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ON THE FLUID MECHANICS OF FIRES

Sheldon R. Tieszen
Sandia National Laboratories, Reactive Processes Department,
P. O. Box 5800, Albuquerque, New Mexico, USA 87185-0836, e-mail: srtiesz@sandia.gov

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ABSTRACT

Fluid mechanics research related to fire is reviewed with focus on canonical flows, multiphysics coupling aspects, experimental and numerical techniques. Fire is a low-speed, chemically-reacting, flow in which buoyancy plays an important role. Fire research has focussed on two canonical flows, the reacting boundary-layer and the reacting free plume. There is rich, multi-lateral, bi-directional, coupling among fluid mechanics and scalar transport, combustion, and radiation. There is only a limited experimental fluid-mechanics database for fire due to measurement difficulties in the harsh environment, and the focus within the fire community on thermal/chemical consequences. Increasingly, computational fluid dynamics techniques are being used to provide engineering guidance on thermal/chemical consequences and to study fire phenomenology.

INTRODUCTION

The study of fire, the primitive, uncontrolled, form of combustion, is primarily motivated by safety. In his look into the 21st century, Cox 1999a, notes that the total cost of fire to the developed nations of the world is about 1% of gross domestic product each year. As a consequence, much of fire research is focussed on fire threats, effects, mitigation, and prevention. It has been twenty years since Howard Emmons reviewed fire for Annual Review of Fluid Mechanics (Emmons 1980). In the intervening time, the subject area has seen very rapid growth, to the extent that it is not possible to provide a comprehensive review of the subject in a single article. The scope of this article is limited to fluid mechanics aspects of fires, and to fires in which buoyancy plays an important role (thus limiting discussion of momentum driven jets and microgravity combustion, which also have fire safety consequences). Even within this limited context, it is not possible to cite all worthwhile contributions to the field. In order to provide the overall context of the field, the author relies on citing reviews in specific topical areas and emphasizes more recent articles, thus undoubtedly missing direct citation of many important foundational papers in fire research.

Fluid mechanics research in fires has generally followed fluids research in other topical areas. Canonical flows have provided the basis for understanding that has been incorporated into correlations and numerical simulation techniques that have been applied to practical fire problems. As the field matures, emphasis is shifting from understanding global, time-averaged characteristics, to detailed understanding of the multiphysics interactions inherent in fires. Data often provides needed insight, and always provides the validation of our knowledge, as science at its base is empirical. This review is divided into four topical areas, canonical flows, multiphysics coupling, fluid mechanical measurements in fires, and numerical simulation of fires.

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CANONICAL FLOWS

Fires occur in any arbitrary geometry as long as fuel, air, and an ignition source exist. However, for phenomenological studies, it is desirable to eliminate geometrical complexity but still remain relevant to the application. Thus two canonical flows have been studied by fire researchers, wall bounded, reacting, boundary-layers and free-field, reacting, plumes, i.e., the reacting analogies of classical non-reacting boundary layer and plume studies.

Reacting Boundary Layers

In fires, transient boundary layer studies are most numerous because of the need to understand the dynamics of flame spread over a combustible solid or liquid. Fernandez-Pello (1995) provides an excellent review and tutorial of the subject for solid materials, linking flame spread studies to fundamental hot gas ignition studies. In spite of all the complex, fluid mechanical, heat transfer, and chemical reactions involved, two time scales control flame spread in boundary layers: the time required to begin material pyrolysis and the time required for the pyrolized material to undergo exothermic reaction. The direction of the bulk-fluid flow relative to that of the propagating flame makes a large difference in the mechanisms which dominate flame spread rates. The bulk fluid-flow may be buoyantly driven, as on a vertical surface, or mechanically forced. As shown schematically in Figure 1, the flame spread can be classified as either opposed or concurrent (wind-aided) depending on the direction of flame spread relative to the flow direction.

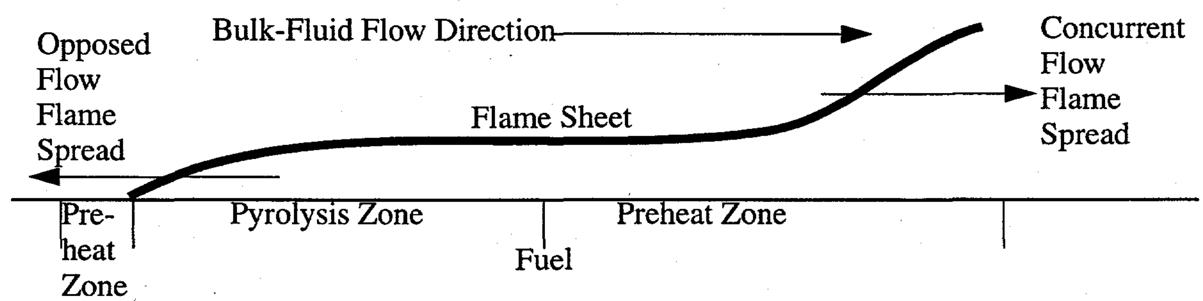

Figure 1. Flame Spread Geometry.

Sirignano & Schiller 1997 review opposed flow-flame spread over solids. In the opposed flow case, the toe of the fire is anchored just upstream of the pyrolysis region and the flow drives the flame over the pyrolizing region. The flame spreads as the anchor point moves upstream against the opposing flow. As a consequence, flame spread is very much influenced by thermal and fluid processes which occur in the immediate vicinity of the flame anchoring point near the wall and most of studies of opposed-flow flame-spread are laminar. The importance and manner in which the velocity is characterized in the near wall region is currently of considerable debate. Early work by deRis 1969 used a uniform (Oseen) flow approximation and its use has continued to date. For example, using the Oseen flow approximation, Rybanin 1996, 1998 examines the effect of finite-rate kinetics on flame spread and finds that the flame anchor moves away from the surface and into the flow as the flame becomes increasingly kinetically controlled. The Oseen approximation results in considerable mathematical simplification but it does not reflect the no-slip condition at the wall. The importance of this fact is pointed out by Bhattacharjee et al 1996 and Wichman & Osman 1998 who suggest that use of a velocity based on the near wall region is more appropriate than use of the bulk velocity in correlating flame spread. On the other hand, Higuera et al 1997 discusses the possibility that wall blowing behind the flame may result in boundary layer separation ahead of the flame. Zhou et al 1990 show that free-stream turbulence does have a quantitative effect on flame spread in the chemical kinetic controlled regime. In general, opposed-flow flame spread is a steady phenomena; however, unsteadiness in certain flow regimes has been noted (Chen & Yang 1998).

