse impeller speed:	1/N (s)
Characteristic mass:	Liquid density and cube of impeller diameter:	ρ D^3 (kg)

Derived quantities

Characteristic velocity:	Impeller diameter and speed:	DN (m/s)
Characteristic pressure:	Density and velocity square:	ρ D^2 N^2 (Pa)
Characteristic flow rate:	Velocity and area	ND^3 $\left(m^3/s\right)$



Reynolds number

$$N_{RE} = \frac{D_a^2 n\rho}{\mu}$$

baffled

Power number

N_P (Fig. 1)

Power

$$P = \frac{N_P n^3 D_a^5 \rho}{g_c}$$

Unbaffled (curve D)

Froude number

$$N_{Fr} = \frac{n^2 D_a}{g}$$

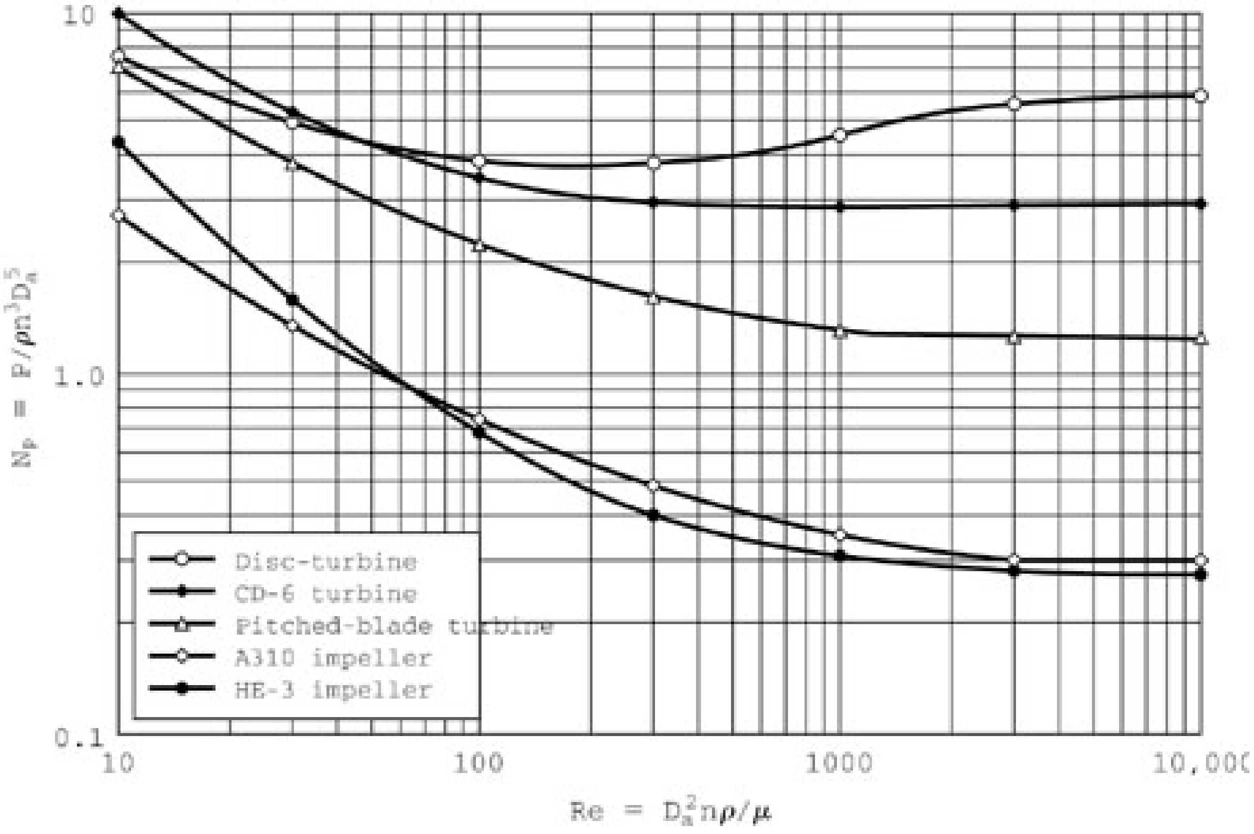
$$N_{P(Corr)} = N_P \text{ X } N_{Fr}^m$$

$$m = \frac{a - \log_{10} N_{\mathrm{Re}}}{b}$$

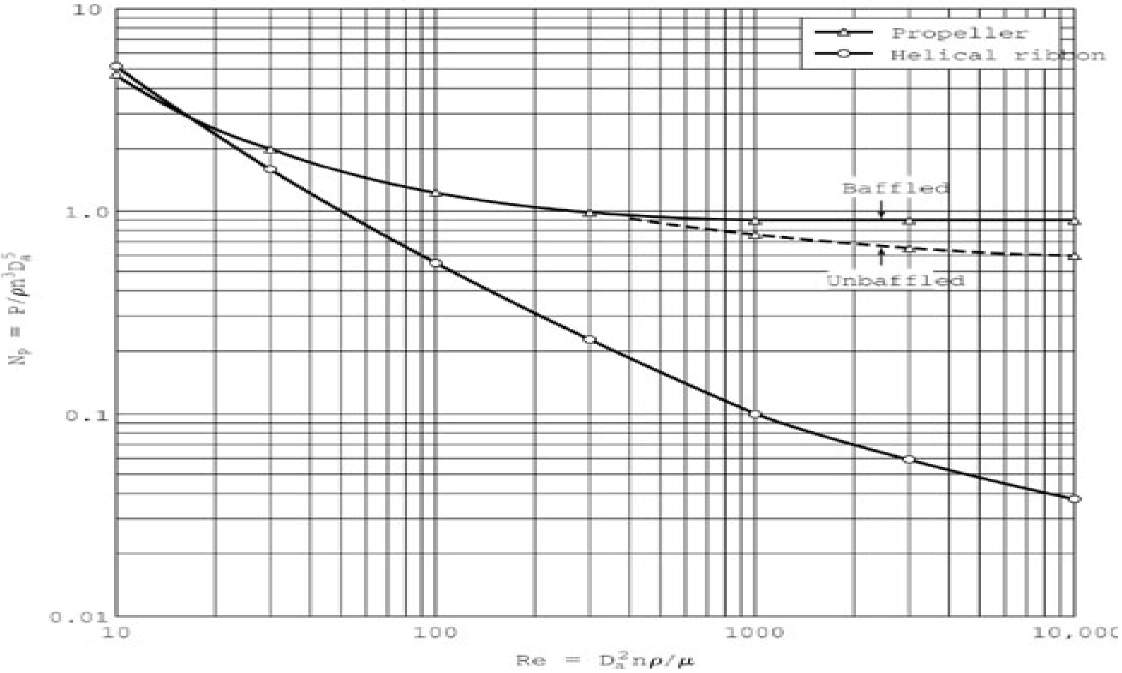
Constants a & b (Table 9.1)

