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Plastics Flammability Handbook
Principles - Regulations - Testing and Approval

3 The Burning Process and Enclosure Fires

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3.1 Introduction

Fire safety of plastic products has been a matter of great concern to legislators, authorities, and manufacturers since the advent of building fire regulations. Most such products are found in buildings, transport vehicles, or enclosures of some kind, and considerable effort is dedicated to minimizing the material reaction-to-fire and the resulting hazard to humans.

Fire is a physical and chemical phenomenon that is strongly interactive by nature. The interactions between the flame, its fuel, and the surroundings can be strongly nonlinear, and quantitative estimation of the processes involved is often complex. The burning process and the processes of interest in an enclosure fire mainly involve mass fluxes and heat fluxes to and from the fuel and the surroundings. Figure 3.1 shows a schematic of these interactions, indicating the complexity of the mass and heat transfer processes discussed here.
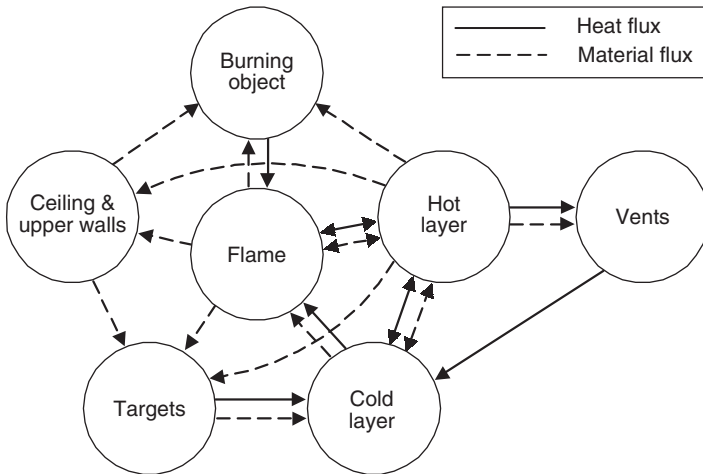
Figure 3.1 Schematic of the heat fluxes and mass fluxes occurring in an enclosure fire (adapted from Friedman [1])

It is important to introduce the reader to the physical and chemical processes that occur during an enclosure fire and the terminology used to describe it, as the environmental conditions in the enclosure are strongly interactive with the burning process. This chapter starts by generally describing the burning process, using the burning of a candle as an example. A qualitative description of enclosure fire development is then given, introducing the physical and chemical processes involved and the terminology used to describe the enclosure fire. Subsequently, the factors influencing the fire development are discussed. Finally, a brief description of enclosure fire simulation models is given.

3.2 General Description of the Process of Combustion

The study of combustion is a complex subject; it includes a number of disciplines such as fluid mechanics, heat and mass transport, and chemical kinetics. Here, we give only an introductory discussion on combustion and use a candle as our fuel; the discussion is therefore limited to a laminar, steady flame on a solid substrate. Later chapters describe the burning process in far greater detail.

The study of a burning candle, however, is very illustrative with regard to the natural processes we are interested in. Michael Faraday, the 19th century scientist, gave lectures on "The Chemical History of a Candle" [2] at the so-called Christmas Lectures at the Royal Institution in London. He claimed that there was no better way by which one could introduce the study of natural philosophy than by considering the physical phenomena of a candle.

3.2.1 A Burning Candle

Consider Fig. 3.2, which shows an illustration of a burning candle and the temperature distribution through the flame. An ignition source, a match for example, heats up the wick and starts melting the solid wax. The wax in the wick vaporizes and the gases move, by the process of diffusion, out into a region where oxygen is found. The gases are oxidized in a complex series of chemical reactions, in regions where the oxygen-fuel mixture is flammable. The candle flame is then stable; it radiates energy to the solid wax, which melts. Because the wax vaporizes and is removed from the wick, the melted wax moves up the wick, vaporizes, burns, and the result is a steady combustion processes.
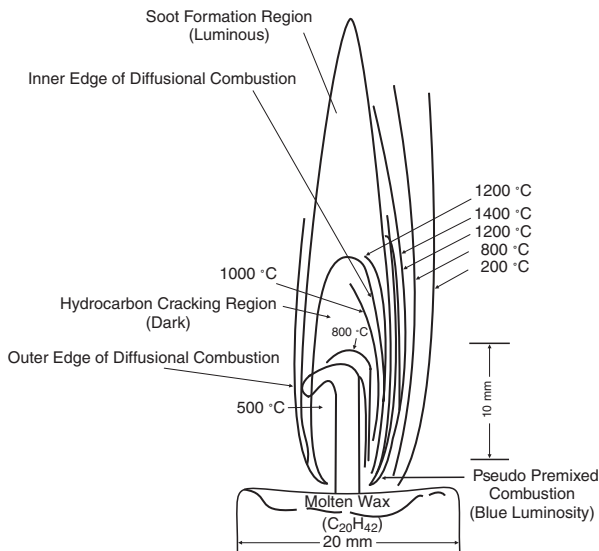
Figure 3.2   A burning candle and the temperature distribution in the flame (from [3])

Because the processes occurring in the flame involve mainly the flow of energy and the flow of mass, we shall briefly discuss these.