As in all aspects of fires, debates over governing fluid mechanics phenomena must be interpreted in the context of the multi-physics environment in fires where the changes in the other physical mechanisms can change the flow character. In the thermally controlled regime, flame spread increases with increased flow velocity (c.f., Fernandez-Pello 1995). In this regime, Di Blasi & Wichman 1995 discuss the differing effects of normal vs. longitudinal conduction and Higuera 1999 discusses the relative importance of heat conduction in the solid versus that in the gas phase. Delichatsios 1996a discusses a means of incorporating flame and external radiation effects into flame spread correlations. In the kinetically controlled regime, flame spread-rate decreases with increased flow velocity (c.f., Fernandez-Pello 1995). As the spread becomes increasingly dominated by kinetic rates, Wolverton et al 1999 point out the need for increasingly sophisticated multi-step kinetic mechanisms to describe the limiting behavior.

In concurrent flame spread, the flame toe remains anchored in the pyrolysis zone and the head of the flame is swept downstream beyond the pyrolizing region over fresh fuel as shown in Figure 1. The spread rate is dependent on the flame length and the time required to heat and pyrolize the solid (c.f., Fernandez-Pello 1995). Concurrent-flow flame-spread-rates are orders of magnitude faster than for opposed spread (c.f., Quintiere 1995). During the early part of concurrent flame spread, the gas flows can be considered laminar and convection from the flame to the solid dominates heat transfer to the fuel (c.f., Di Blasi 1995a). As the flame length grows beyond a few centimeters, radiation plays an increasingly dominant role (c.f., Orloff et al 1975) and turbulence becomes important. Many materials that will not naturally propagate a flame in a concurrent spread configuration due to self-induced buoyancy, such as wood products, will do so with an externally applied radiation source (c.f., Brehob & Kulkarni 1998, for a recent example). The role of free stream turbulence on flame spread has been studied by Zhou & Fernandez-Pello 1993 and Chao & Fernandez-Pello 1995. Steady state boundary layers have also been studied in the concurrent flow mode by Zhou & Fernandez-Pello 1992. Joulain 1996 reviews a series of studies at Poitiers that show that wall blowing has a minor effect on the fluid flow in unconfined, reacting boundary layers but becomes increasingly important with confinement resulting in a change of heat transfer mode to the surface from radiative to convective.

Hirano & Suzuke 1993, Ross 1994, Sirignano & Schiller 1997 review studies on flame spread over liquids. The propagation speed is generally dependent on the liquid temperature relative to its flash point, i.e., that temperature at which sufficient combustible vapor is produced to reach the lower flammability limit. For liquid temperatures in the subflash regime, two propagation modes are present, a steady mode and a pulsating mode. In both modes, liquid recirculation due to temperature induced surface tension variations is important. Sirignano & Schiller 1997 note that the liquid recirculation results in flame spread rates that are typically an order of magnitude higher than in solids. Di Blasi 1995b describes the separation between the steady and unsteady mode as being due to the location of the recirculating liquid relative to the flame front; however, Sirignano

& Schiller 1997 note some disagreement among predictions from computational models for the extent of liquid motion ahead of the flame front in the steady regime.

In the pulsating mode, both liquid and gas phase flows are important. Through a series of recent papers the mechanisms underlying the pulsation have been described with increasing clarity (Ross & Miller 1996, Schiller et al 1996, Miller & Ross 1998, Kim 1998, Higuera & Garcia-Ybarra 1998, Ito et al 1999). Temperature induced surface-tension gradients are a major driving force for pulsating flame spread. During the slow phase of the pulse, liquid recirculation occurs in front of the flame toe, with high temperature fluid being transported along the surface in the direction of flame travel. From the no-slip condition at the liquid/gas interface, the surface-tension-gradient-driven liquid flow in turn drives a gas flow in front of the flame in the direction of flame propagation. However, the general boundary layer flow in a quiescent atmosphere is opposed to the direction of flame propagation due to lofting of the flame behind the leading edge due to buoyancy. The counter currents in the gas phase result in an eddy in front of the flame that traps the vapor being generated by the surface-tension driven liquid recirculation zone. When the vapor concentration in the gas phase exceeds the flammability limit, the flame propagates through the gas as a premixed flame until it reaches the end of the recirculation zone. Then the pattern of vapor build up and burn out repeats itself. Ross & Miller 1998 show differences in propagation behavior caused by low velocity opposed and concurrent flows. It should be noted that all these studies have involved laboratory scale experiments or computations based on laminar flow conditions. White et al 1997 note early studies that show channel widths need to be at least 20 cm for the flame spread results to be independent of scale, larger than most of the laboratory scale studies discussed above.

Hirano & Suzuke 1993 review flame spread processes for liquid temperatures above the flash point. In this regime, vapor phase processes dominate and flame spread can be several times the laminar flame speed, with the gas in front of the flame driven outward by the flame front. In concurrent flame spread, the flame speed can match the driving speed of the concurrent flow. The transition to vapor phase domination does not occur at the flash point but several degrees above it, allowing for a more robust fuel/air mixture to form. White et al 1997 note vapor phase dominated flame spread occurs at approximately fifteen degrees above the flash point for aviation fuels.

Reacting Buoyant Plumes

Unlike boundary layer studies in fires, plume studies are primarily steady state. When the gravity vector is normal to, and directed at, a surface, buoyancy results in the flames leaving the fuel surface in the form of a reacting plume. In general, if the geometry surrounding the fire is sufficiently open to allow entrainment, the fuel source is contiguous, and the pyrolization/vaporization rate is above a minimum value, a single plume forms. The reacting plume is the most commonly studied type of free flow for fires and is often called a pool fire. Joulain 1998, provides a comprehensive review of the literature on the subject, therefore, only a brief review will be given here.

