1

Introduction to Fire

1.1 Fire in History

Fire was recognized from the moment of human consciousness. It was present at the creation of the Universe. It has been a part of us from the beginning. Reliance on fire for warmth, light, cooking and the engine of industry has faded from our daily lives of today, and therefore we have become insensitive to the behavior of fire. Mankind has invested much in the technology to maintain fire, but relatively little to prevent it. Of course, dramatic disastrous fires have been chronicled over recorded history, and they have taught more fear than complete lessons. Probably the low frequency of individually having a bad fire experience has caused us to forget more than we have learned. Fire is in the background of life in the developed world of today compared to being in the forefront of primitive cultures. Fire rarely invades our lives now, so why should we care about it?

As society advances, its values depend on what is produced and those sources of production. However, as the means to acquire products becomes easier, values turn inward to the general societal welfare and our environment. Uncontrolled fire can devastate our assets and production sources, and this relates to the societal costs of fire prevention and loss restoration. The effects of fire on people and the environment become social issues that depend on the political ideology and economics that prevail in the state. Thus, attention to fire prevention and control depend on its perceived damage potential and our social values in the state. While these issues have faced all cultures, perhaps the twentieth century ultimately provided the basis for addressing fire with proper science in the midst of significant social and technological advances, especially among the developed countries.

In a modern society, the investment in fire safety depends on the informed risk. Reliable risk must be based on complete statistics. An important motivator of the US government’s interest to address the large losses due to fire in the early 1970s was articulated in the report of the National Commission on Fire Prevention and Control (America Burning [1]). It stated that the US annually sustained over $11 billion in lost
resources and 12,000 lives were lost due to fire. Of these deaths, 3500 were attributed to fires in automobiles; however, a decimal error in the early statistics had these wrong by a factor of 10 (only 350 were due to auto fires). Hence, once funding emerged to address these issues, the true annual death rate of about 8000 was established (a drop in nearly 4000 annual deaths could be attributed to the new research!). The current rate is about 4000 (4126 in 1998 [2]). A big impact on this reduction from about 8000 in 1971 to the current figure is most likely attributed to the increasing use of the smoke detector from nearly none in 1971 to over 66% after 1981 [3]. The fire death rate reduction appears to correlate with the rate of detector usage. In general, no clear correlation has been established to explain the fire death rates in countries, yet the level of technological and political change seem to be factors.

While the estimated cost of fire (property loss, fire department operations, burn injury treatment, insurance cost and productivity loss) was $11.4 billion in the US for 1971 [1], it is currently estimated at 0.875% of the Gross Domestic Product (GDP) ($11.7 \times 10^{12}$) or about $102$ billion [2]. The current US defense spending is at 3.59% of GDP. The fire cost per GDP is about the same for most developed countries, ranging from 0.2 to 1.2% with a mean for 23 countries at 0.81% [2]. The US is among the highest at per capita fires with 6.5/1000 people and about 1.7 annual deaths per $10^5$ people. Russia tops the latter category among nations at 9.87. This gives a perceived risk of dying by fire in an average lifetime (75 years) at about 1 in 135 for Russia and 1 in 784 for the US. Hence, in the lifetime of a person in the US, about 1 in 800 people will die by fire, about 10 in 800 by auto accidents and the remainder (789) will most likely die due to cancer, heart disease or stroke. These factors affect the way society and governments decide to invest in the wellbeing of its people.

Fire, like commercial aircraft disasters, can take a large quantity of life or property cost in one event. When it is realized that 15 to 25% of fires can be attributed to arson [2], and today terrorism looms high as a threat, the incentive to invest in improved fire safety might increase. The 9/11 events at the World Trade Center (WTC) with a loss of life at nearly 3000 and a direct cost of over $10$ billion cannot be overlooked as an arson fire. In the past, such catastrophic events have only triggered ‘quick fixes’ and short-term anxiety. Perhaps, 9/11 – if perceived as a fire safety issue – might produce improved investment in fire safety. Even discounting the WTC as a fire event, significant disasters in the twentieth century have and should impact on our sensitivity to fire. Yet the impact of disasters is short-lived. Events listed in Table 1.1 indicate some significant fire events of the twentieth century. Which do you know about? Related illustrations are shown in Figures 1.1 to 1.4. It is interesting to note that the relatively milder (7.1 versus 7.7) earthquake centered in Loma Prieta in 1989 caused an identical fire in San Francisco’s Marina district, as shown in Figure 1.2(b).