Power Number Curves for Various Type of Impeller

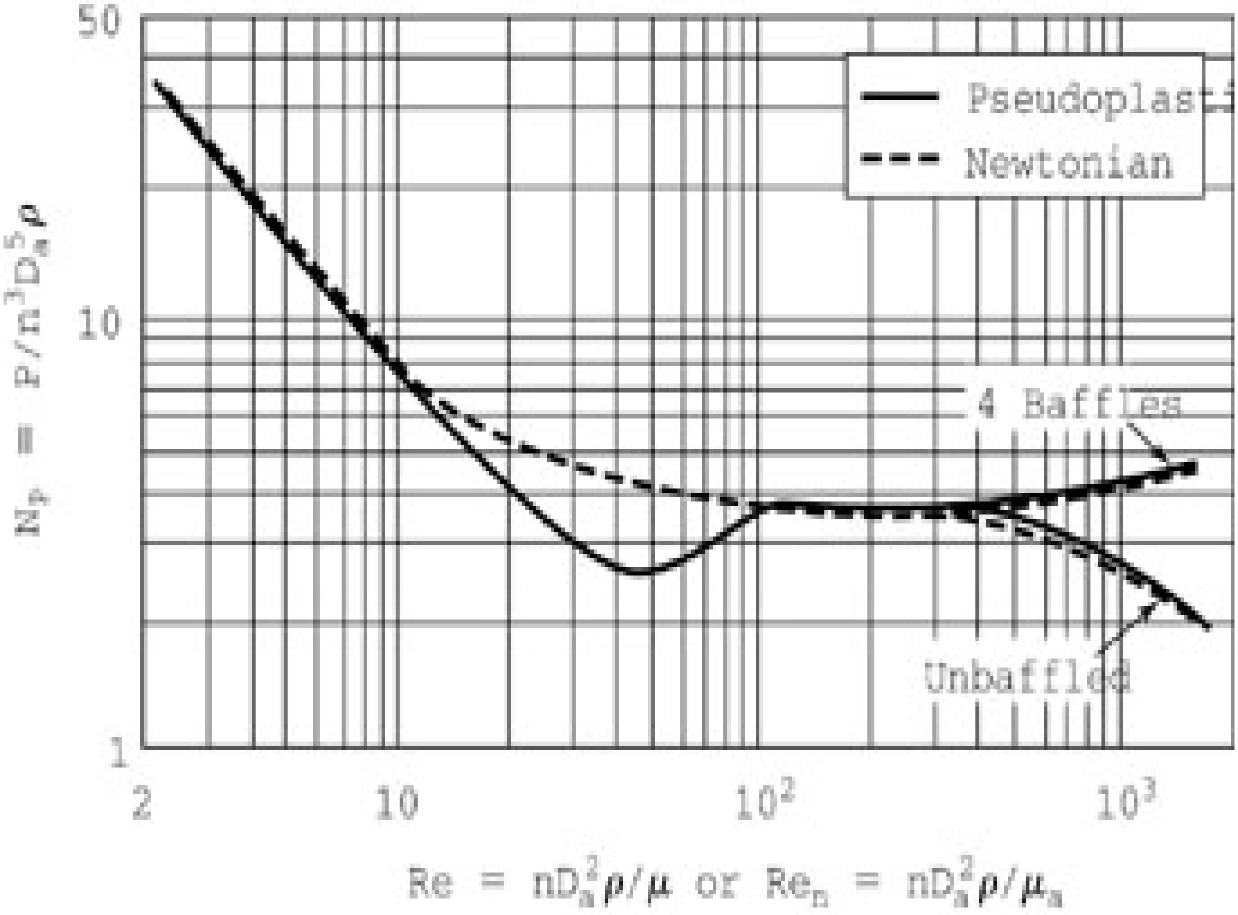
(i) Power number N_P vs. Reynolds number Re for turbines and impellers



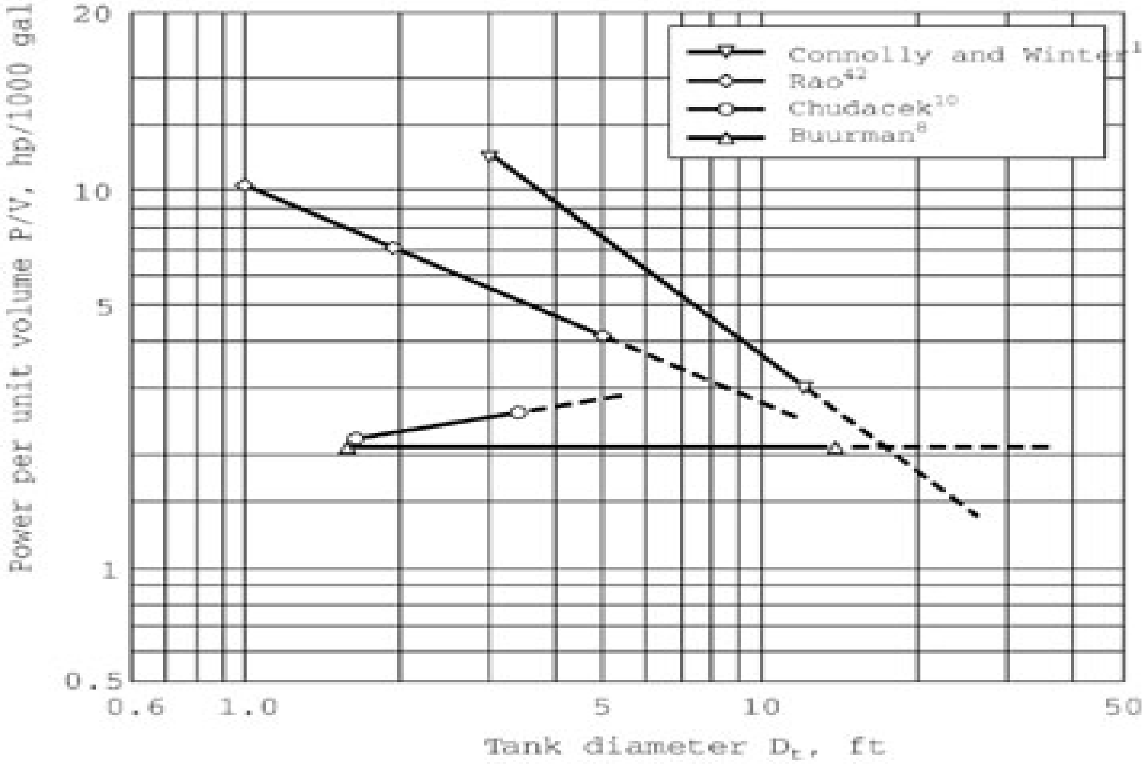
(ii) Power number N_P vs. Reynolds number Re for marine propellers and helical ribbons



(iii) Power correlation for a 6-blade turbine in pseudo plastic liquids



(iv) Power required for complete suspension of solids in agitated tanks using pitched-blade turbines