Fluid mechanics research has focussed on three areas: the length of reacting plume (i.e., height of the fire), the transport characteristics of the post-combustion plume above the fire, and entrainment into the both fire and plume. Fire height has been the subject of many studies (c.f., McCaffrey 1995 for review prior to 1988) and continues to be an area of active research (Peters and Göttgens 1991, Delichatsios 1995, Heskestad 1998a, 1998b, Blake & Cote 1999), with recent efforts focussing on a universal flame height correlation for both buoyancy dominated fires and momentum dominated jet flames.

Above the active combustion region of the fire, the hot gas plume is treated as emanating from a point source and self-similar relations are used in accordance with classical non-reacting plume theory (Rooney & Linden 1996) with consideration that Boussinesq approximations are not appropriate until several flame lengths above the fire (Rooney & Linden 1997). The buoyant force, i.e., the mean density difference, is related to the convective heat release (product of mass flow rate of fuel, heat of combustion, and the fraction of heat not lost through radiation) of the fire. Heskestad 1998a, reviews the work in this area. The plume growth is related to air entrainment and its width scales linearly with distance from the source. Due to the entrainment, the temperature difference between the centerline and ambient scales as the -5/3 power with the distance from the source, and the centerline velocity scales as the -1/3 power with the distance from the source. The largest discrepancy in the data appears to be the ratio of the temperature radius to velocity radius (where each reaches 1/2 the centerline value) with data ranging from 0.86 to 1.5. Quintiere & Grove 1998, provide a unified analysis for square, line, and round source geometries using the Boussinesq approximations.

As with plume growth, the height of the flames in a fire is related to air entrainment rates. While there is general agreement as to the entrainment rates in the plume above a fire, there is quantitative disagreement on both magnitudes and scaling within a fire. For example, in the first three articles in the SFPE Handbook section on fire dynamics, different estimates are given for the magnitude of air entrained relative to the stoichiometric amount required at the flame height. McCaffrey 1995, indicates that "15 to 20 would be a 'reasonable' value"; Heskestad 1995, "12 times", and Delichatsios 1995, "ten times." Zukoski 1995, compares five models that have different air entrainment vs. versus distance from the fuel source scaling, with entrainment proportional to the distance to a power which varies from model to model between 3/4 to 3/2. Blake & Cote 1999, note models with scales running from 3/2 to 5/2 power for buoyant jet flames. Delichatsios 1995, suggests a scaling of 1/2 power with distance from the source at the base of a fire through 3/2 power at the collapse of the vapor dome to 5/2 power along the reacting column until the flame height. Cetegen et al 1984 and 1995 suggest that the data show a linear scaling with distance from the source, although recent entrainment data by Zhou et al 1996, suggest a 3/4 power. All these correlations are based on time-averaged data although Delichatsios 1995, notes the critical role of large-scale turbulent features in fires. Cetegen 1998, has proposed a dynamical model that involves the large-scale vortical structures. He integrates the model through a puffing cycle to obtain an average entrainment rate. He finds the entrainment is linearly proportional to distance from the base of the fire and slightly more than linearly dependent on fire diameter. All other correlations generally show entrainment as scaling approximately linearly with diameter.

If the fuel source is distributed, or is too weak (Heskestad 1998a), a single fire plume is not formed and multiple plumes exist. These fires are termed 'mass fires'. Canonically, mass-fires have flow structures similar to the simpler Rayleigh-Benard-type flow in that neighboring plumes interact but insufficient entrainment exists at the edges of the mass fire to force the individual plumes into a single coherent plume. In the same vein, the base of a coherent fire-plume shares characteristics with simpler Rayleigh-Benard-type flow with imposed shear. The 'rib and channel' structure noted by Weckman & Sobesiak 1988 is perhaps a consequence of the interaction of shear, imposed by radial entrainment into the fire, and the upward buoyant flow at the base of the fire.

One of the most striking characteristics of the canonical fire plume is that it puffs at a characteristic frequency that is inversely proportional to the square root of the source diameter (c.f., Zukoski et al 1984, Weckman & Sobesiak 1988, Pagni 1990, Cetegen & Ahmed 1993, Hamins et al 1992, Malalasekera et al 1996). This phenomenon is a fluid dynamic, as opposed to a combustion, instability. Hamins et al 1992, demonstrates that it does not depend on heat flux to the surface of the pool and that isothermal, helium plumes exhibit puffing behavior, but with a somewhat different dependence on source diameter. Cetegen & Kasper 1996, explain the different scaling between the helium plumes and fire, by noting the difference in convective velocity of the shed vortex due to the fact that combustion sustains the driving density difference in a fire while the density difference decreases with mixing in the helium plume.

The nature of the instability is still a matter of debate. Ghoniem et al 1996 cites studies that propose various causes including buoyant dynamics, shear instability, buckling inviscid instability, and formation of large scale structures. Very recent work by Cetegen & Dong, 2000 shows that laminar flames are subject to both varicose and sinuous instabilities at small scales, but the varicose mode becomes dominant for source diameters over 10 cm. In momentum dominated flows, the varicose mode is attributed to a Kelvin-Helmholtz instability (Coats 1996). However, even in jets, density differences can be important. Kennedy & Chen 1998 show that in planar heated jets, hot jet instabilities have an order-of-magnitude higher growth rate than isothermal counterparts. In plumes, Cetegen & Kasper 1996, attribute the puffing to a Rayleigh-Taylor instability and Ghoniem et al 1996, attribute it to both. Cetegen 1997a discusses whether the instability should be considered a convective or absolute instability and favors a convective-type instability. In favor of absolute instability is the fact that a vertical column of helium in air represents a Rayleigh-Taylor problem with gravity parallel, as opposed to perpendicular, to the interface. Hence, baroclinic vorticity generation from the misalignment of the hydrostatic gravity gradient and the horizontal density gradient will result in the formation of a vortex sheet without any velocity field. Also, the instability manifests itself very near the source, a fact Maxworthy 1999 notes in support of a global instability. On the other hand, in numerical simulations in which the effect of the local hydrodynamic acceleration field could be turned on and off, Mell et al 1996 note that the high acceleration at the base of a plume/fire has a stronger role than gravity in determining the puffing frequency. This result would favor puffing being the result of a convective-type instability.

