Fire Dynamics: A Practical Oriented Course for Safety Engineers

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Abstract

The topic of "Fire Dynamics" is extremely important in fire protection engineering and building design engineering. The goal is to improve scientific and technical understanding of fire behavior for safety engineers. Problems may begin from the extremely dangerous release of toxic, flammable and/or explosive materials into the atmosphere. Focused topic areas are: fire investigation, combustion, evolution of flammable material, dispersion and ignition of flammable materials, burning rates, simplified calculations, radiant ignition of other items, fire spread rates, ventilation limit imposed by size of opening, flashover criteria, computer modeling and sample problems and solutions. These are the main components related to the fire dynamic issues involved in real-world structural fires. The goal is to provide an understanding of the physics of fires and to improve our ability to more accurately predict their occurrence and simulate their fire growth and hazards. Information, analysis and calculations of fire dynamic phenomena can assist in understanding and applying scientific information to real-world fire situations, an important aspect of safety engineering.

1. Introduction

The goal of a short course or full university course in Fire Dynamics is to improve scientific understanding of fire behavior, in structural, vehicle and outdoor fires. Of course, the degree of coverage, and extent of involvement, experiments and projects will vary. This paper summarizes important information in key topic areas related to the understanding of fire development: evolution, spread and ignition of flammable material from leaks in appliances and process equipment, combustion, burning rates, radiant ignition of other items, fire spread rates, ventilation limit imposed on the fire growth because of size of opening for fresh air, and prospects for the occurrence of flashover. Within each topic area, there is information dealing with background, theory, comments, sample experimental data and calculations. The references given provide a good cross-section of recent studies related to the understanding of real-life fires, including a short course by Lilley (2004), and chapter in the Safety Professionals Handbook, see Lilley (2008). Course learning objectives include:

1. Develop an understanding of fire dynamic phenomena, from fuel release, dispersion and ignition, through fire spread, growth, and possible flashover, to the devastation produced and subsequent investigation
2. Gain an appreciation of the safety and loss prevention issues involved in the occurrence of fires, and factors that can mitigate the extent of subsequent damage
3. Cultivate an ability to calculate useful information from empirical equations that describe the observed fire phenomena, so permitting deductions to be made for other situations that are interpolated or extrapolated from a limited amount of experimental data
4. Establish mathematical modeling concepts related to the computer-based calculation procedures known as the Zone method and the Computational Fluid Dynamic CFD method for simulating fire growth and smoke production and travel from fires

2. Combustion

In the release and dispersion of flammable material, a vapor cloud is formed which spreads and disperses as the released material mixes and is carried downstream in the atmosphere. It is important to know if a potential ignition source is located where the fuel concentration is within the flammable or explosive limits, these being the percentage (usually by volume) of a substance in air that will burn once ignited. Most substances have both a lower (lean) and an upper (rich) flammable (explosive) limit, called the LFL and UFL, respectively. They are also called LEL and UEL, respectively. Either too much or too little fuel in the vapor-air mixture can prevent burning. But, at the edge of a fuel rich vapor cloud will be a region with other more flammable fuel-air ratios, so that (as such a cloud approaches) ignition is certainly possible from an ignition source. There is a wide range of fuels with different flammable limits. Higher temperatures and/or higher pressures generally increase the range over which a given fuel-air mixture is capable of being ignited and burned. Beyler (2002) gives an extensive table of values for many gaseous fuels, and discusses temperature and pressure effects on the LFL and UFL. Drysdale (2003) discusses the chemistry and physics of fire. Slye (2002) concentrates on flammable and combustible liquids, Babrauskas (2003) provides a wealth of information about the ignition problem. Crowl and Louvar (1990) address chemical safety issues of, among other things, limits of flammability of gaseous mixtures, temperature and pressure effects, and explosions.

3. Evolution of Flammable Material

The release of flammable material falls within the science of chemical process safety, health and loss prevention, topics addressed in SFPE (2002), NFPA (2003), Crowl and Louvar (1990) and AIChE (1990). These and other authors discuss the many principles, guidelines, and calculations that are necessary for safe design and operation, and analysis of failures, including: fires and explosions, vessel overpressure protection, hazards identification and risk assessment, source models, and dispersion modeling. For example, material may be released from holes and cracks in tanks and pipes, from leaks in flanges, pumps, and valves, and a large variety of other sources.