The flow of energy occurs by the processes of radiation, convection, and conduction. The dominant process is that of radiation; it is mainly the soot particles produced by combustion that glow and radiate heat in all directions. The radiation down toward the solid is the main

heat transfer mode that melts the solid, but convection also plays a role. The convective heat flux is mainly upwards, transferring heat up and away from the combustion zone. The larger and more luminous the flame, the quicker the melting process is.

The radiative energy reaching the solid is, however, not sufficient to vaporize the wax, only to melt it. The wick is therefore introduced as a way to transport the melted wax up into the hot gases, where the combined processes of radiation, convection, and conduction supply sufficient energy to vaporize the melted wax.

The mass transfer and the phase transformations are also exemplified by the burning candle. The fuel transforms from solid to liquid state. The mass balance requires that the mass, which disappears from the wick by vaporization, be replaced and thus the liquid is drawn up into the wick by capillary action. Once there, the heat transfer from the flame causes it to vaporize and the gases move away from the wick by the process of diffusion. The inner portion of the flame contains insufficient oxygen for full combustion, but some incomplete chemical reactions occur, producing soot and other products of incomplete combustion. These products move upwards in the flame due to the convective flow and react there with oxygen. At the top of the flame nearly all the fuel has combusted to produce water and carbon dioxide, the efficiency of the combustion can be seen by observing the absence of smoke emanating from the top of the candle flame.

This self-sustained combustion process can be changed most easily by changing the dimensions and properties of the wick, and thereby the shape and size of the flame. A longer and thicker wick will allow more molten wax to vaporize, resulting in a larger flame and increased heat transfer to the solid. The mass and heat flows will quickly enter a balanced state, with steady burning as a result.

To a chemist, fuel consists of the whole of the gaseous products evolving from combustible (solid or molten) materials. These gases arise from pyrolysis or incomplete oxidation of the initial polymeric materials. The general public, however, would use the word fuel for various combustible materials that can also be in solid or liquid state (gasoline, coal, etc). We shall here use the latter to describe enclosure burning.

3.2.2 Other Solid Fuels

Without the wick the candle will not sustain a flame, as is true for many other solid fuels. Factors such as the ignition source, the type of fuel, and the amount and surface area of the fuel package determine whether the fuel can sustain a flame or not. A pile of wooden sticks may sustain a flame while a thick log of wood may not do so. Once these factors are given, the above-discussed processes of mass and energy transport will determine whether the combustion process will decelerate, be steady, or accelerate.

Also, the phase transformations of other solid fuels may be much more complicated than the melting and vaporizing of the candle wax. The solid fuel may have to go through the process of decomposition before melting or vaporizing, and this process may require considerable energy. The chemical structure of the fuel may therefore determine whether the burning is sustained or not.

For fuels more complex than the candle it is difficult to predict fire growth. The difficulty is due not only to the complexity of the physical and chemical processes involved, but also due to the dependence of these processes on the geometric and other fuel factors mentioned earlier and the great variability in these.

When the fuel package is burnt in an enclosure, the fire-generated environment and the enclosure boundaries will interact with the fuel, as seen in Fig. 3.1, making predictions of fire growth even more complex.

It is currently beyond the state of the art of fire technology to predict the fire growth in an enclosure fire with any generality, but reasonable engineering estimates of fire growths in buildings are frequently obtained using experimental data and approximate methods. Such test methods are described in later sections of this book.

3.3 General Description of Fire Growth in an Enclosure

A fire in an enclosure can develop in a multitude of different ways, mostly depending on the enclosure geometry and ventilation and the fuel type, amount, and surface area. The following is a general description of the various phenomena that may arise during the development of a typical fire in an enclosure. Methods for quantitatively estimating the variables mentioned are generally well known and are discussed in several handbooks, for example, [4], [5], and [6].

Ignition: After ignition, the fire grows and produces increasing amounts of energy, mostly due to flame spread. In the early stages the enclosure has no effect on the fire, which then is fuel controlled. Besides releasing energy, a variety of toxic and nontoxic gases and solids are produced. The generation of energy and combustion products is a very complex issue, as mentioned previously, and the engineer must rely on measurements and approximate methods in order to estimate energy release rates and the yield of combustion products. The issue of energy release rate and combustion product yields measurements is dealt with in later chapters.

Plume: The hot gases in the flame are surrounded by cold gases and the hotter, less dense mass will rise upwards due to the density difference, or rather, due to buoyancy. The buoyant flow, including any flames, is referred to as a fire plume.