MULTI-PHYSICS COUPLING

Inherent in all fires is the coupling between the momentum field and the scalar fields, the combustion chemistry, and the radiation. For turbulent flows this coupling occurs simultaneously over a spectrum of length and time scales and for the most part is bi-directional.

Momentum/Scalar Interactions

The momentum equations are coupled to scalar transport through the effect of gas density variations and gravity. However, the simplicity of the buoyancy term in the momentum equations is in contrast to the underlying complexity of the interaction. Density variations may be due to molecular weight and/or temperature differences (neglecting ambient pressure fluctuations). The clearest physical picture of the interaction is given by kinematic Helmholtz decomposition of the velocity field into its curl (the vorticity), its divergence (the dilatation), and boundary conditions (c.f., Baum & McCaffrey 1988, Knio et al 1996, Najm et al 1998). Baum & McCaffrey 1988 apply the technique to fires. The vorticity field is dominated by the intense vorticity created by the large density gradients at the edge of a fire. The dilatation field is dominated by heat release due to combustion.

In the decomposition, the buoyancy term ends up explicitly in the vorticity transport equations and is called baroclinic vorticity generation. It is due to a misalignment of density gradients with the local acceleration field including gravity (c.f., Najm et al 1998 for a convenient acceleration vs. pressure gradient form). As vorticity is produced along density gradients (misaligned with the local acceleration field), and turbulent mixing causes density gradients to exist at length scales across the entire spectrum from diffusive to global scales, baroclinic vorticity generation can be expected to occur over the same spectrum. Thus, even though the buoyancy term in the Navier-Stokes equations is linear, the effect of buoyancy on momentum transport is expressed as vorticity generated in the flow field along density gradients (that are misaligned with the local acceleration field) having a broad spectrum of length scales. The vorticity results in rotational motion across a broad spectrum of length scales and in this regard buoyancy may be thought of as generating turbulence in fires.

At whatever scale the vorticity is being locally generated by buoyancy, turbulent advection processes will result in a length scale cascade. Ghoniem et al 1996, note that the Kelvin-Helmholtz instability will result in the roll-up of the vorticity produced at the edge of a fire. Amalgamation of large-scale structures can be seen in their simulations and are readily seen in fires (Tieszen et al 1996). The presence of the baroclinic vorticity may affect the quantitative pairing of vortices as found by Soteriou and Ghoniem 1994 in a mixing layer, but it does not suppress them.

It should be noted that if the density of the fuel and the air on either side of the flame zone are the same, then there is no net vorticity generation across a flame zone (Knio et al 1996). Rather a vortex dipole is created with counter-rotating vortices on either side of the flame zone which advect themselves (and the flame zone). The presence of vorticity of different sign can be seen experimentally in the work of Zhou & Gore 1998.

The coupling between the momentum field and the scalar field is bidirectional. The turbulent momentum field results in the entrainment of air deep into the fire plume as shown by the simulations of Ghoniem et al 1996. The result is a very large increase in the combusting surface area and a relatively short flame height. While the entrainment of air by large scale structures and the resultant turbulence spectrum are very effective at creating flame surface area relative to laminar diffusive processes, they result in very poor mixing relative to that in man-made combustion systems as evidenced by energy release per unit volume measurements (Cox 1995) for which fires have lower values by factors of 10 to 1000.

Momentum/Combustion Interactions

Fires are large, turbulent, diffusion flames and as such, the interaction between turbulence and combustion is the same as that found in the non-premixed turbulent combustion literature with perhaps one exception. While large fires are fully turbulent, the time scales for the dissipation of concentration fluctuations at the small length scale end of the spectrum tend to be much longer than in jet flames (Cox 1995). The turbulent intensities at length scales near typical flame zone thicknesses (millimeters) are moderate in fires compared to jet flows, since in fires the turbulence is generated baroclinically at length scales proportional to density gradients or advected from relatively low speed boundary layers. Thus, visualization of fires suggests flame zone structure exists in sheets (c.f. Weckman & Strong 1996) even for large fires (Tieszen et al 1996) and can be thought of as wrinkled laminar flames as long as sufficient oxygen is available.

The effect of turbulence on non-premixed combustion is to produce an unsteady strain with amplitude, frequency, and curvature effects on the flame zone structure. Unsteady strain, without curvature, appears to have relatively little effect on the major species concentrations for hydrocarbon flames until the amplitude becomes close to the quench limit (c.f., Sivathanu & Faeth 1990, Sung et al 1995). Sung et al 1995, show that the thickness of the flame is inversely proportional to the square root of the imposed strain. Im et al 1999, note that minor species concentrations are strongly affected by fluctuating strain. They suggest that flames are more strongly affected by low frequency fluctuations than high frequency fluctuations and are increasingly sensitive to imposed unsteadiness near the extinction limit.

Fundamental studies of turbulence/flame-sheet interactions have focused on single vortex-flame interactions (c.f., Ashurst 1989, Mueller & Schefer 1998, Renard et al 1999). Flame zones are noted to roll-up into the vortices, producing areas of high curvature, extensional as well as compressional strains on the flame, and flame-flame interactions as the rolled-up flame burns out the eddy core. With sufficiently high velocity, vortices can produce local quenching of flame zones. The degree to which this occurs in fires is not known but given the moderate turbulence intensities, it is not nearly as important as in combustors. Moderate turbulence levels do not imply that the turbulence time scales are always long relative to chemical time scales in fires. Long chemical time scales can occur due to low temperatures and/or poorly mixed reactants. For example, some fuel pyrolysis may occur in the vapor dome of large fires (Tieszen et al 1996) which are at moderate temperatures (Gritzo et al 1998a) relative to the reaction zones. Cox 1999a, notes that in general, if the fire burns in less than adequate air or entrains combustion products with the air stream, the fast chemistry assumption fails. Further, hot product layers are notorious for the production of carbon monoxide (c.f., Pitts 1995). Assuming similar processes occur during the burnout of a long lived, fuel rich eddy, the pyrolized but unoxidized fuel is speculated to be a likely source for the ubiquitous smoke seen in large fires (Tieszen et al 1996).