(v) Power correlation for a 3-blade Propeller Type agitator

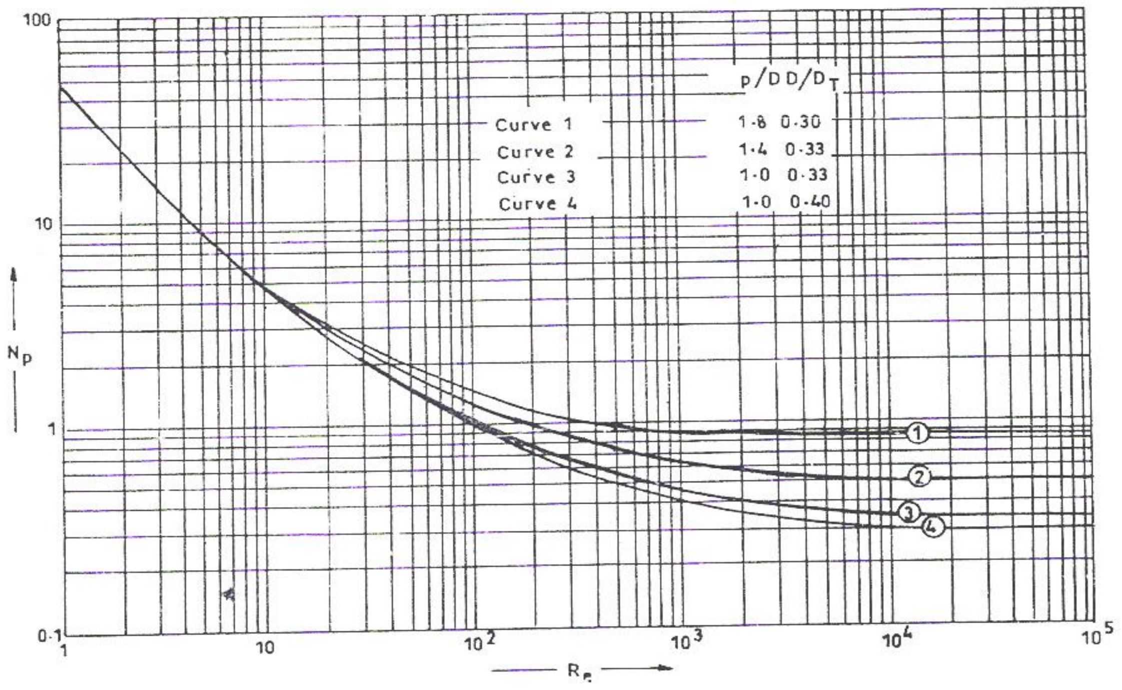


Fig. 4.6 Power correlations for single three bladed propellers

(vi) for turbine type agitator with 6 flat blades liquid height equal to vessel height and 4 baffles are installed

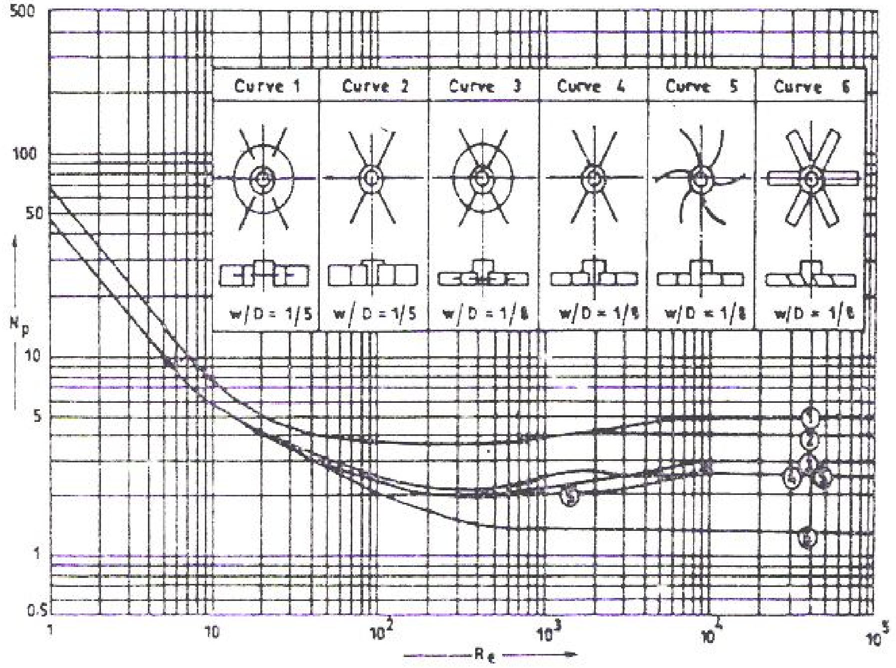


Fig. 4.9 Power correlations for baffled turbine impellers

impeller width ; D – impeller diameter.

Power Consumption

- Power required to drive impeller $q = nD_a^3 N_Q,\quad E_k = \dfrac{\rho (V_2^{'})^2}{2g_c}$
- V'$_2$ slightly less than tip speed, u$_2$ $\alpha = V_2^{'}/u_2$ $V_2^{'} = \alpha \pi n D_a$
- Power Requirement $P = \dfrac{\rho n^3 D_a^5}{g_c}\left(\dfrac{\alpha^2 \pi^2}{2} N_Q\right)$ $P = \dfrac{N_P n^3 D_a^5 \rho}{g_c}$
- At low N$_{Re}$ (<10), density is no longer a factor $N_P = \dfrac{K_L}{N_{Re}}$

$$P = \frac{K_L n^2 D_a^3 \mu}{g_c}$$

- At N$_{Re}$>10,000 in baffled tanks, P is independent of N$_{Re}$ and viscosity is not a factor

$$N_P = K_T$$

$$P = \frac{K_T n^3 D_a^5 \rho}{g_c}$$

- K_L and K_T are constants for various types of impellers and tanks

Type of Impeller	K_L	K_T
Propeller, 3 blades	41	0.32
Pitch 1.0	55	0.87
Pitch 1.5		
Turbine	65	5.75
6-blade disk (S_3=0.25 S_4=0.2)	70	4.80
6 curved blades (S_4=0.2)	-	1.63
6 pitched blades (45°, S_4=0.2)	44.5	1.27
4 pitched blades (45°, S_4=0.2)		
Flat paddle, 2 blades (45°, S_4=0.2)	36.5	1.70
Anchor	300	0.35

Example

A flat-blade turbine with six blades is installed centrally in a vertical tank. The tank is **1.83 m** in diameter, the turbine is **0.61 m** in diameter & is positioned **0.61 m** from the bottom of the tank. The turbine blades are **127mm** wide. The tank is filled to a depth of **1.83m** with a solution of 50% caustic soda at 65.6°C, which has a viscosity of **12cP** and a density of **1498 kg/m^3**. The turbine is operated at **90 rpm**. What power will be required to operate the mixer if the tank was baffled?