As the hot gases rise, cold air will be entrained into the plume. This mixture of combustion products and air will impinge on the ceiling of the fire compartment and cause a layer of hot gases to be formed. Only a small portion of the mass impinging on the ceiling originates from the fuel; the greatest portion of this mass originates from the cool air entrained laterally into the plume as it continues to move the gases toward the ceiling. As a result of this entrainment the total mass flow in the plume increases and the average temperature and concentration of combustion products decrease with height.

Ceiling Jet: When the plume flow impinges on the ceiling the gases spread across it as a momentum driven circular jet. The velocity and temperature of this jet is important because quantitative knowledge of these variables will allow estimates to be made on the response of any smoke and heat detectors and sprinkler links in the vicinity of the ceiling.

The ceiling jet eventually reaches the walls of the enclosure and is forced to move downwards along the wall as seen in Fig. 3.3. However, the gases in the jet are still warmer than the surrounding ambient air and the flow will turn upwards due to buoyancy. A layer of hot gases will thus be formed under the ceiling.

Gas Temperatures: Experiments have shown for a wide range of compartment fires, that it is reasonable to assume that the room becomes divided into two distinct layers: a hot upper layer consisting of a mixture of combustion products and entrained air and a cold lower layer consisting of air. Further, the properties of the gases in each layer change with time but are assumed to be uniform throughout each layer. For example, it is commonly assumed when using engineering methods that the temperature is same throughout the hot layer at any given time.

The Hot Layer: The plume continues to entrain air from the lower layer and transports it toward the ceiling. The hot upper layer therefore grows in volume and the layer interface descends toward the floor. The smoke filling process and methods for calculating smoke filling times are discussed in handbooks, for example [4], [5] and [6].
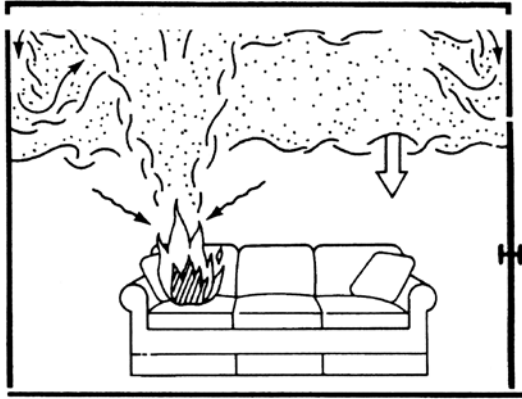
Figure 3.3   Schematic of the development and descent of a hot smoke layer (from [4])

Heat Transfer: As the hot layer descends and increases in temperature, the heat transfer processes are augmented. Heat is transferred by radiation and convection from the hot gas layer to the ceiling and walls, which are in contact with the hot gases. Heat from the hot layer is also radiated toward the floor and the lower walls, and some of the heat will be absorbed by the air in the lower layer. In addition, heat is transferred to the fuel bed, not only by the flame, but also to an increasing extent by radiation from the hot layer and the hot enclosure boundaries. This leads to an increase in the burning rate of the fuel and the heating up of other fuel packages in the enclosure.

Vent Flows: If there is an opening to the adjacent room or out to the atmosphere, the smoke will flow out through it as soon as the hot layer reaches the top of the opening. Often, the increasing heat in the enclosure will cause the breakage of windows and thereby create an opening. Methods for calculating the mass flow rates through vents are discussed in handbooks (e.g., [4], [5], and [6]).

Flashover: The fire may continue to grow, either by increased burning rate, by flame spread over the first ignited item, or by ignition of secondary fuel packages. The upper layer increases in temperature and may become very hot. As a result of radiation from the hot layer toward other combustible material in the enclosure, there may occur a stage at which all the combustible material in the enclosure is ignited, with a very rapid increase in energy release rates. This very rapid and sudden transition from a growing fire to a fully-developed fire is called flashover. The fire can thus suddenly jump from a relatively benign state to a state of awesome power and destruction.

The solid line in Fig. 3.4 shows the initiation of the transition period at point A, resulting in a fully-developed fire at point B. Once point B has been reached (the fully-developed fire), flashover is said to have taken place.

The Fully-Developed Fire: At the fully-developed stage flames extend out through the opening and all the combustible material in the enclosure is involved in the fire. The fully-developed fire can go on for a number of hours, as long as sufficient fuel and oxygen are available for combustion.