The coupling between combustion and the turbulence field is bi-directional. In addition to producing vorticity through density gradients, combustion is coupled back into the momentum field through dilatation and high viscosity in the high temperature region. Unlike baroclinic vorticity generation, dilatation is a sink term in the vorticity transport equations, hence it can be expected to reduce the turbulence in a flow field. While the studies in fires are limited, this result is found in widely varying reacting flows. Soteriou & Ghoniem 1994, show that dilatation in a mixing layer reduces the spinning of the eddies and delays the onset of instabilities and note experimental studies that confirm that heat release reduces the growth of the mixing layer. Chen & Kollmann 1994, Tanahashi & Miyauchi 1995, and Mahalingam et al 1995 using Direct Numerical Simulation (DNS) find that dilatation damps the turbulence intensity compared to non-combustion cases.

Since chemical reaction produces a source term (baroclinic), a sink term (dilatation), and a broadening term (high viscous diffusion), the net effect could be to strengthen or weaken the turbulence. Visualization of fires show strong rotational motion indicating that the baroclinic term dominates at large scale. Baum & McCaffrey 1988, and Zhou & Gore 1998, note that the flow field surrounding a fire is dominated by the vorticity driven flow. The dominance of baroclinic generation is noted in other combusting flows (Tanahashi & Miyauchi 1995, Daou & Rogg 1998).

Momentum/Radiation Interactions

The coupling of the fluid mechanics and radiation occurs over a broad length-scale range and is essentially decoupled in time. The reason for the latter is that photon transport occurs at the speed of light and the flow field is stationary over this time scale. Over flame length scales, Gore & Jang 1992 suggest that radiation is dominated by soot emission and is dependent on the soot temperature to the fifth power, soot volume fraction, and soot optical properties. The peak soot temperatures are substantially lower than the peak flame temperatures (c.f., Sivathanu & Faeth 1990) due to the location of the peak soot volume fraction to the fuel rich side. The zones of high soot concentrations are very narrow due to low soot diffusivity (c.f., Zimberg et al 1998). The combination of high temperatures and narrow zones of high soot volume fractions suggests that processes which directly affect radiative emission are substantially sub-millimeter.

Larger-scale turbulent strain rates and mixing processes can affect radiative emission in the same manner as they affect combustion processes in general. Scaling of radiation suggests that strains at the diffusive Kolmogorov scale are the most important (Delichatsios & Orloff 1988). Fluctuating strains can affect soot formation rates by altering soot pathlines into high temperature, fuel rich regions for extended periods (Kaplan et al 1996). Fluctuating strains can also affect the location of the soot relative to the peak gas temperatures producing a distribution of soot temperatures at the optimal mixture fractions for growth (Zimberg et al 1998). Zimberg et al 1998 also note that dynamic coupling between fluid mechanic and soot formation time scales is important; an increasingly common view. More research is needed in this area to define the nature and extent of the coupling of the momentum field and scalar property fluctuation affecting radiative emission. Many studies conducted on turbulence/radiation interactions have focussed on the effects of scalar fluctuations on radiation, but have not addressed issues of how turbulence in the momentum field creates the scalar fluctuations of importance to radiation. Burns 1999 has recently reviewed some of these turbulence/radiation interaction studies and discusses numerical modeling of radiation with spatially fluctuating scalar properties.

The coupling between turbulence and radiation is bi-directional through absorption. Unlike emission, absorption is dominated by long length scales. Of vital importance is the absorption of radiation by solid or liquid fuel boundaries that subsequently pyrolize and produce the fuel which sustains the fire (c.f., Babrauskas 1986). Within the fire itself, typical absorption length scales for large fires are on the order of tenths of meters (Gritzo et al 1998b). In this manner, energy is transferred from small scale, high temperature regions on the rich side of the flames (Gore & Jang 1992) to longer length scale, lower temperature regions. Therefore, radiation affects the length scales of gas density gradients, which through baroclinic vorticity generation will affect the momentum field. It appears that this coupling has not been quantitatively studied in terms of its importance on the momentum distribution in fires. However, it is generally acknowledged in sooting fires that a large percentage of the combustion energy, roughly 25-35%, is transported by thermal radiation out of the fire (c.f., Hamins et al 1996).

FLOW MEASUREMENTS

As in all areas of fluid mechanics, flow visualization is a valuable diagnostic. The relatively low velocities in fires, and having soot as a natural marker particle, makes visualization useful for understanding the nature of turbulent structures in fires (Tieszen et al 1996, Cetegen & Dong 2000). Semi-quantitative measurements can be made with flow visualization, for example, flame heights and puffing frequencies (c.f., Zukoski et al 1984, Hamins et al 1996). In the review of Malalasekera et al 1996, the role of photography and cinematography, both visual and infrared, is noted. Emmons 1995, notes that from the visualization of the smoke flow from a room fire, the neutral plane height can be obtained and flow rates estimated. Virtually all large fire tests employ some form of photography and/or cinematography.

Quantitative flow measurements in fires are difficult to make because of the extreme temperature and density variations (in both amplitude and frequency) in fires. Two measurement techniques have been developed by the fire community. Cetegen et al 1984 developed an entrainment measurement technique which consisted of putting an exhaust hood over the plume and sampling the exhaust for CO_2 and O_2 concentrations. While the technique has been supplanted by non-invasive technology, Heskestad 1998a notes that this data is still the basis for entrainment correlations even with 20-50% uncertainty. Heskestad developed a robust pitot-tube type device called a bi-directional velocity probe (McCaffrey & Heskestad 1976, Kent & Schneider 1987, Liu et al 1990, Emmons 1995). These devices provide useful measurements of the dynamic head ($1/2\rho V^2$) and are insensitive to the inflow velocity direction up to about 50 degrees from the incident axis.

The extraction of a velocity measurement from the device introduces some complexity. The density must be known. Usually the density is estimated from temperature measurements and assumptions about species distributions. Moreover, the relationship between velocity and dynamic pressure is non-linear and neither temperature or species measurements are available at sufficient frequency to ensure the correctly weighted velocity average is obtained. The probe has seen limited use in laboratory scale fires (McCaffrey 1979) because of the development of non-intrusive laboratory diagnostics. However, virtually all field/room-scale fire tests in which velocity measurements are made, use this technique (c.f., Steckler et al 1984, Koseki & Yumoto 1988, Schneider et al 1989).