Solution:

Solution (a) baffled

n = 90rpm / 60 s = 1.5 r/s

D_a = 0.61m

μ = 12cP = 12x10^{-3} kg/ms

$$N_{RE} = \frac{D_a^2 n \rho}{\mu} = \frac{(0.61)^2(1.5)(1498)}{12 \text{ X } 10^{-3}} = 69600$$

For Re > 10000, Np = K_T = 5.8 from curve A for baffle (NRe = 69600),
NP = 5.8 (or from table 2 given before)

$$P = \frac{N_P n^3 D_a^5 \rho}{g_c}$$

$$= (5.8)(1.5)^3(0.61)^5(1498) = 2476.6\ mN/s = 2476.6W$$

Solution (b) unbaffled

n = 90rpm / 60 s = 1.5 r/s

D_a = 0.61m

μ = 12cP = 12x10^{-3} kg/ms

$$N_{RE} = 69600$$

From Fig 1, curve D (N_{Re} = 69600), N_P = 1.07

Froude number,

$$N_{Fr} = \frac{n^2 D_a}{g} = \frac{(1.5)^2(0.61)}{9.81} = 0.14$$

$$m = \frac{a - \log 10\, N_{Re}}{b} = \frac{1.0 - \log_{10} 69600}{40} = -0.096$$

$$N_{P(Corrected)} = N_P \text{ X } N_{Fr}^m = 1.07\text{X}0.14^{-0.096} = 1.29$$

Thus power,

$$P = \frac{N_P n^3 D_a^5 \rho}{g_c} = (1.29)(1.5)^3(0.61)^5(1498)$$

$$= 550 mN / s = 550\, W$$

Newtonian and non-Newtonian Fluids

- Newtonian fluids:
  Fluids which obey the Newton's law of viscosity are called as Newtonian fluids. Newton's law of viscosity is given by
- Non-Newtonian fluids:
  Fluids which do not obey the Newton's law of viscosity are called as non-Newtonian fluids. Generally non-Newtonian fluids are complex mixtures: slurries, pastes, gels, polymer solutions etc.

$$\tau_{xy} = \mu \frac{\partial v_x}{\partial y}$$

There is also one more - which is not real, it does not exist - known as the ideal fluid. This is a fluid which is assumed to have no viscosity. This is a useful concept when theoretical solutions are being considered - it does help achieve some practically useful solutions.

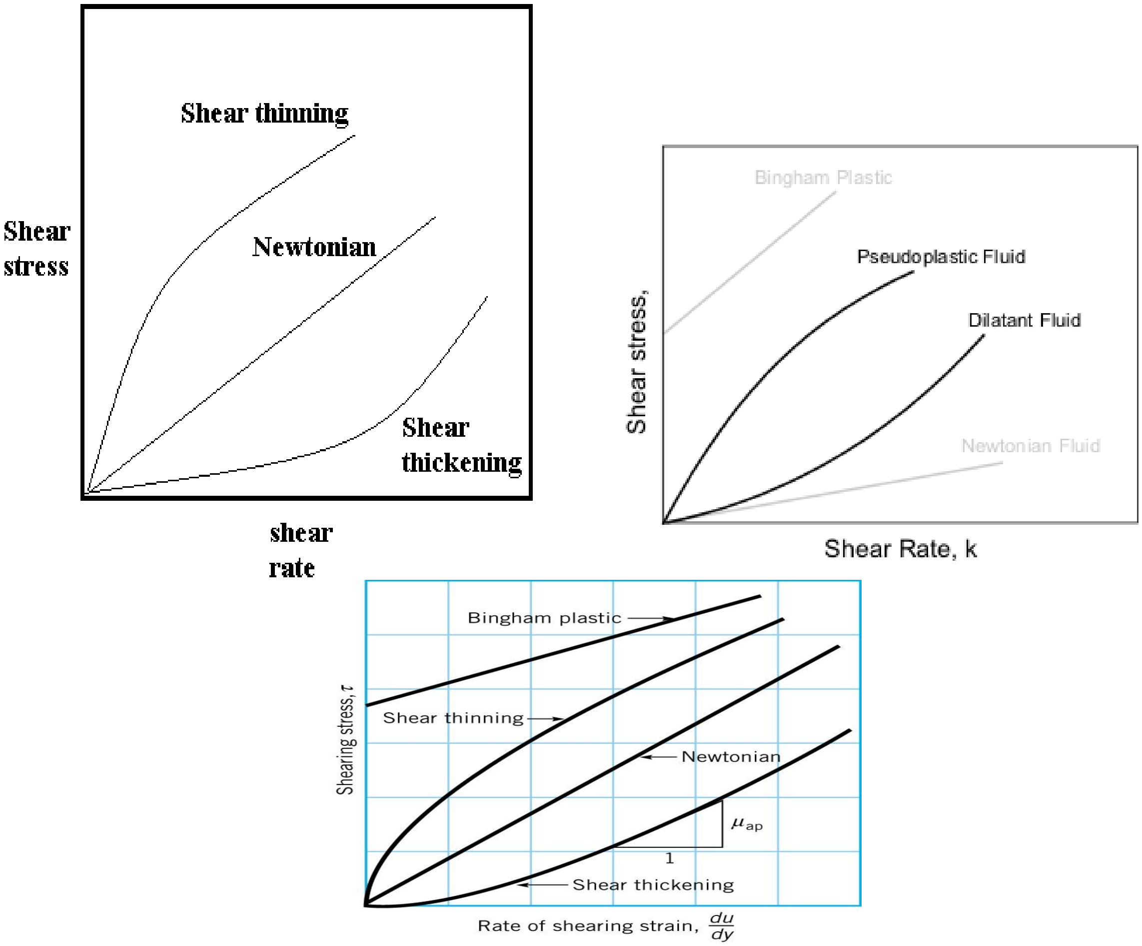


Fig. 19. Various Non-Newtonian Fluids

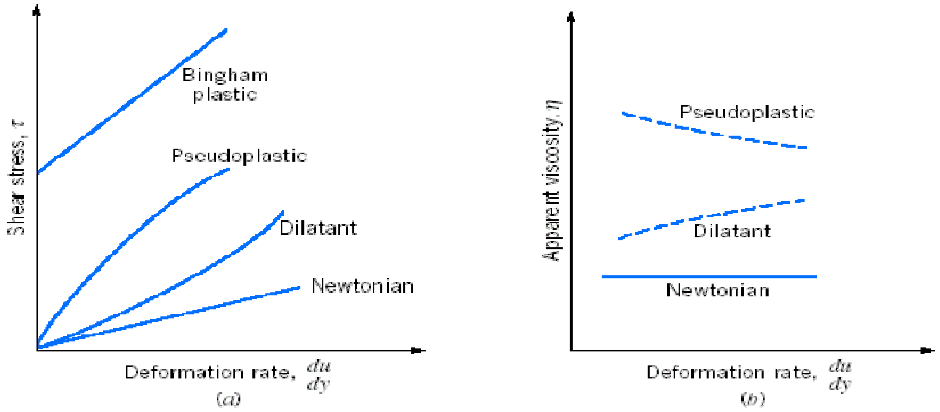


Fig. 2.8 (a) Shear stress, τ, and (b) apparent viscosity, η, as a function of deformation rate for one-dimensional flow of various non-Newtonian fluids.