Oxygen Starvation, the Underventilated Fire: For the case where there are no openings in the enclosure or only small leakage areas, the hot layer will soon descend toward the flame region and eventually cover the flame. The air entrained into the combustion zone now contains little oxygen and the fire may die out due to oxygen starvation. The dotted line in Fig. 3.4 shows that a fire may reach point A and start the transition period toward flashover, but due to oxygen depletion the energy release rate decreases, as well as the gas temperature.
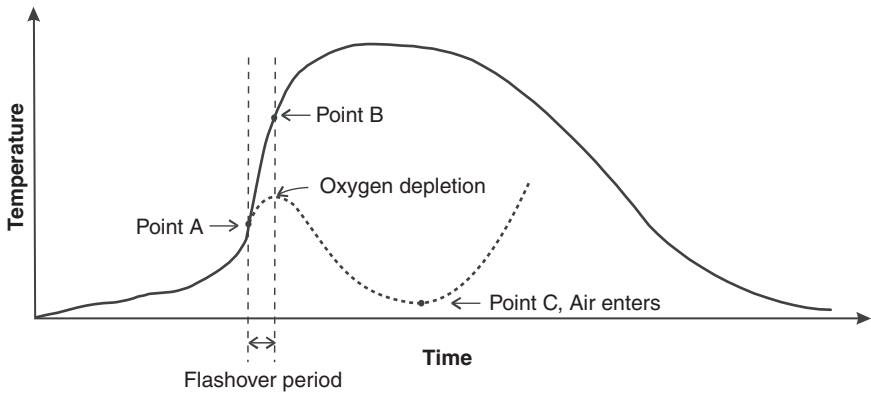
Figure 3.4   Enclosure fire development in terms of gas temperatures: some of the many possible paths a room fire may follow (from Karlsson and Quintiere [6])

Even though the energy release rate decreases, the pyrolysis may continue at a relatively high rate, causing the accumulation of unburnt gases in the enclosure. If a window breaks at this point, or if the fire service creates an opening, the hot gases will flow out through the top of the opening and cold and fresh air will flow in through its lower part. This may diminish the thermal load in the enclosure but the fresh air may cause an increase in the energy release rate. The fire may then grow toward flashover as shown by the dotted line in Fig. 3.4.

3.4 Factors Influencing the Fire Development in an Enclosure

The factors that influence the development of a fire in an enclosure can be divided into two main categories: those that have to do with the enclosure itself and those that have to do with the fuel. We can specifically mention

- The size and location of the ignition source,
- The type, amount, position, spacing, orientation and surface area of the fuel packages,
- The geometry of the enclosure,
- The size and location of the compartment openings,
- The material properties of the enclosure boundaries.

Ignition Source: An ignition source can consist of a spark with very low energy content, a heated surface, or a large pilot flame, to name a few examples. The source of energy is chemical, electrical, or mechanical. The greater the energy of the source, the quicker the subsequent fire growth on the fuel source is. A spark or a glowing cigarette may initiate smoldering combustion, which may continue for a long time before flaming occurs, often producing low heat but considerable amounts of toxic gases. A pilot flame usually produces flaming combustion directly, resulting in flame spread and fire growth.

The location of the ignition source is also of great importance. A pilot flame positioned at the lower end of, say, a window curtain may cause rapid upward flame spread and fire growth. The same pilot flame would cause much slower fire growth were it placed at the top of the curtain, resulting in slow, creeping, downward flame spread.

Fuel: The type and amount of combustible material is of course one of the main factors determining the fire development in an enclosure. In building fires the fuel usually consists of solid materials; in some industrial applications the fuel source may also be in liquid state.

Heavy, wood-based furniture usually causes a slow fire growth but can burn for a long time. Some modern interior materials include porous lightweight plastics, which cause more rapid fire growth but burn for a shorter time. A high fire load therefore does not necessarily constitute a greater hazard; a rapid fire growth is more hazardous in terms of human lives.

The position of the fuel package can have a marked effect on the fire development. If the fuel package is burning away from walls, the cool air is entrained into the plume from all directions. When placed close to a wall, the entrainment of cold air is limited. This causes not only higher temperatures but also higher flames, as combustion must take place over a greater distance.

Figure 3.5 shows temperatures measured above fires in 1.22 m (4 ft) high stacks of wood pallets [7]. Curve A shows temperatures as a function of height above pallets burning without the presence of walls. Curve B is for a similar stack near a wall and curve C is for a stack in a corner.
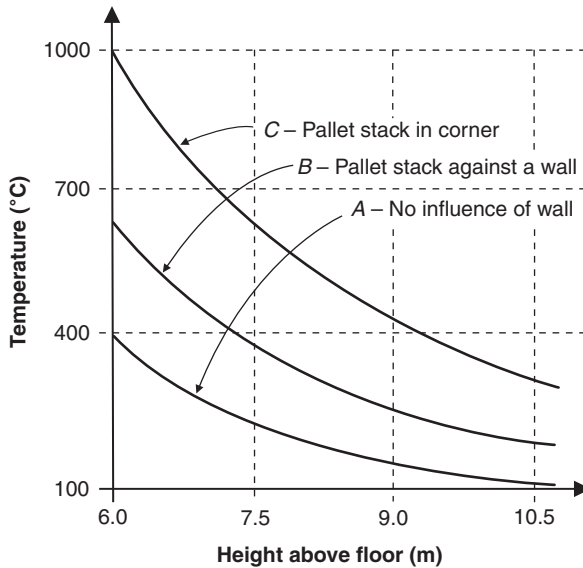

Figure 3.5   The temperature in the fire plume as a function of height above a burning stack of wood pallets. A, B, and C indicate burning away from walls, by a wall, and in a corner, respectively (adopted from Alpert et al. [7])

The spacing and orientation of the fuel packages are also important. The spacing in the compartment determines to a considerable extent how quickly the fire spreads between these. Upward flame spread on a vertically oriented fuel surface will happen much more rapidly than lateral spread along a horizontally oriented fuel surface.