The standard intrusive point measurement technique used for iso-thermal flows is hot-wire anemometry. Because of its sensitivity to temperature it has seen only limited, albeit important, use in fire applications, for example in the far field of a thermal plume (c.f., Shabbir and George 1994). Some attempts have been made to extract a velocity measurement using a cross-correlation of thermocouple data (c.f., Cox & Chitty 1980, Motevalli et al 1992). Non-intrusive measurement techniques for velocity used in, and around, fires include Laser Doppler Anemometry (LDA or equivalently Velocimetry, LDV) and Particle Image Velocimetry (PIV).

LDV is the most commonly employed velocity measurement technique in laboratory scale (< 0.35 meter diameter) fires. It has been used in wall bounded fires (Most et al 1989, Annarumma et al

1991a, Annarumma et al 1992), non-reacting buoyant plumes (Guillou et al 1986, Ramaprian & Chandrasekhara 1989, Dai et al 1995a, 1995b, Cetegen & Kasper 1996), in fire plumes (Walker & Moss 1984, Gengembre et al 1984, Crauford et al 1985, Weckman et al 1986, Zhou & Gore 1995, Weckman & Strong 1996, among others), and in fire-induced flows (Murakami et al 1995). Weckman and coauthors have systematically improved LDV measurements in pool fires in a series of studies over a decade (c.f., Weckman et al 1986, Weckman & Strong 1996). The most complete velocity data set available for fires is the LDV data by Weckman & Strong 1996, in a 31 cm diameter methanol fire. In addition to two-dimensional velocity measurements throughout the fire and the entrained air, they also use fine wire thermocouples to estimate the temperature fluxes, thus allowing the turbulent enthalpy flux to be estimated. Ancimer & Fraser 1994 discuss LDV errors induced by flames and indicate they are 5-10%.

Particle-tracking has been used by Ito et al 1999, to examine flame spread over a liquid pool with velocity measurements in both the liquid pool and in the gas phase, and by Venkatesh et al 1996 to measure flows through the laminar anchoring zone of small pool fires. PIV, a form of particle tracking, has been used by Zhou et al 1996, Cetegen 1997b, and Zhou & Gore 1998. Zhou et al 1996 determine the air entrainment rate into 15 and 30 cm diameter fires of methanol, heptane, and toluene. They note that PIV allows significantly faster collection of velocity field data over LDV and that the PIV data around a 7.1 cm toluene fire matched earlier LDV data (Zhou & Gore 1995) within 10% when averaged over 100 PIV velocity fields. Zhou & Gore 1998, also use PIV to examine the velocity and vorticity fields for the 7 cm toluene flame. In addition to the significant cost savings PIV affords over LDV, it enables simultaneous time and space resolved velocity measurements in fires. A PIV system is currently under development (O'Hern et al 1998) for use in meter diameter fires.

Heat flux, temperature, soot concentration, and trace species are often the primary measurements sought in a fire. Many of the techniques are reviewed by Joulain 1998 as they apply to pool fires. A full review of these measurement techniques is beyond the scope of the current fluid-mechanics based review. However, since the momentum field is tied to the density difference between the fire and surroundings for buoyant flows, some comments are in order. Density is not measured directly in fires but is inferred through the ideal-gas equation of state. It depends on the species composition (through the molecular weight) and on the temperature.

There are a surprisingly limited number of studies on the major species distributions (CO_2, CO, O_2, H_2O) in canonical fire plumes. All measurements to date use either an intrusive isokinetic, or grab sample technique. Measurements in fires less than 0.7 meter in diameter include Yumoto & Koseki 1982, Gengembre et al 1984, Fischer et al 1987, Orloff et al 1987, Bouhafid et al 1988, and Smith & Cox 1992. Measurements for larger fires are not at all common but include Alger et al 1979 at 3 meter diameter and Johnson et al 1982 at 15 meter diameter. All measurements represent long-time averages due to mixing in the lines. Orloff et al 1987 show that the major species (but not soot) scale well with elemental mixture fraction. Smith & Cox 1992 add a caution that there is some residual dependence on heat release rate. Similarly, sampling has been done in the 'well-mixed' hot layer above a fire plume as it enters a hood or ceiling (c.f. Cetegen et al 1984).

Next to photography/cinematography, temperature is the most commonly measured variable in a fire. However, simultaneous temperature and velocity measurements are quite limited in turbulent fires. Mean and fluctuating temperatures separate from the velocity fluctuations were obtained by Gengembre et al 1984 and Crauford et al 1985, while joint temperature-velocity fluctuating statistics were obtained by Weckman & Strong 1996. Uncertainties associated with transient thermocouple measurements in turbulent fires can be as much as 25-30% (Crauford et al 1985, Weckman & Strong 1996). Thermocouples or thermistors have also been employed to obtain joint temperature/velocity statistics in classical, heated plume studies (c.f. Ramaprian & Chandrasekhara 1989, Shabbir & George 1994) relevant to fire research. Young 1998, has recently reviewed thermocouple uncertainty and compensation techniques. For such a common measurement tool, thermocouples are deceptively complex.

Non-intrusive scalar measurement techniques for either species or temperature have seen limited application to fires to date. However, that limitation is beginning to change. Dai et al 1995b, use laser induced fluorescence (LIF) to look at scalar fields in isothermal plumes. Planar LIF can be used in conjunction with PIV for simple helium flows to obtain joint fluctuating statistics. Ito et al 1999, use holography in the boundary layer above a liquid fuel pool simultaneously with a particle tracking technique. Joulain & Cottereau 1996, review temperature measurement techniques, both thermocouple and spectroscopic. Fluctuating species measurements will become possible with Tunable Diode Lasers (TDL). TDL development is being driven by the communications industry and promises relatively cheap, reliable optical sources for spectroscopy. TDL's have yet to be applied to fires, but that is expected to change shortly as several fire groups are known to be working on them (CR Shaddix, personal communication).