Power Consumption in Non-Newtonian Liquids

Newtonian fluid:

$$\tau_{xy} = \mu \frac{d\mathrm{v}_{\mathrm{x}}}{\mathrm{dy}} = \mu \dot{\gamma} \qquad : \qquad \dot{\gamma} = \frac{d\mathrm{v}_{\mathrm{x}}}{\mathrm{dy}}$$

Power Law Fluid:

$$\tau_{xy} = K \dot{\gamma}^{n} \qquad : \qquad \mu_a = \frac{\tau_{xy}}{\dot{\gamma}} = K \dot{\gamma}^{n-1}$$

When n<1, viscosity decreases with shear

When n>1, viscosity increases with shear

- Non-Newtonian liquids – viscosity varies with shear rate
- Use apparent viscosity, μ_a

$$N_{\mathrm{Re},n} = \frac{n D_a^2 \rho}{\mu_a}$$

$$\mu_a = K' \left(\frac{du}{dy} \right)_{av}^{n'-1}$$

- For a straight-blade turbine in pseudoplastic liquids

$$\left(\frac{du}{dy} \right)_{av} = 11n$$

SHAFT DESIGN

→ Shaft can be attached to the vessel in vertical, horizontal or angular positions.

→ It is preferable to use the bearing either at top of the vessel or at bottom. It can be placed externally or internally to the vessel.

Scale Up of Mixing Process

The main objective of scale-up is to design a large scale mixing system that will achieve the same mixing quality as in a laboratory tank. Since the distributions of shear rate and energy dissipation widen as the volume is increased, the mixer design must be adjusted to obtain the same process result. Therefore, it is important to understand the impact of these differences on the process. The scale-up criteria depend strongly on the process type and requirements.

Some scale-up methods emphasize geometric similarity. This refers to holding constant the impeller geometry, the impeller dimensional ratios (such as D/T, W/D, C/T), the liquid height/tank diameter ratio, and baffling. There are many situations when complete geometric similarity is not feasible: for example, when the aspect ratio of commercial scale tanks needs to be larger than the laboratory tank.

There are two commonly used scale-up criteria based on holding power per unit volume (P/V) or torque per unit volume (TQ/V) constant on scale-up.

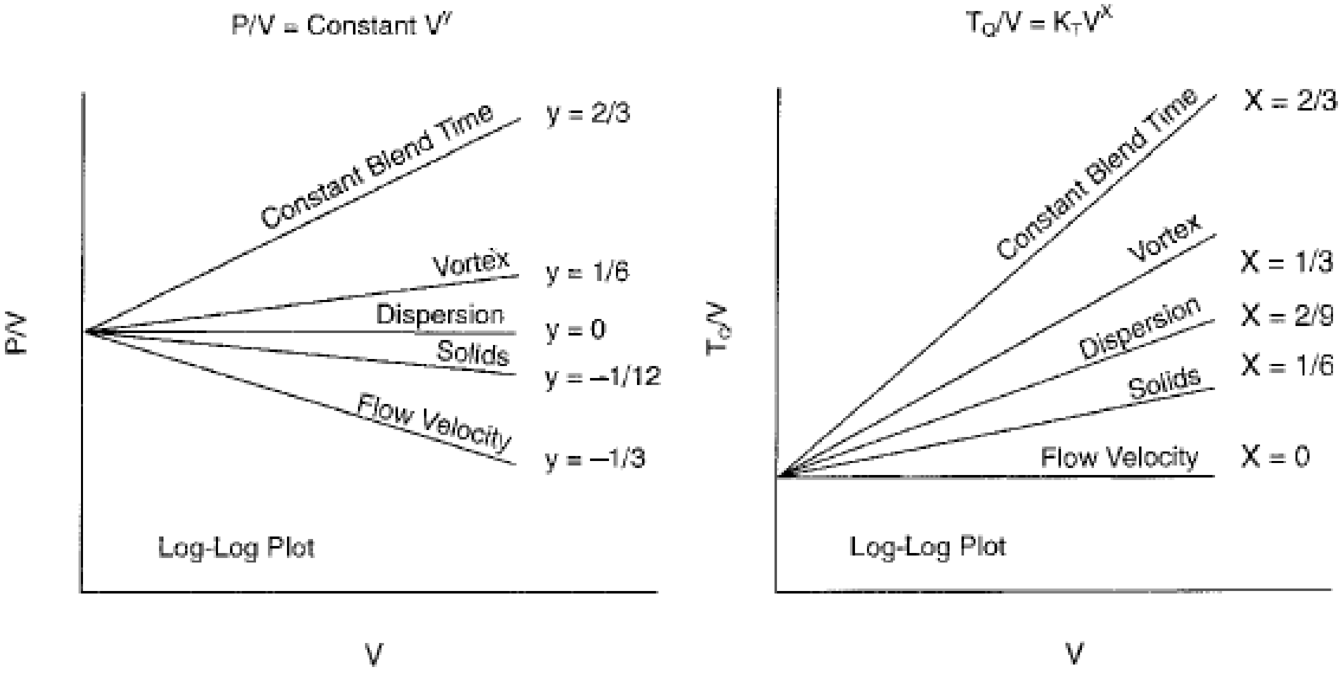


Fig. 1 Scale up method for different types and requirement

Figure 6-28 shows changes in these parameters as the vessel volume is increased for several processes. The exponents x and y in Figure 6-28 should be determined experimentally or verified even for the processes listed in these plots. Some mixing equipment vendors prefer to use the TQ/V criterion because it has a direct impact on the overall size and cost of the mixer, including the gearbox.

When choosing a scale-up method, one must consider changes in other flow and power parameters and their impact on the process result. Table 6-8 shows how these important parameters change on scale-up to 10 times the diameter and 1000 times the volume of laboratory mixing tank. Scale-up methods based on constant blend time require the mixer speed in the commercial vessel to be the same as in the laboratory vessel. This, however, results in a very large increase in the motor power. Such a demanding criterion is necessary for very fast to instantaneous reactions where the reaction lifetime may be a few seconds. Commercial reactors for such systems are, therefore, relatively small in size. Using constant P/V, the mixer speed decreases by 78%, but the blend time increases by a factor of 4.6. If constant P/V is used in scaling up a reacting system, the reactors may need to be sized for longer residence time than the laboratory reactor because of the increase in blend time.