Combustible lining materials, mounted on the compartment walls and/or ceiling, can cause very rapid fire growth. Figure 3.6 shows results from a small-scale room test where the lining material is mounted on the walls only (with noncombustible ceiling) and when the material is mounted on both walls and ceiling [8]. In both cases an initial flame was established on the lining material along one corner of the room. With material mounted on the ceiling, the flame spreads with the flow of gases (concurrent-flow flame spread), causing rapid growth. With noncombustible ceiling the flame spreads horizontally (opposed-flow flame spread) across the material, a process that is much slower and requires the lining material to be heated consider-
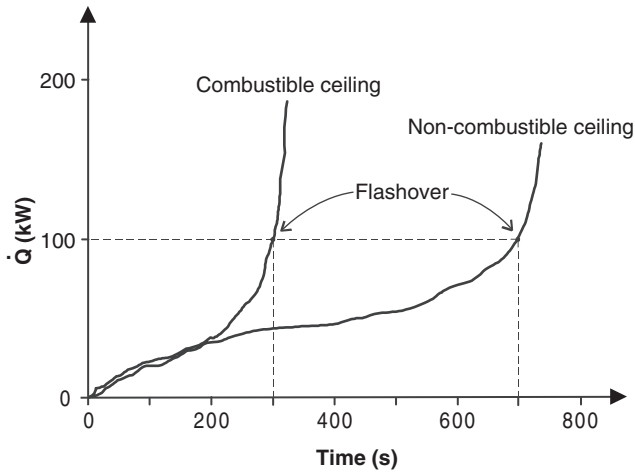
Figure 3.6   Energy release rate versus time in a small room with a combustible material mounted on walls only and with combustible material mounted on walls and ceiling. Flashover occurs when the energy release rate is 100 kW in this compartment.

ably before the flame can spread rapidly over it. As a result, the time to flashover is 4 min in the former case and 12 min in the latter.

A fuel package of a large surface area will burn more rapidly than an otherwise equivalent fuel package with a small surface area. A pile of wooden sticks, for example, will burn more rapidly than a single log of wood of the same mass.

Enclosure Geometry: The hot smoke layer and the upper bounding surfaces of the enclosure will radiate toward the burning fuel and increase its burning rate. Other combustible items in the room will also be heated up. The temperature and thickness of the hot layer and the temperature of the upper bounding surfaces thus have a considerable impact on the fire growth.

A fuel package burning in a small room will cause relatively high temperatures and rapid fire growth. In a large compartment, the same burning fuel will cause lower gas temperatures, longer smoke filling times, less feedback to the fuel, and slower fire growth.

The fire plume entrains cold air as the mixture of combustion products and air moves upwards toward the ceiling. The amount of cold air entrained depends on the distance between the fuel source and the hot layer interface. In an enclosure with a high ceiling this causes relatively low gas temperatures, but owing to the large amount of air entrained, the smoke filling process occurs relatively rapidly. The smaller the floor area, the faster the smoke filling process.

With a low ceiling the heat transfer to the fuel will be greater. In addition, the flames may reach the ceiling and spread horizontally under it. This results in a considerable increase in the feedback to the fuel and to other combustibles, and a very rapid fire growth is imminent.

For enclosures with a high ceiling and a large floor area the flames may not reach the ceiling and the feedback to the fuel is modest. The fire growth rather occurs through direct radiation from the flame to nearby objects, where the spacing of the combustibles becomes important.

In buildings with a large floor area but a low ceiling height the feedback from the hot layer and ceiling flames can be very intensive near the fire source. Further away, the hot layer has entrained cold air and has lost heat to the extensive ceiling surfaces, and the heat flux to the combustible materials, in the early stage of the fire, is therefore lower than the heat flux closer to the fire source.

We can conclude that the proximity of ceilings and walls can greatly enhance the fire growth. Even in large spaces, the hot gases trapped under the ceiling can heat up the combustibles beneath and result in extremely rapid fire spread over a large area. The fire that so tragically engulfed the Bradford City Football Stadium in England, 1985 is a clear reminder of this [9].

Compartment Openings: Once flaming combustion is established the fire must have access to oxygen for continued development. In compartments of moderate volume that are closed or have very small leakage areas, the fire soon becomes oxygen starved and may self-extinguish or continue to burn at a very slow rate depending on the availability of oxygen.

For compartments with ventilation openings, the size, shape, and position of these become important for the fire development under certain circumstances. During the growth phase of the fire, before it becomes ventilation controlled, the opening may act as an exhaust for the hot gases, if its height or position is such that the hot gases are effectively removed from the enclosure. This will diminish the thermal feedback to the fuel and cause slower fire growth. For other circumstances the geometry of the opening does not have a very significant effect on fire growth during the fuel-controlled regime.