In summary, in comparison with isothermal flows, there is far less fluid mechanics data in reacting flows. In comparison with momentum driven reacting flows, fire data is sparser still. The problem is not in the number of tests, for there are a very large number of fire experiments that have been run for the purpose of qualifying a material, fire barrier, or suppression system. The problem is the difficulty and cost of instrumenting a fire where the environment is very harsh, the gradients (spatial and temporal) are very steep, and the scales required to become fully turbulent are large. To date, the scientific data has primarily been taken in transitionally turbulent fires less than 0.7m in diameter. There is a significant need for fluid mechanics measurements in the 1-3 meter fire range where the turbulent transition is near the toe of the fire. Of particular importance are data sets that can be used for validation of numerical simulations.

NUMERICAL SIMULATION

Much of the experimental work in fire prior to the last decade has been to capture global fire properties for the creation of engineering correlations. While these correlations have value in their own right, impetus for global correlations has also been provided by their incorporation into numerical 'zone' models used to simulate enclosure fire phenomena. Quintiere 1989, provides a general phenomenology review, and Mitler,1991, describes the mathematics employed, in zone model methodology. Zone models solve conservation of mass and energy in a control-volume sense for each zone. One weakness of zone modeling is that momentum conservation is captured only through use of loss coefficients at openings and through the use of flow correlations to create zones within open volumes (rooms). The strength of zone models is that they are very fast compared to computational fluid mechanics (CFD) based models (c.f., Chow 1995, Luo et al 1997). Therefore, zone models have been used extensively in the risk management and fire protection engineering businesses. A listing can be found in Friedman 1992. Peacock et al 1991 discuss validation of zone models.

Beginning in the 1980's CFD has been employed in the study of fires (c.f. Kumar 1983). The approach is commonly called 'field' modeling in the fire community to distinguish between it and 'zone' modeling. The use of CFD allows for momentum conservation to be considered as well as much finer spatial and temporal resolution of species and energy distributions. The difficulty of applying CFD to fires is that the range of length scales involved exceeds that of the turbulent cascade found in constant density flows. The length scale range in fires is bounded by the thermal radiation -> fuel vaporization -> turbulent stirring -> molecular mixing -> chemical reaction -> high temperature soot formation -> thermal radiation loop which extends from order 10-100 nanometer emitting soot particles (Mulholland et al 1996, Williams & Gritzo 1998) to order 10-100 meter fuel-source length-scales for practical problems. Thus, some nine to ten orders of magnitude are required to capture this loop (which still does not completely encompass the length scales required for a first principle analysis since the heterogeneous molecular chemistry leading up to 10 nanometer soot particles is not captured). If one takes a simple uniform node spacing estimate of 10 nodes per linear decade of length-scale in three directions, one obtains a problem of the size 10^{27}-10^{30} nodes (ignoring for the moment that we have left continuum at the small length scales). Currently, large simulations are using order 10^6 nodes, capturing only about two orders of magnitude in length scales (c.f., Baum et al 1997). Cox 1999a, provides a chart of grid nodes vs. year of publication showing decade increases in node utilization about every 6.5 years for CFD simulations. Assuming that fire catches the leading edge, and that we can extrapolate the trend of the last 50 years, we can expect to see first-principles solutions of the soot/thermal radiation loop in fires in practical applications in the decades following the start of the twenty second century.

In the meantime, for use in solving practical fire problems, the conservation equations must be filtered such that the high temporal and spatial frequencies that cannot be captured by discrete representation of the conservation equations are represented as integrally-averaged effects within the equations. Both temporal, RANS (Reynolds Averaged Navier Stokes), and spatial, LES (Large Eddy Simulation), filters have been employed in computational models of fires. Due to large density differences, the variables are density weighed (Favre averaging, c.f., Cox 1999b). Scales below the filter width must be modeled and are called submodels, or subgrid models. In constant-density, momentum-dominated flows, submodels generally are only required to capture energy dissipation, thus, while the flow is not independent of them, in many cases it is not highly dependent on them either. McGrattan et al 1994 note this effect for fire-induced flows significantly far from the fire source, suggesting that an approach without turbulence models should be considered. However, within the fire itself, submodels must provide the source terms for both buoyancy and radiant energy which are the global forcing functions of the problem. A consistent over prediction in a submodel of fuel consumption, or effective radiative emissivity, will result in aliasing directly into the global spatial modes of the fire regardless of the type of filtering employed. The combination of tight coupling between the smallest and the largest scales, through both momentum transport (buoyancy) and thermal transport (radiation) and the vast range of length scales make numerical simulation of fires challenging.

The models commonly employed in RANS fire simulations are the more mature forms of those in the turbulence and combustion communities (c.f., Cox 1999b). The most common form of turbulence model is the k-ε model (c.f., Jones & Launder 1972) with a buoyancy term to account for stratification (Rodi 1980). Buoyant turbulence has generally not been addressed in fires (Bilger 1989, 1994) but some attempts to include it are appearing (Wang & Joulain 1996). Two combustion models are commonly used, the Eddy Dissipation Concept (EDC) models (Magnussen et al 1978, Gran & Magnussen 1996) and the presumed Probability Density Function (PDF) methods (c.f., Bilger 1989, Moss 1995). The EDC models typically assume the chemistry is fast relative to the mixing and the mixing is a function of the turbulence Reynolds number. Presumed PDF models assume the shape of the statistical closure distribution and treat chemistry either as in equilibrium or as a collection of laminar flamelets. The more sophisticated combustion models have not been extensively tested in fires. The formation of soot, radiative properties, and radiation/turbulence interaction must also be modeled to get the heat feedback to the fuel source. A review of soot models is given by Kennedy 1997. In general, soot concentration does not scale on mixture fraction to nearly the same degree as major species. Radiative properties are discussed by Smyth & Shaddix 1996. Burns 1999 gives a short review of the turbulence/radiation interaction topic. For LES simulations Baum 1992, has developed a Lagrangian thermal element model and a simplified strategy for radiation (Baum & Mell 1998). In the combustion community, there has been an adaptation of combustion models developed for RANS to LES (Desjardin & Frankel 1999) but in the area of fire, only limited experimentation of mature RANS combustion models in an LES format has occurred (Tieszen et al 1996).