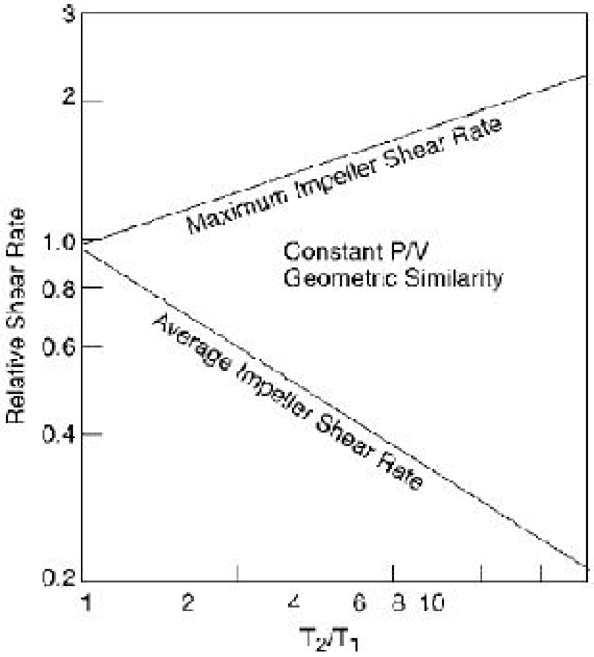


Fig. 2. Changes in maximum and average shear rate on scale-up.

It should be noted that the Reynolds number increases by a factor of 21.5, and therefore, the flow regime may significantly change and affect the mixing quality. Also, the Weber (We) number increases by a factor of 48.4, which may decrease the dispersed phase drop size on scale-up of an immiscible liquid system. Constant tip speed and equal TQ/V are some other scale-up criteria and are used only when flow velocities in the impeller region need to be the same as in the laboratory tank.

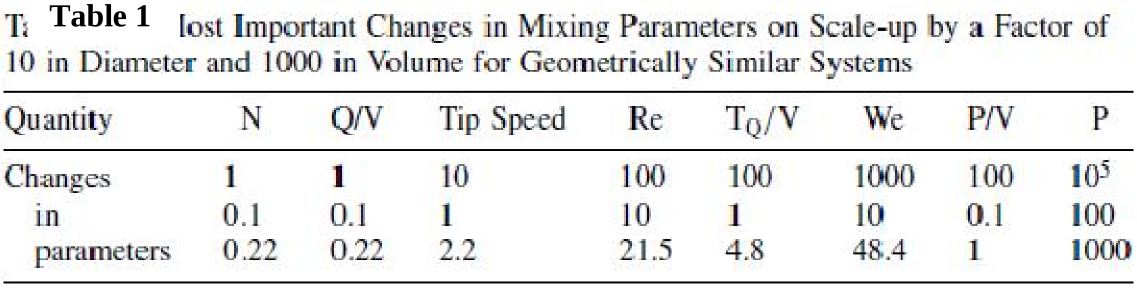


Table 1 lost Important Changes in Mixing Parameters on Scale-up by a Factor of 10 in Diameter and 1000 in Volume for Geometrically Similar Systems

Quantity	N	Q/V	Tip Speed	Re	T_Q/V	We	P/V	P
Changes	1	1	10	100	100	1000	100	10^5
in	0.1	0.1	1	10	1	10	0.1	100
parameters	0.22	0.22	2.2	21.5	4.8	48.4	1	1000

It must be recognized that rotational speed and shear rate change significantly on scale-up at constant P/V.

SCALE UP OF SOLID-LIQUID MIXING

Scale-up is an effort to understand the fundamental phenomena occurring in a process in order to predict the performance in larger scale equipment. It begins with process research at the bench scale, often in small glassware, through pilot scale studies to full production. The value of scale-up is captured in the following comment attributed to L. H. Baekland, the father of plastics: “Commit your blunders on a small scale and make your profits on a large scale.”

In solid–liquid mixing applications, the purpose of scale-up is to determine the operating conditions at different scales at which mixing yields equivalent process results. The tasks involve:

a. Definition of the appropriate desired process result, such as level of uniformity of the solid distribution in a vessel, the time to achieve complete dissolution, the rate of reaction between a solid and a liquid reactant, and so on.
b. Developing reliable correlations that describe the effects of key process properties, mixer design, and operating variables on the desired process result by either experimentation or mathematical analysis of the physicochemical phenomena
c. Determining and confirming the key controlling physicochemical phenomena and the associated correlating parameters, preferably in dimensionless form
d. Applying the key correlations to predict the process performance at different scales

SCALE UP OF GAS-LIQUID MIXING

In the example a gas–liquid reaction with particulate solids (e.g., a catalyst) operating in regime II in a stirred reactor with a Rushton turbine is to be scaled up. The primary process requirement is for the same degree of reaction conversion at each scale, which means the same number of moles of gas transferred per mole of liquid fed:

$$\frac{k_L a V (C_A^* - C_A)}{C_{LBfeed} Q_L} = \text{constant}$$

Assume for simplicity that CA = 0 (a good approximation for regime II) and that the degree of gas backmixing is the same at all scales (this should be checked at the end of the calculation and reiterations performed if necessary). Given a constant feed concentration at all scales,

$$k_L a V C_L \propto Q_L$$

Sometimes it is necessary for the outlet gas concentration to be constant (e.g., with hazardous gases); then from the mass balance this becomes

$$k_L a V \propto Q_G$$

Substituting a suitable correlation for $k_L a$, for example

$$k_L a \propto \left(\frac{P}{V}\right)^{0.7} (v_S)^{0.6}$$

and a curve fit for the gassed power curve, such as

$$P = N^{3.3} D^{6.3} Q_G^{-0.4}$$

not necessarily reliable! an expression such as

$$N^{3.4} T^{6.0} \propto Q_L$$

Will Result.

Another constraint will then fix the design. In this example maintaining $N > N_{JS}$ for the suspension of the catalyst particles is important, so $NT^{0.76}$ = constant could be added (although not strictly applicable to gassed systems), giving

$$Q_G \propto Q_L \propto T^{3.4}$$

This scale-up method has the effects, on increasing the scale, of:

- Increasing vS, so foaming and entrainment become more likely
- Decreasing P/V
- Decreasing the heat transfer flux per unit throughput
- Nearer approach to poor gas dispersion
- Longer liquid mixing time

SCALE UP OF LIQUID-LIQUID MIXING

Scale-up of agitated immiscible liquid–liquid systems can be a challenge that should not be taken lightly. The problems arise from incomplete or inaccurate process information and few quantitative tools to deal with complex technology. In this section we describe some proven practices for scale-up and caution that liquid–liquid dispersion technology is highly system specific.

Most problems are not observed in glass bench scale equipment because unrealistically high rates of circulation mask coalescence and suspension problems. These problems usually surface at the time of scale-up. Throughout this chapter it has been emphasized that production scale vessels are dominated by coalescence, whereas small vessels are dominated by dispersion. As discussed previously, Sprow (1967b) worked with a coalescing system in a small bench scale vessel and found that different regions of the vessel responded differently to agitation. The technology to cope with these complex issues lags other mixing operations, such as blending and solids suspension. Often, all three flow dependent phenomena—dispersion, coalescence, and drop suspension—must be dealt with simultaneously.

A successful scale-up does not mean that identical results are obtained at two different scales, but rather, that the scale-up results are predictable and acceptable. Problem correction at large scale is costly, time consuming, and sometimes not possible (see Section 12-9.2.2). Scale-up errors can lead to losses in capacity, quality, safety, and profits. For example, an explosion resulted from increasing agitation for an inadequately suspended mixed acid nitration. Faster agitation created a large increase in interfacial area at reaction temperatures and led to an uncontrolled exothermic reaction and property loss.