### 1.2 Fire and Science

Over the last 500 years, science has progressed at an accelerating pace from the beginnings of mathematical generality to a full set of conservation principles needed to address most problems. Yet fire, one of the earliest tools of mankind, needed the last 50 years to give it mathematical expression. Fire is indeed complex and that surely helped to retard its scientific development. But first, what is fire? How shall we define it?
A flame is a chemical reaction producing a temperature of the order of at least 1500 K and generally about 2500 K at most in air. Fire is generally a turbulent ensemble of flames (or flamelets). A flamelet or laminar flame can have a thickness of the order of $10^{-3}$ cm and an exothermic production rate of energy per unit volume of about $10^8$ W/cm$^3$. However, at the onset of ignition, the reaction might only possess...
about $10^{-2}$ W/cm$^3$. This is hardly perceptible, and its abrupt transition to a full flame represents a jump in thermal conditions, giving rise to the name thermal explosion.

A flame could begin with the reactants mixed (premixed) or reactants that might diffuse together (diffusion flame). Generally, a flame is thought of with the reactants in the gas phase. Variations in this viewpoint for a flame or fire process might occur and are defined in special terminology. Indeed, while flame applies to a gas phase reaction, fire,
Figure 1.3 Oakland Hills fire storm, 1991

Figure 1.4 Collapse of the south tower at the World Trade Center
and its synonym combustion, refers to a broader class of reactions that constitute a significant energy density rate. For example, smoldering is a combustion reaction (that could occur under temperatures as low as 600 K) between oxygen in air and the surface of a solid fuel. The combustion wave propagation through dynamite might be termed by some as an explosion, yet it is governed by premixed flame theory. Indeed, fire or combustion might more broadly represent an exothermic chemical reaction that results from a runaway rate caused by temperature or catalytic effects. Note that we have avoided the often-used definition of fire as ‘a chemical reaction in air giving off heat and light’. However, a flame may not always be seen; e.g. an H2 flame would be transparent to the eye and not easily seen. A flame could be made adiabatic, and therefore heat is not given off. This could occur within the uniform temperature soot-laden regions of a large fire. Moreover, oxygen in air might not be the only oxidizer in a reaction termed combustion or fire. In general, we might agree that a flame applies to gas phase combustion while fire applies to all aspects of uncontrolled combustion.