As CFD models slowly displace zone model approaches, the term 'field model' will perhaps become an anachronism. However, with the level of modeling that must be employed for the foreseeable future, perhaps the moniker should be retained so that it is clear that field models are engineering tools. Sources of uncertainty include submodels, boundary conditions, and numerics (discretization/solution). Rank ordering of these uncertainties by magnitude depends on the problem, but given some six or more orders of magnitude in length scale that is being modeled and lack of boundary condition measurements for practical applications suggest that they will be substantive. The uncertainties under the most direct control are numerical. As Mitler 1991, points out, these must not be so poor as to produce incorrect results that are falsely attributed to physics. On the other hand, Mitler also points out, "the adequacy with which the physics and chemistry is represented... is far more important than the precision of the numerical solutions; thus, integrating the equations to within 1% (or even 5%) is perfectly adequate." Obviously, software 'bugs' represent unbounded uncertainty and careful software verification is a requirement.

Comparison with data, i.e., validation, provides a basis for assessing model uncertainty (Bilger 1994, Yang 1994) and sensitivity studies provide a basis for assessing boundary condition uncertainty. Boundary layer fires are complicated by complex material decomposition which is why tests are usually done on non-charring PMMA (c.f., Di Blasi 1993). To separate the material issues from the gas phase behavior, a number of wall fires have been conducted at Poitiers with gas injection through porous plates (c.f., Joulain 1996). In building fires, most compare with the Steckler et al 1982 data for flow measurements in doorways. LDV data has been taken in a scale room by Murakami et al 1995 and illustrates one of the problems with comparisons. For most of the room, the flow is nearly laminar and the models generally do not do well with laminar to turbulent (and vice versa) transitions. Similarly, for fire plumes, good detailed measurements exist only for fires with small base diameters 0.3 m and below (c.f., Weckman & Strong 1996). As pointed out by Strong & Weckman 1996, data suggest that the 'constant' in the k-ε eddy viscosity model does not become constant until over 1 diameter elevation for these small fires. Joulain 1996 concludes that the flame 'is better described as a fluctuating, laminar, diffusion flame, which later becomes a turbulent intermittent one' for small diameter fires. Engineering applications are generally fully turbulent and more validation quality data in fully turbulent conditions would be of great utility to the field modeling community.

With uncertainties characterized, field modeling has unparalleled potential as an engineering estimator of fire consequence. Its use is increasing year by year and is now employed in a wide variety of applications, for example, petrochemical industry fires (Holen et al 1990, Wen et al 1998) building fires (Yan & Holmstedt 1996, Lewis et al 1997, Jia et al 1999), tunnel fires (Woodburn & Britter 1996, Tuovinen & Holmstedt 1996), and forest fires (Lopes et al 1995) among others. Dozens of groups are employing it and a number of commercial CFD tools have fire capabilities in them. As computational hardware continues to improve, this trend will only continue. Parallel architecture has been exploited for fire simulations (Cox et al 1990, Galea & Ierotheou 1992) and massively parallel (thousands of processors) computers have become a reality.

LES modeling approaches are very promising, not only to capture the large scale features of the far field flow as repeatedly demonstrated by Baum and colleagues (Mell et al 1996, Baum et al 1997, Rehm et al 1997, McGratten et al 1998), but also as a means to provide time-resolved information to submodels within the fire itself. No matter how sophisticated the submodel, filtering limits the amount of information that can be exchanged. The smaller the filter width, the more information that can be passed to a submodel permitting ever more sophisticated submodels, including transient, spatially resolved models (Kerstein 1999). Careful explicit filtering for LES in both time and space, not currently employed in fires, should permit the numerical error and submodel error to be separated as it is in RANS approaches, thus promoting a broader acceptance of LES by the CFD community.

Numerical simulation is by no means limited to solution of filtered equations for engineering purposes. Approaches that are free of advective-process closure-models (i.e., model free, Givi 1989) provide useful insight for transient laminar flows, for both boundary layer fires (Di Blasi 1994, Di Blasi 1995a, Schiller et al 1996) and fire plumes (Mell et al 1996, Lee & Baek 1998). In a large number of articles, Baum and colleagues have championed the cause of model free approaches for fire-induced-flows since the late 1970's (c.f., Baum & Rehm 1984, McGrattan et al 1994, McGrattan et al 1997) arguing that the largest turbulent scales control the problem away from the fire source. Direct Numerical Simulation (DNS), which fully captures the turbulence over limited scales, has not been applied directly to fires but has been applied to non-premixed combustion in general (Vervisch & Poinsot 1998). Of specific interest to fire are the studies which have examined coupling of the turbulence field to the combustion (dilatation, high viscosity gradients) and the scalar field (baroclinic vorticity generation) (c.f., Higuera & Moser 1994, Chen & Kollman 1994, Tanahashi & Miyauchi 1995, Mahalingam et al 1995). Numerical approaches are not limited to an Eulerian framework. Both Lagrangian (Ghoniem et al 1996) and mixed (Najm et al 1998) approaches provide insight into the physics of fire. Model free approaches show great promise in understanding the physical issues related to fire such as mixing, flame-flame interactions, and scalar quenching resulting in smoke formation.

CONCLUDING REMARKS

Over the last decade, the phenomenological understanding of fires has deepened dramatically. Research that has focussed on canonical flows, such as the reacting boundary layer and reacting plume, is in the process of moving from attempting to understand global features of a fire to attempting to understand the underlying coupling between the momentum and scalar transport, combustion, and radiation processes. This move is being driven by the shift from the engineering application of correlation based methods such as zone models to filtered discrete solution of conservation equations by CFD based techniques. These CFD based techniques can simulate the global features but are highly dependent on the small-scale modeled processes and process couplings. Progress now requires that these processes be understood and modeled to the best fidelity attainable given the quality of the information that can be supplied to them. The shift in experimental techniques from global measurement to detailed measurements is also taking place. What has not changed is that fires are a difficult environment in which to take measurements. The amount of data available is very small compared with isothermal or even reacting jet flows. The need for data to ensure growth in this field cannot be overemphasized.

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