Source models represent the material release process. They provide useful information for determining the consequences of an accident, including the rate of material release, the total quantity released, and the physical state of the material. Source models are constructed from fundamental or empirical equations representing the physico-chemical processes occurring during the release of materials. Several basic source models are available, each applicable to the particular release scenario:

1. Flow of liquids through a hole
2. Flow of liquids through a hole in a tank
3. Flow of liquids through pipes
4. Flow of vapor through holes
5. Flow of vapor through pipes
6. Flashing liquids
7. Liquid pool evaporation or boiling

and problem parameters come into play in determining the amount of release or rate of release. The purpose of the source model is to determine: the form of material released (solid, liquid or vapor), the total quantity of material released, and the rate at which it is released.

4. Dispersion of Released Material

The information about source release is required for any quantitative dispersion model study, as now described. Dispersion models describe the airborne transport of materials away from the accident site. After a release, the airborne material is carried away by the wind in a characteristic plume or a puff. The maximum concentration occurs at the release point (which may or may not be a ground level). Concentrations downwind are less, due to turbulent mixing and dispersion of the substance with air. A wide variety of parameters affect atmospheric dispersion of toxic materials:

1. Wind speed
2. Atmospheric stability
3. Ground conditions, buildings, water, trees
4. Height of the release above ground level
5. Momentum and buoyancy of the initial material released

Two types of vapor cloud dispersion models are commonly used: the plume and puff models, collectively known as the Pasquill-Gifford model using dispersion coefficients that empirically specify the rates of spread of the dispersing material. The plume model describes the steady-state concentration of material released from a continuous source. The puff model describes the temporal concentration of material from a single release of a fixed amount of material. Models are available that permit concentration (kg/m^3) and volumetric concentration percent (%) to be calculated at location (x,y,z) as a function of time (t) after initial release. It is important to determine if the mixture is within the flammability limits at a nearby ignition source, in the case of fuel release. Useful references include AIChE (1990), ASME (1973), Crowl and Louvar (1990), EPA, NOAA and NSC (1992), Hanna and Drivas (1987) and Lilley (1996). Sprays of liquid droplets and particles may be handled via computation of particle trajectories, including air resistance and wind effects, as outlined by Chow (1979) and Lilley (1992).

In both plume and puff models, it is common to utilize the dispersion coefficients, σ_x, σ_y, and σ_z. These represent the standard deviations of the concentration in the downwind, crosswind, and vertical (x, y, and z) directions, respectively. The dispersion coefficients are a function of atmospheric conditions and the distance downwind from the release. The atmospheric conditions are classified according to six different stability classes shown in Table 3. The stability classes depend on wind speed and quantity of sunlight. During the day, increased wind speed results in greater atmospheric stability, while at night the reverse is true. This is due to a change in vertical temperature profiles from day to night. The Pasquill-Gifford dispersion coefficients ($\sigma_x = \sigma_y$ for horizontal dispersion and σ_z for vertical dispersion) for a continuous source are available, and described further with examples of their use in Lilley (2004).

5. Burning Rates

The "burning rate" is usually expressed either as a mass loss rate (kg/s) or as a heat release rate (kW) with the latter being more commonly used. Calculation procedures for fire effects in enclosures require knowledge of the energy release rate of the burning fuel. The term energy release rate is frequently used interchangeably with heat release rate, and it is usually expressed in units of kilowatts (kW) and symbolized by $\dot{Q}$. Major references are the National Fire Protection Association Handbook (NFPA 2003) and the Society of Fire Protection Engineers Handbook (SFPE 2002). The energy release rate from burning fuels cannot be predicted from basic measurements of material properties. It depends on the fire environment, the manner in which the fuel is volatilized and the efficiency of the combustion. Therefore, one must rely on available laboratory test data. In addition, knowledge of the complete energy release rate history may be required for many situations. This is particularly desirable where the fuel package exhibits unsteady burning. For those cases where only limiting conditions or worst-case analysis is required, it may be reasonable to assume that the fuel is burning at a constant rate, which simplifies the calculation considerably.