It is first when the fire becomes controlled by the availability of oxygen that the opening size and shape becomes all-important. Kawagoe [10] found, mainly through experimental work, that the rate of burning depended very strongly on the "ventilation factor," defined as $A_o\sqrt{H_o}$, where A_o is the area of the opening and H_o is its height. The importance of this factor can also be shown by theoretically analyzing the flow of gases in and out of a burning compartment. It can be shown that the rate of burning is controlled by the rate at which air can flow into the compartment. An increase in the factor $A_o\sqrt{H_o}$ will lead to an equal increase in the burning rate. This is valid up to a certain limit when the burning rate becomes independent of the ventilation factor and the burning becomes fuel controlled.

Properties of Bounding Surfaces: The material in the bounding surfaces of the enclosure can affect the hot gas temperature considerably and thereby the heat flux to the burning fuel and other combustible objects. Certain bounding materials designed to conserve energy, such as mineral wool, will limit the amount of heat flow to the surfaces so that the hot gases will retain most of their energy.

The material properties controlling the heat flow through the construction are the conductivity (k), the density (ρ), and heat capacity (c). These are commonly collected in a property called thermal inertia and given as the product $k\rho c$. Insulating materials have a low thermal inertia; materials with relatively high thermal inertia, such as brick and concrete, allow more heat to be conducted into the construction, thereby lowering the hot gas temperatures.

3.5 Engineering Models for Enclosure Fires

The rapid progress in the understanding of fire processes and their interaction with buildings has resulted in the development of a wide variety of models that are used to simulate fires in compartments. The models can be classified as either deterministic or probabilistic. Probabilistic models do not make direct use of the physical and chemical principles involved in fires, but make statistical predictions about the transition from one stage of fire growth to another. Such models are not discussed further here. The deterministic models can roughly be divided into three categories: CFD models; zone models; and hand-calculation models.

CFD Models: The most sophisticated of these are termed "field models" or "CFD models" (Computational Fluid Dynamics models). The CFD modeling technique is used in a wide range of engineering disciplines. Generally, the volume under consideration is divided into a very large number of subvolumes and the basic laws of mass, momentum, and energy conservation are applied to each of these. Figure 3.7 shows a schematic of how this may be done for a fire in an enclosure. The governing equations contain as further unknowns the viscous stress
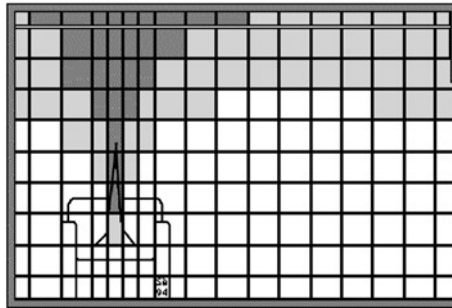
Figure 3.7   CFD models divide the enclosure into a large number of subvolumes.

components in the fluid flow. Substitution of these into the momentum equation yields the so-called Navier-Stokes equations, and the solution of these is central to any CFD code.

The myriad of engineering problems, which can be addressed by CFD models, is such that no single CFD code can incorporate all of the physical and chemical processes that are important. There exist, therefore, only a handful of CFD codes that can be used for problems involving fire. These, in turn, use a number of different approaches to the subprocesses that need to be modeled. Some of the most important of these subprocesses can be considered to be turbulence modeling, radiation and soot modeling, pyrolysis and flame spread modeling, and combustion modeling. The subprocesses are usually modeled at a relatively fundamental level and an understanding of these requires expert knowledge in a number of specialized fields of physics and chemistry. Cox [11] provides an excellent summary of the main issues.

With regard to the burning process, CFD models generally need as input the fuel supply rate to calculate the energy release rate. Further, various assumptions are made to estimate species produced. Recently, however, some work has been published in which the burning process and the environmental conditions are linked by incorporating flame spread, pyrolysis, and fire growth models into CFD codes. An example of such work is given by Yan [12] and Holmstedt, who developed and described a flame spread model and by Tuovinen et al. [13], who incorporated the model into the CFD code SOFIE [14]. Such models are still under development and they currently offer the only practical way to link the burning process with the fire-induced environment in the enclosure.

Using CFD models requires considerable computational capacity as well as expert knowledge, not only in physics and chemistry, but also in numerical methods and computer science. In addition, to set up the problem, run it on the computer, extract the relevant output, and present the results is very time consuming and costly, so practical use for fire safety engineering design is relatively rare. However, such a modeling methodology can be very useful when dealing with complex geometries and may be the only way to proceed with certain design problems.