The scale-up of certain liquid–liquid processes can be straightforward. Dilute dispersions are the easiest processes to scale up. The most difficult ones involve simultaneous coalescence, dispersion, suspension, mass transfer, and chemical reaction. If multiple complex reactions are involved, inadequate mixing often leads to yield losses.

The first step is to understand the goals of the process and to acquire accurate data for all components, including physical, chemical, and interfacial properties as well as reaction kinetics. This also includes the influence of minor impurities. Differences in the quality of raw materials need to be considered.

It is important to undertake bench scale studies that simulate the poorer mixing conditions in the larger vessel. For example, simulate the large scale vessel circulation time. Although dispersion is apt to be unrealistic, coalescence and settling problems can be observed. Examination of the flow patterns in the proposed full scale vessel using CFD can help visualize potential problems related to design.

Once the CFD model has been developed and validated, design and operating parameters can be compared to determine design sensitivities. One observation seems to hold universally—better results are always obtained in small equipment.

Identify applications by types likely to cause problems, and separate these from more trivial applications.

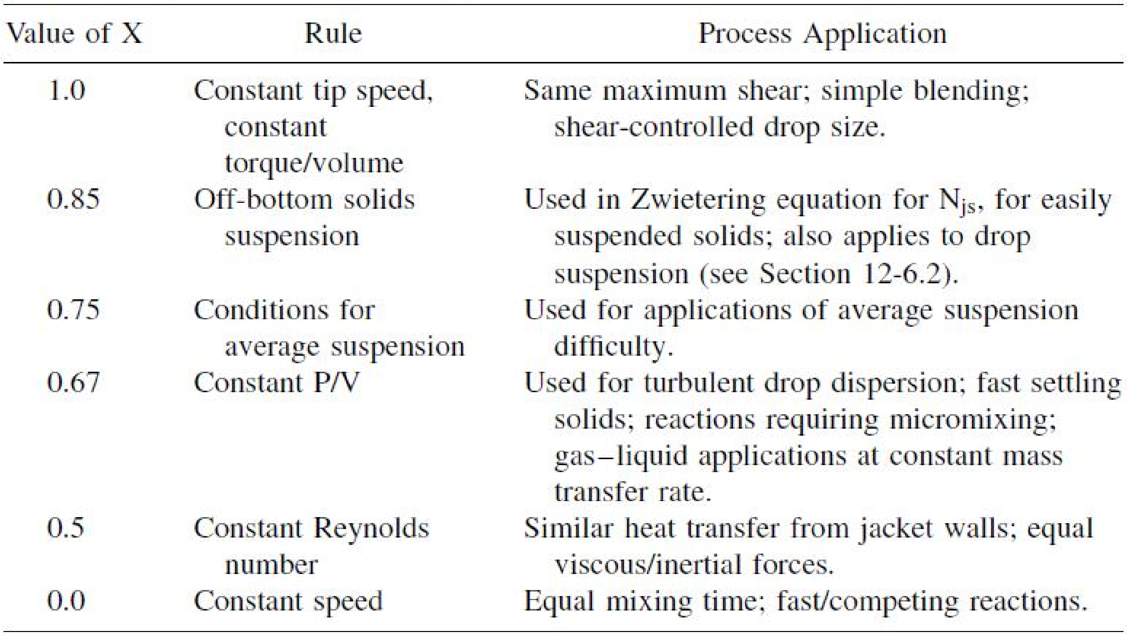
For example, mixing is critical in the following applications:
- Chemical reactors/polymerizers in which reaction rates are equal to, or faster than, mixing rates
- Competing chemical reactions when yields depend on good mixing
- Mass transfer dependent reactions involving coalescence and dispersion

Less demanding tasks include:
- Heat transfer
- Reactors involved with slow chemical reactions

Scale-up Rules for Dilute Systems

Many processes have been scaled successfully using ND^X = constant. This simple rule is based on years of industrial experience. To apply it, the tank Reynolds number must be greater than 10^4 and vessels must be geometrically similar. Table 2 lists the rule and the application best suited to the rule. Other operations, such as blending and solids suspension, are included to provide the reader with an overview of how the exponent on impeller diameter varies from operation to operation. One can see from the table that different scale-up rules apply for suspension, dispersion, heat

Table 2 “Rules” for Scale-up of Geometrically Similar Vessels at Turbulent Conditions, Based on ND^X = Constant



Value of X	Rule	Process Application
1.0	Constant tip speed, constant torque/volume	Same maximum shear; simple blending; shear-controlled drop size.
0.85	Off-bottom solids suspension	Used in Zwietering equation for N_{js}, for easily suspended solids; also applies to drop suspension (see Section 12-6.2).
0.75	Conditions for average suspension	Used for applications of average suspension difficulty.
0.67	Constant P/V	Used for turbulent drop dispersion; fast settling solids; reactions requiring micromixing; gas–liquid applications at constant mass transfer rate.
0.5	Constant Reynolds number	Similar heat transfer from jacket walls; equal viscous/inertial forces.
0.0	Constant speed	Equal mixing time; fast/competing reactions.

transfer, and reaction, making it necessary to focus on the most important or limiting task. As mentioned earlier, the indiscriminate use of rules can lead to problems.

Scale-up of Concentrated, Non-coalescing Dispersions

Dilute, low viscosity dispersions are nearly always controlled by turbulence. At high dispersed phase concentrations, small scale turbulent eddies are damped out by the drops and bulk viscosity increases. As a result, laminar shear forces can control drop dispersion in concentrated systems. Turbulence theories developed for dilute dispersions can sometimes apply to concentrated, noncoalescing systems. However, in other cases, they may not. This is illustrated, by example, below for the scale-up of a suspension polymerization application, described by Leng and Quarderer (1982).

The system consisted of free radical initiated styrene–divinylbenzene monomers dispersed in water containing 0.2% dissolved polyvinyl alcohol. The dispersed phase was 50 vol %. The process was to be carried out in a vessel containing a loop impeller operating at low-shear conditions. Bench scale studies showed important variables to be speed, impeller diameter, baffling, selection of the suspending agent, and continuous phase viscosity. Polymerization reactions were completed and bead size distributions were determined by sieve analysis.

Theories based on laminar and turbulent dispersion conditions were developed, and tested by comparing bead size against each specific variable. Results showed that beads of size greater than 300 μm were formed under laminar shear-controlled conditions, and smaller beads were formed under turbulence controlled conditions.

Leng and Quarderer (1982) reasoned that dispersion occurred in the boundary layer adjacent to the loop impeller surfaces and that the impeller vertical elements could be approximated by cylinders moving through the suspension at the relative impeller tip speed. When laminar shear forces predominated, it was shown that

$$d_{max} = C_{28}\sigma \left(\frac{D_C}{\mu_c \rho_c}\right)^{1/2} \frac{1}{[ND(1-k_v)]^{3/2}} \left(\frac{(\mu_d/\mu_c)+1}{1.19(\mu_d/\mu_c)+1}\right) f(\mu_d/\mu_c)$$

where DC is the diameter of the cylinder and kv is the ratio of the tangential velocity at the impeller tip to the tip speed. All other variables follow earlier use.