Budnick ***et al.*** (2003) discuss simplified calculations for enclosure fires in their chapter in the NFPA Handbook (NFPA 2003). They show the simple calculations for evaluating fire conditions in enclosures during the pre-flashover fire growth period. They include discussion about the maximum mass loss rate at ventilation-limited burning conditions. The rigorous treatment of energy release rates is available for selected material types such as wood cribs, wood and plastic slabs, and liquid pool fires where experimental correlations have been established. Section 3, Chapter 15, in SFPE Handbook of Fire Protection Engineering, see SFPE (2002), provides a detailed discussion of the prediction of burning rates for liquid pool fires. Data on mass loss rates for selected fuel packages are available in several publications: Alpert and Ward (1983), Babrauskas and Krasny (1985), Babrauskas ***et al.*** (1982), and Lawson ***et al.*** (1984). Also detailed discussions of energy release rates for specific fuels are available in publication by Babrauskas(1985), and Lawson and Quintiere (1985).

Babrauskas (2002), in his chapter in the SFPE Handbook (SFPE 2002), also discusses heat release rates and heat flux rates in full scale, intermediate scale and bench scale experimental measurements. He discusses modeling of these, and the prediction of full scale heat release rates from bench scale data. He usefully includes heat release rate (in kW) versus time (in seconds) for a large variety of real products, including categorizing a great deal of previous research information into sections dealing with pools (with liquid or plastic fuel), cribs (regular arrays of sticks), wood pallets, upholstered furniture, mattresses, pillows, wardrobes, television sets, Christmas trees, curtains, electric cable trays, trash bags and containers, and wall and ceiling lining materials. Thus, a wealth of information is available with detailed referencing to the original data source.

Also, data are available for heat release rate vs. time for many items in Babrauskas and Grayson (1992). Babrauskas and Williamson (1985), and Pettersson ***et al.*** (1976) introduce post-flashover fires in the case of a worst-case approach and a schematized approach receptively. Where an exact burning rate is not required, the worst-case approach can be applied. Also, the schematized approach can be used where all of the burning rate information is expressed solely as a fuel loading. Janessens and Parker (1992) developed the principle of oxygen consumption calorimetry as a measurement technique. More researchers studied about burning rate, and Babrauskas (2002) summarizes available data in SFPE Handbook (SFPE 2002).

6. Simplified Calculations

Estimates of flame height L can be important in determining exposure hazards associated with a burning fuel. Experimentally determined "mean" flame heights have been correlated by several researchers. A simple correlation for flame heights for pool or horizontal burning fuels has been developed by Heskestad (1983). Under usual standard atmospheric conditions, this equation often can be simplified to a most often used formula. Since flames are unstable, the mean flame height L is generally taken to be the height above the fire source where the flame tip is observed to be at or above this point 50 percent of the time. The above correlation is considered suitable for pool fires or for horizontal surface burning. Another expression for flame height is the NFPA 921 (2007) equation which additionally, the proximity of a wall or corner may be taken into account via the value of k. That is, k = 1 (no nearby walls), k = 2 (adjacent to a wall), and k = 4 (adjacent to a corner).

The plume centerline excess temperature and velocity at elevations above the mean flame height can be estimated from empirical equations. These two equations permit plume centerline excess temperature and velocity to be estimated at elevations above the flame. While methods exist to calculate excess temperature and velocities at locations other than along the plume centerline, the highest confidence is placed on centerline estimates.