Two-Zone Models: A second type of deterministic fire models are those that divide the room into a limited number of control volumes or zones. The most common type is termed "two-zone models" in which the room is divided into an upper, hot zone and a lower, cold zone. The equations for mass and energy conservation are solved numerically for both zones for every time step. The momentum equation is not explicitly applied; instead, information needed to calculate velocities and pressures across openings come from analytically derived expressions where a number of limiting assumptions have been made. Several other subprocesses are modeled in a similar way, such as plume flows and heat transfer. The section on hand calculations below lists a number of these processes.

In general, zone models describe the production of species in terms of yields per mass loss rate of the pyrolyzing material. The energy release rate is required as input but is usually expressed as a mass loss rate times the actual heat of combustion. Both terms are very much dependent on the ventilation conditions. For well-ventilated fires the energy release rate and the species production can be reasonably constant for a given fuel. In general, these can vary with time and can significantly vary as ventilation-limited conditions are approached and achieved. In particular, they vary with the equivalence ratio, defined as

$$\phi = \frac{(\dot{m}_f / \dot{m}_{air})_{act}}{(\dot{m}_f / \dot{m}_{air})_{stoich}} \tag{1}$$

where ϕ is the equivalence ratio, $(\dot{m}_f / \dot{m}_{air})_{act}$ is the actual relationship between the mass flow rate of fuel and the mass flow rate of air, and $(\dot{m}_f / \dot{m}_{air})_{stoich}$ is the same relationship at stoichiometry. Stoichiometry gives the exact proportions of the reactants (fuel and air) for complete conversion to products, where no reactants are remaining. The equivalence ratio may be computed in a zone (or upper layer) in which combustion has occurred by computing the mass concentration of the available fuel and oxygen in the zone. This method of predicting concentrations is still under study, but it currently offers the only practical zone model approach for estimating species, such as CO, under ventilation-limited conditions in enclosure fires.

Many two-zone models (see Fig. 3.8) have been described in the literature. Some of these only simulate a fire in a single compartment; others simulate fires in several compartments, linked by doors, shafts or mechanical ventilation. In addition, the degree of verification, documentation, and user friendliness vary greatly between these models.
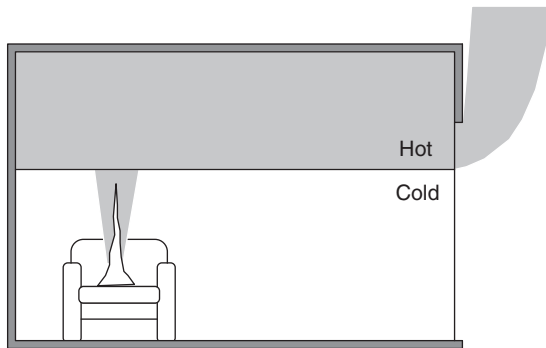
Figure 3.8   Two-zone modeling of a fire in an enclosure

In recent years there has been an upsurge in the use of two-zone models in fire safety engineering design. This is partly due to the increasing availability and user-friendliness of the computer programs. However, any serious use of such models requires that the user is well acquainted with the assumptions made and the limitations of the models, that is, that the user has had some training in the subject of enclosure fire dynamics.

Hand-Calculation Models: A third way of analytically describing some basic fire processes is to use simple hand-calculation methods. These are basically a collection of simplified solutions and empirical methods to calculate flame heights, mass flow rates, temperature and velocities in fire plumes, time to sprinkler activation, room overpressure, and many more variables.

The remainder of this section describes summarily the hand-calculation models. The methods discussed below can, for convenience, be divided into three categories: Those that deal with combustion, those that estimate the resulting environmental conditions, and those that have to do with heat transfer. These methods have highly varying limits of applications, and the user must have some knowledge of classical physics to apply them correctly.

3.5.1 Energy Evolved and Species Generated

Calculating fire growth and the amount to energy evolved from the primary fire source requires knowledge of the heat flux to the fuel bed, the flame heat flux to the fuel bed, and a large number of material parameters. Later chapters describe fundamental models for the burning process when the external conditions are given as well as methods for determining material parameters.

However, the heat fluxes are mainly a function of the enclosure fire environment, the ventilation conditions, and enclosure geometry. Models that link the burning process with the fire-induced environment are scarce.

In Fire Safety Engineering, a rough estimate of the energy release rate from a fire source requires that the type and amount of fuel involved be known. Typical burning rates and the heat of combustion for a range of liquid fuels, burning in the open, have been experimentally determined and are given in the literature. This allows the energy evolved to be roughly estimated if the area of the liquid spill is known. If the amount of spilt liquid is known then the time to burnout can also be calculated. Fire growth information for solids and other burning objects is available from several sources. Energy release rates for many items of furniture, curtains, and different types of materials are available. Such values are also available for species production rates, allowing species concentrations to be calculated.

The rate of energy evolved in a compartment is also dependent on the rate of supply of oxygen. Knowledge of the ventilation conditions can therefore be used to evaluate the maximum rate of energy release inside a compartment. Any excess, unburnt fuel will then be burnt outside the fire compartment, where oxygen is available.