The equation for turbulent dispersion was based on the classical development of Chen and Middleman (1967) (see Section 12-2), with the energy dissipation term calculated for drag on a cylinder. Two cases were assumed for the dissipation volume in the wake region behind the cylindrical impeller blade. The first was that an eddy length proportional to the cylinder diameter determined the dissipation volume. The second was that this volume was proportional to the velocity of the cylinder (tip speed) and a characteristic eddy decay time. Equation (12-74) results from the second case. It showed reasonable agreement with data taken at higher speeds.

Design Calculation

The conditions in the large vessel are close as possible to the pilot scale/lab scale unit

Criterion (i) Constant Mixing Time

When the volume of the vessel is increased the length of the flow path for bulk also increases. To keep mixing time constant, the velocity of the fluid in the larger tank should be increased in proportion to the size. Power input per unit volume is proportional to the square of the velocity.

So large power is needed to maintain constant mixing time and so this is not feasible. So this criterion for scale up cannot be used.

Criterion (ii): Constant power input per Unit Volume

$$P = \frac{N_P n^3 D_a^5 \rho}{g_c} \qquad V = \frac{\pi}{4} D_t^{\,2} H \qquad \frac{P}{V} = \frac{N_p \rho n^3 D_a^{\,5}}{\frac{\pi}{4} D_t^{\,2} H}$$

$$D_t = \phi_1 D_a \qquad H = \phi_2 D_t \qquad H = \phi_2 \phi_1 D_a$$

$$\frac{D_t}{D_a} = \phi_1 \qquad \frac{H}{D_t} = \phi_2 \qquad \frac{P}{V} = \frac{N_p \rho\, n^3 D_a^{\,2}}{\frac{\pi}{4} \phi_1^{\,3} \;\; \phi_2}$$

$$\frac{P}{V} = \frac{N_p \rho\, n^3 D_a^{\,5}}{\frac{\pi}{4} \phi_1^{\,2} D_a^{\,2} \;\; \phi_2 \phi_1 D_a} \qquad \frac{P}{V} = \frac{N_p \rho\, n^3 D_a^{\,5}}{\frac{\pi}{4} \phi_1^{\,3} \;\; \phi_2 D_a^{\,3}}$$

$$\frac{P}{V} = K n^3 D_a^{\,2} \qquad \left(\frac{P}{V}\right)_{plant} = K n_{plant}^{\;\;3} D_{plant}^{\;\;2} \qquad \left(\frac{P}{V}\right)_{lab} = K n_{lab}^{\;\;3} D_{lab}^{\;\;2}$$

If we will say $\left(\frac{P}{V}\right)_{lab} = \left(\frac{P}{V}\right)_{plant}$ then

$$K n_{lab}^{\;\;3} D_{lab}^{\;\;2} = K n_{plant}^{\;\;3} D_{plant}^{\;\;2}$$

$$\frac{n_{lab}}{n_{plant}} = \left(\frac{D_{aplant}}{D_{a\,lab}}\right)^{2/3}$$

Criterion (iii) Same impeller tip speed

- nt_m- dimensionless no. represents the number of stirrer rotations required to homogenize the liquid. At high Re, $n_i t_m$ is independent of Re.

$$nt_m = \frac{1.54V}{D_a^{\,3}}$$

Problems:

1. A fermentation liquid of viscosity 0.1 poise and density of volume 2.7 m^3 using Rushton turbine impeller with 1000 kg/m^3 is agitated in a baffled than Estimate the mixing time for a dia of 0.5 m and stirring at a sped of 600 rpm. Estimate the mixing time.

$$n_i t_m = \frac{1.54V}{D_a^{\ 3}} \qquad t_m = \frac{1.54V}{n_i D_a^{\ 3}}$$

$$t_m = \frac{1.54 \times 2.7}{600 \times (0.5)^3} = 0.055 \min = 3.32s$$

2. A pilot plant vessel 1 ft (305 mm) in dia is agitated by a six blade turbine impeller 4 in (102 mm) in dia. When the impeller Re no. is 10000, the blending time of two immiscible liquids is found to be 15 s. The power required is 2 Hp/1000 gal (0.4 kW/m^3. (a) What power input is required to give the same blending time in a vessel 6 ft (1830 mm) in dia (b) What would be the blending time in the 6 ft (1830 mm) vessel if the power input per unit volume were the same as in the pilot plant vessel?

$$N_P = K_T$$

At high Re no's

$$P = \frac{K_T n^3 D_a^5 \rho}{g_c}$$

For a given density

$$\frac{P}{D_a^{\ 3}} = K' n^3 Da^2 \qquad \frac{P}{V} \propto n^3 Da^2$$

$n_a = n_b$ (given)

The ratio of the power inputs per unit volume in the two vessels are

$$\frac{P_b / V_b}{P_a / V_a} = \frac{n_b^{\ 3} D_{ab}^{\ 2}}{n_a^{\ 3} D_{aa}^{\ 2}} = \left(\frac{D_{ab}}{D_{aa}}\right)^2 = \left(\frac{6}{1}\right)^2 = 36$$

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$$\frac{P_b}{V_b} = 36 \frac{P_a}{V_a} = 36 \times 0.4 = 14.4 kW / m^3$$

(For constant blending time)

(b) If the power input per unit volume is same then

$$\frac{P_a}{V_a} \propto n_a^{\ 3} D_a^{\ 2} \qquad \frac{P_b}{V_b} \propto n_b^{\ 3} D_b^{\ 2}$$

$$\frac{P_a}{V_a} = \frac{P_b}{V_b}, then\ n_a{}^3 D_a{}^2 = n_b{}^3 D_a{}^2$$

$$\frac{n_b}{n_a} = \left(\frac{D_a}{D_b}\right)^{2/3} = \left(\frac{6}{1}\right)^{2/3} = 3.3$$

$$The\ blending \quad time \quad in \quad 6\,ft\ vessel = 3.3 \times 15s = 49.5s$$

3. A vertical tank 2.4 m dia is provided with a flat blade turbine impeller (6 blades) mounted centrally in the tank at a height of 0.8 m from bottom. The turbine is 0.8 m in dia and the blades are 167 mm wide. The tank is filled to a depth of 2.4 m With rubber latex compound having density 1120 kg/m^3 and viscosity 120 kg/m.s. If the tank is baffled and turbine is Rotated at 90 rpm, what is the power consumption in hP? Take N_p. Re = 65 for laminar flow and 5.75 for turbulent flow.

$$\mathrm{Re} = \frac{D_a{}^2 n\rho}{\mu} = \frac{0.82 \times 90 \times 1120}{60 \times 120} = 8.96 \angle 10$$

$$(So \quad la\min ar)$$

N_p x Re = 65; N_p = 65 /8.96 = 7.25

$P = N_{P.} N^3 Da^5 \rho$= 8980 W= 12hP