Other simplified empirical equations for the calculation of other events during the evolution of an enclosure fire are available in NFPA (2003) and SFPE (2002). The algebraic equations are based principally on experimental correlations, and permit the user to make estimates of the results of a fire burning inside a given structure. The equations correlate experimental data and results versus other parameters for several cases of special interest for the fire dynamicist:

1. Room Model for Smoke Layer Depth and Temperature
2. Atrium Smoke Temperature
3. Buoyant Gas Head Pressure
4. Ceiling Jet Temperature
5. Ceiling Plume Temperature
6. Egress Time
7. Fire/Wind/Stack Forces On A Door
8. Mass Flow Through A Vent
9. Lateral Flame Spread
10. Law's Severity Correlation
11. Plume Filling Rate
12. Radiant Ignition Of A Near Fuel
13. Smoke Flow Through An Opening
14. Sprinkler/Detector Response
15. Thomas' Flashover Correlation
16. Upper Layer Temperature
17. Ventilation Limit

The relevant equations are embodied in computer programs like FPETool, FASTLite and HAZARD, so that making calculations of fire behavior becomes straightforward, provided one appreciates correctly the physics involved. Further details appear in Bukowski *et al.* (1989), Peacock *et al.* (1994) and Portier *et al.* (1996).

7. Radiation Ignition

It is of interest to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire to determine if secondary ignitions are likely. Will the second item ignite? This very important question is discussed at length in the detailed handbook on ignition, see Babrauskas (2003). The formulas for estimating the energy level required of a free burning fire to ignite a nearby item have been developed, on the basis that the exposed fuel item is not so close as to be in contact with the flame of the exposure fire. The relationships expressed by this procedure were developed empirically from tests and reported by Babrauskas (1981). Budnick *et al.* (2003) discuss the simple expression in their chapter in the NFPA Handbook (NFPA 2003). Tewarson (2002) explains fire initiation (ignition) and shows experimental data in the view of concepts governing generation of heat and chemical compounds in fires in the SFPE Handbook (SFPE 2002).

8. Fire Spread Rates

Flame spread tests are probably the best known fire performance tests. The most widely used of these are the Steiner Tunnel Test. These tests attempts to simulate the spread of fire across a plane surface and may include the imposition of a known external heat radiant flux, see Clarke (1991) and Belles (2003). For details about the test method as an ASTM standard, see ASTM (1969).

Fire spread applies to the growth of the combustion process including surface flame spread, smoldering growth, and the fire ball in premixed flame propagation. In flame spread, and in fire growth generally, the rate of spread is highly dependent on the temperatures imposed by any hot smoke layer heating the unburned surface, but also gravitational and wind effect are important. The flows resulting from the fire's buoyancy or the natural wind of the atmosphere can assist (wind-aided) or oppose (opposed-flow) flame spread. Quintiere and Harkleroad (1984) derive formulas and describe material properties involved in the lateral speed of a fire spreading in a direction other than that impinged by flame from the burning material; generally this means lateral or downward spread from a vertical flame. Quintiere (1994) summarizes surface steady flame spread rates.

Magee and McAlevy (1971) studied the rate of flame spread over strips of filter paper with different orientations (inclined angles), see Drysdale (1998) for discussion. According to Hicks (2003), fire spread rarely occurs by heat transfer through, or structural failure of, wall and floor-ceiling assemblies. The common mode of fire spread in a compartmented building is through open doors, unenclosed stairways and shafts, unprotected penetrations of fire barriers, and nonfire-stopped combustible concealed spaces. Even in buildings of combustible construction, the common gypsum board or lath-on-plaster protecting wood stud walls or wood joist floors provides 15 to 30 min of resistance to a fully developed fire, as determined by a standard fire test, see NBFU (1956). When such barriers are properly constructed and maintained and have protected openings, they will normally contain fires of maximum expected severity in light-hazard occupancies. However, no fire barrier will reliably protect against fire spread if it is not properly constructed and maintained, and openings in the barrier are not protected.

Fire can spread horizontally and vertically beyond the room or area of origin and though compartments or spaces that do not contain combustibles. Heated unburned pyrolysis products from the fire will mix with fresh air and burn as they flow outward. This results in extended flame movement under noncombustible ceilings, up exterior walls, and through noncombustible vertical opening. This is a common way fire spreads down corridors and up open stairways and shafts. Hicks (2003) explains fire spread and suggests fire protection in the following categories: concealed spaces, vertical openings, room or suite compartmentation, protection of corridors, building separation, fire plumes above roofs, and structural stability of fire walls. Ramachandran (2002) shows stochastic models of fire growth governed by physical and chemical processes. Quintiere (2002a) discusses flame spread applied to the phenomenon of a moving flame in close proximity to the source of its fuel originating from a condensed phase, that is, solid or liquid. Details are in their chapters in SFPE Handbook (SFPE 2002).