Computer programs with material databases are also available where the user is assisted in choosing an appropriate energy release rate curve.

3.5.2 Fire-Induced Environment

The basic principles used for calculating the environmental conditions due to a fire in a compartment are the conservation of mass, energy, and momentum. The application of the conservation laws will lead to a series of differential equations. By making certain assumptions on the energy and mass transfer in and out of the compartment boundaries, the laws of mass and energy conservation can result in a relatively complete set of equations. Owing to the complexity and the large number of equations involved, a complete analytical solution is not possible and one must resort to numerical analysis through computer programs.

However, analytical solutions can be derived by making use of results from experiments and a number of limiting approximations and assumptions. Such solutions have generated innumerable expressions that may be used to predict a variety of environmental factors in a fire room. Examples of a number of these are given below.

The buoyant gas stream rising above a burning fuel bed is often referred to as the fire plume. The properties of fire plumes are important in dealing with problems related to fire detection, fire venting, heating of building structures, smoke filling rates, and so forth. By using dimensional analysis, the conservation equations, and data from experiments, expressions for various plume properties have been developed. These include expressions for plume temperature, mass

flow and gas velocities at a certain height above the fire as well as flame height. Similar expressions have been derived for the jet that results when the plume gases impinge on a ceiling.

Mass flow in and out of compartment openings can be calculated, as the pressure differences across the opening can be estimated. The use of classical hydraulics and experimentally determined flow coefficients has resulted in hand-calculation expressions for such mass flows.

The gas temperature in a naturally or mechanically ventilated compartment can be calculated by hand, using regression formulas. These are based on experimentally measured gas temperatures, in a range of fire scenarios, and a simplified energy and mass balance. Such expressions are available for both pre- and post-flashover fires. By using similar expressions, the onset of flashover can be estimated.

By combining the expressions for gas temperature, plume flows, and vent flows, the descent of the smoke layer as a function of time can be calculated. The resulting expressions are usually in the form of differential equations but certain limiting cases can be solved by hand. Such solutions usually require an iteration process or the use of precalculated curves or tables.

Several other types of hand-calculation expressions have been developed. These include expressions for mass flow through roof openings, buoyant pressure of hot gases, species concentration, fire-induced room pressures, flame sizes from openings, and so forth. Some of such expressions have been collected in relatively user-friendly computer programs.

3.5.3 Heat Transfer

There are three mechanisms by which heat is transferred from one object to another: radiation, convection, and conduction. Classical textbooks on heat transfer provide innumerable hand-calculation expressions for calculating heat fluxes to and from solids, liquids, and gases as well as expressions for estimating the resulting temperature profiles in a target. These analytical expressions are usually arrived at by setting up the energy balance, by assuming constant properties and homogeneity in the media involved and by ignoring the heat transfer mechanisms that seem to be of least importance in each case.

The radiative heat flux from flames, hot gases, and heated surfaces impinging on a solid surface can be estimated using classical heat transfer and view factors. The same applies for convective heat transfer to solids and conductive heat transfer through solids. The surface temperature of a solid subjected to a radiative, convective, or conductive heat flux can be calculated by hand assuming the solid to be either semiinfinite or to behave as a thermally thin material. Numerous types of heat transfer problems can be solved in this way; a few examples are given below.

Assuming that a secondary fuel package is subjected to a known heat flux, and that it has a certain ignition temperature and constant thermal properties, then the time to ignition can be calculated. Similarly, if the activation temperature of a sprinkler bulb is known, the activation time can be estimated. Several other problems can be addressed in this way such as temperature profiles in building elements, flame spread over flat solids, heat detector activation, spread of fire from one building to another, and so forth. Analytical solutions to such problems can be found in common textbooks on heat transfer.

3.6 Summary

Most plastic products are found in buildings, transport vehicles, or enclosures of some kind, and the enclosure fire environment has a considerable and decisive effect on the burning process of such products. This chapter has given a description of enclosure fire development and the models used to predict its environmental consequences.

In an enclosure fire, two environmental factors have a decisive influence on the burning behavior of a combustible material: the flame heat flux (from the flames above the burning combustible) and the external heat flux (from hot gases, hot surfaces, and flames on other burning combustibles). The former is very much controlled by ventilation conditions and possible oxygen starvation; the latter has much to do with enclosure geometry, ventilation conditions, and surface materials. Before any reasonable prediction of real burning behavior can be made, these factors must be quantified.

A number of different models exist for predicting the environmental consequences of an enclosure fire, but most of these require the fire properties of the combustible (energy release rate and species production) be given as input. Only a few models exist that allow the prediction of both, in which the burning process is predicted and the enclosure variables calculated; the variables are then coupled to the burning process calculations. These models are under development and are still not used in engineering.

Most fuels are complex in nature, and the conditions they burn in are not often well defined. Engineers therefore often rely on measurements and tabulated data from small- or large-scale experiments to make estimates of energy release rate and species production as a function of time. Later chapters describe such experiments and the resulting data.

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