9. Ventilation Limit

One of the enclosure effects is the availability of oxygen for combustion. If the air in the space, plus that drawn in through openings, plus that blown into the space by HVAC systems or other means is insufficient to burn all the combustible products driven from the fuel package, then only that amount of combustion supportable by the available oxygen can take place. This situation is referred to as ventilation-limited burning. When ventilation-limited burning occurs, the combustible products driven from the fuel package and not burned in the room often burn when they combine with air outside the room and this appears as flame extensions from the room. Also, ventilation-limited burning changes the mass loss rate.

Kawagoe and Sekine (1963) originally presented the idea that fire heat release rate within a compartment could be limited by ventilation geometry. This idea has been followed, and many subsequent post-flashover experiments have been performed, see for example Babrauskas (1979) and Fang and Breese (1980). Heskestad (2003) covers venting practices as they would be applied to nonsprinklered buildings and Campbell (2003) covers fire modeling in ventilation-limited fire in their chapters in the NFPA Handbook (NFPA 2003). Emmons (2002) shows equations for the measurement of velocity, volume flow, and mass flow for vent flows relating to orifice, nozzle and vent flows for buoyant and nonbuoyant flows. Quintiere (1995) reviews vent-limited effects on zone models. Walton and Thomas (2002) shows the simplified mass flow rate equation using the ventilation factor, see the SFPE Handbook (SFPE 2002), for details.

10. Flashover

Flashover is characterized by the rapid transition in fire behavior from localized burning of fuel to the involvement of all combustibles in the enclosure, see Walton and Thomas (2002). High radiation heat transfer levels from the original burning item, the flame and plume directly above it, and the hot smoke layer spreading across the ceiling are all considered to be responsible for the heating of the other items in the room, leading to their ignition. Warning signs are heat build-up and "rollover" (small, sporadic flashes of flame that appear near ceiling level or at the top of open doorways or windows of smoke-filled rooms). Factors affecting flashover include room size, ceiling and wall conductivity and flammability, and heat- and smoke-producing quality of room contents. Water cooling and venting of heat and smoke are considered to be ways of delaying or preventing flashover. Several methods have been developed to estimate flashover, as described in Lilley (2008), as well as temperature and heat flux calculations ensuing from computer calculations as discussed in the nest section.

11. Computer Fire Modeling

According to Friedman (1991) in his international survey of computer models for fire and smoke, 36 actively supported models are identified around the world. Among those, 12 models are zone type models, which are in use. A later updated survey by Olenick and Carpenter (2003) shows a significant increase in available fire models over the last 10 years, including field models. Zone models solve the conservation equations for distinct regions. A number of zone models exist, varying to some degree in the detailed treatment of fire phenomena. The dominant characteristic of this class of model is that it divides the room(s) into hot upper layers and cold lower layers. The basic assumption of a zone model is that properties can be approximated throughout the zone by some uniform function. The uniform properties are temperature, smoke, and gas concentrations, which are assumed to be exactly same at every point in a zone. Zone modeling has proved to be a practical method for providing estimates of fire processes in enclosures. Experimental observations show that the uniform properties zone assumption yields good agreement (see Jones *et al.*, 2000).

Potentially greater accuracy of simulating enclosure fires is available via "field models" or computational fluid dynamic "CFD models." The structure is divided into a very large number of subvolumes and the basic laws of conservation representing mass, momentum, and energy are written as partial differential equations. These represent the variation of the dependent variables (velocity components, density, temperature, and species) as a function of position and time throughout the 3-D domain of interest, perhaps one or many rooms, corridors, and stairways within a building. This CFD approach has been used extensively for nonfire applications over the last 40 years in many areas of fluid flow, turbulence, heat transfer, and combustion with many other sophistications included in the simulations, see, for example, Gupta and Lilley (1984). Only recently, however, over the last ten years, has this fundamental differential equation method been applied to fire situations, see for example, Karlsson and Quintiere (2000), SFPA (2002) and NFPA (2003).

Fire computer modeling plays an important role in fire protection engineering and building design engineering. Two different modeling techniques are commonly used in fire modeling: zone modeling and field modeling (computational fluid dynamics technique). The zone method represents a more mature field for fire and smoke transport; the methods have been developed and applied for many years. In field modeling, computational demands are large, and correct simulation ultimately depends on the empirical-specification of things like ignition, burning rates, fire spread, ventilation-limitation, etc. At this time, field models are being developed and applied for the simulation of structural fires. These topics are now addressed in the light of the relevant equations being embodied in computer programs from NIST like CFAST (see Jones *et al.* (2005) and Peacock *et al.* (2005)) for zone modeling, the Fire Dynamics Simulator FDS (see McGrattan *et al.* (2008a and 2008b)) for CFD modeling, and the smoke visualization program SMOKEVIEW that supports both CFAST and FDS, see Forney (2008). SMARTFIRE is a CFD fire modeling code from the University of Greenwich, UK, with especially useful features. Its companion EXODUS is also available. Distinctive attributes include: highly flexible system capable of extensive enhancements, integrated modular simulation environment, interactive unstructured meshing, and fully featured comprehensive CFD engine, see Ewer *et al.* (2008). Galea (2007 and 2008) provides a lecture and extensive information about the code and its availability.

Of particular concern in the modeling of fires is the activation of smoke detectors, heat detectors and sprinklers. The appropriate information for their activation is well documented, from previous experimental data and modeling, and the simulation is incorporated in the popular modeling codes. The accuracy of the FDS code, in particular, has been demonstrated via model evaluation. This entails both verification that the equations are indeed being solved correctly, and via validation that the equations really model correctly the physical phenomena. Typically, validation involves comparing model results with experimental measurement, see McDermott *et al.* (2008) and McGrattan (2008c).

12. Conclusions

Fire Dynamics is the topic with important information relating to safety: evolution, spread and ignition of flammable material from leaks in appliances and process equipment, combustion, burning rates, radiant ignition of other items, fire spread rates, ventilation limit imposed on the fire growth because of size of opening for fresh air, and prospects for the occurrence of flashover. These are the main components related to the fire dynamic issues involved in real-world structural fires. The goal has been to improve our understanding of the physics of fires and to improve our ability to more accurately predict their occurrence and simulate their fire growth and hazards. Safety engineers can develop an appreciation for technical/scientific understanding of the phenomena and its applicability to real-world practical down-to-earth situations.

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Dr. David G. Lilley is a Professor in the School of Mechanical and Aerospace Engineering, Oklahoma State University, with expertise in combustion aerodynamics. His active consulting practice Lilley & Associates is primarily concerned with litigation emphasizing fires, combustion, fuels, aerodynamics, fluid dynamics, heat transfer, fuel sprays, and computer simulation. He was born in England and obtained his education at Sheffield University, from which he received the Bachelor and Master degrees in Mathematics in 1966 and 1967, and the Ph.D. degree in Engineering in 1970. The "higher doctorate" D.Sc. degree was awarded in 1991 by Sheffield University for many years of successful research, publication of high quality original research work, international recognition, and standing as an authority in the field Combustion Aerodynamics. The "Energy Systems Award" was given in 1992 by AIAA for distinguished contribution as a teacher, researcher and consultant in the areas of swirl flows in combustors and furnaces, mathematical modeling, fuels and fires. In 1993 he was elected to the grade of Fellow of the AIAA - an honor bestowed upon people of distinction who have made notable and valuable contributions to the arts, sciences, or technology of aeronautics or astronautics. In 2000 he was elected to the grade of Fellow of the ASME and awarded the "George Westinghouse Gold Medal" for notable contributions to the Power Field of Mechanical Engineering, specifically for distinguished contributions as a teacher, researcher and consultant in power engineering, including the publication of quality scholarly papers and studies on safety, energy efficiency and environmentally compliant power systems. In 2008, he was awarded the ASME "Holley Medal" for exemplary contributions to the development of science and engineering of fires, their growth and fire accident prediction and practical aspects of fire investigation that has resulted in greater public safety and reliability from a wide range of fuels use and application.