The science of fire required the development of the mathematical description of the processes that comprise combustion. Let us examine the historical time-line of those necessary developments that began in the 1600s with Isaac Newton. These are listed in Table 1.2, and pertain to macroscopic continuum science (for examples see Figures 1.5 and 1.6). As with problems in convective heat and mass transfer, fire problems did not require profound new scientific discoveries after the general conservation principles and constitutive relations were established. However, fire is among the most complex of transport processes, and did require strategic mathematical formulations to render solutions. It required a thorough knowledge of the underlying processes to isolate its dominant elements in order to describe and effectively interpret experiments and create general mathematical solutions.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Key initiator</th>
</tr>
</thead>
<tbody>
<tr>
<td>~1650</td>
<td>Second law of motion (conservation of momentum)</td>
<td>Isaac Newton</td>
</tr>
<tr>
<td>1737</td>
<td>Relationship between pressure and velocity in a fluid</td>
<td>Daniel Bernoulli</td>
</tr>
<tr>
<td>~1750</td>
<td>First law of thermodynamics (conservation of energy)</td>
<td>Rudolph Clausius</td>
</tr>
<tr>
<td>1807</td>
<td>Heat conduction equation (Fourier’s law)</td>
<td>Joseph Fourier</td>
</tr>
<tr>
<td>1827</td>
<td>Viscous equations of motion of a fluid</td>
<td>Navier</td>
</tr>
<tr>
<td>1845</td>
<td></td>
<td>Stokes</td>
</tr>
<tr>
<td>~1850</td>
<td>Chemical History of the Candle Lectures at the Royal Society</td>
<td>Michael Faraday</td>
</tr>
<tr>
<td>1855</td>
<td>Mass diffusion equation (Fick’s law)</td>
<td>A. Fick</td>
</tr>
<tr>
<td>1884</td>
<td>Chemical reaction rate dependence on temperature</td>
<td>S. Arrhenius</td>
</tr>
<tr>
<td>~1900</td>
<td>Thermal radiation heat transfer</td>
<td>Max Planck</td>
</tr>
<tr>
<td>1928</td>
<td>Solution of diffusion flame in a duct</td>
<td>Burke and Schumann</td>
</tr>
<tr>
<td>~1940</td>
<td>Combustion equations with kinetics</td>
<td>Frank-Kamenetskii</td>
</tr>
<tr>
<td>~1930</td>
<td></td>
<td>Semenov</td>
</tr>
<tr>
<td>~1950</td>
<td></td>
<td>Zel’dovich</td>
</tr>
<tr>
<td>~1950</td>
<td>Convective burning solutions</td>
<td>H. Emmons, D. B. Spalding</td>
</tr>
<tr>
<td>~1960</td>
<td>Fire phenomena solutions</td>
<td>P. H. Thomas</td>
</tr>
<tr>
<td>~1970</td>
<td>Leadership in US fire research programs</td>
<td>R. Long, J. Lyons</td>
</tr>
</tbody>
</table>
Figure 1.5  Bernoulli’s treatise on hydrodynamics

Figure 1.6  Significant scientists in (a) heat transfer (Jean Baptiste Joseph Fourier), (b) chemistry (Svante August Arrhenius, Nobel Prize in Chemistry 1903) and (c) combustion (Nikolay Semenov, Nobel Prize in Chemistry 1956)
While Newton forged the basis of the momentum equation, he also introduced the concept of mass, essentially defined by \( m = F/a \). Joule established the equivalence between work and energy, and the first law of thermodynamics (energy conservation) introduces the concept of energy as the change due to heat loss and work done by a system. Heat is then defined as that energy transferred from the system due to temperature difference. Of course, the second law of thermodynamics (Clausius) does not enter into solution methods directly, but says a system cannot return to its original state without a cost. That cost involves transfers of mass and energy, and these transport fluxes become (approximately) related to the gradient of their associated intensive properties; e.g. heat flux is proportional to the temperature gradient as in Fourier’s law and species mass flux is proportional to its concentration gradient as in Fick’s law. The nonlinear transport of heat due to radiation provides a big obstacle to obtaining analytical solutions for fire; and turbulence, despite the exact formulation of this unsteady phenomena through the Navier–Stokes equations over 150 years ago, precludes general solutions to fluid flow problems. Hence, skill, ingenuity and broad knowledge are needed to formulate, solve and understand fire phenomena. The Russian scientists Semenov [6], Frank-Kamenetskii [7] and Zel’dovich et al. [8] provide much for the early formulation of combustion problem solutions. These problems addressed the role of kinetics and produced the Zel’dovich number, \( (E/RT)/(1 + c_pT/\Delta h_f) \), \( E/RT \) being the Arrhenius parameter. Spalding [9] and Emmons [10] laid a foundation for solutions to diffusive burning of the condensed phase. This foundation served as a guidepost to other far more complex problems involving soot, radiation and flame spread. The Spalding B number is a key dimensionless group that emerges in these problems, and represents the ratio of energy released in combustion to that needed for fuel vaporization. The energy production rate by fire (more specifically its rate of change of enthalpy due to chemical changes at 25 °C and 1 atmosphere pressure) will be termed here as firepower. Many have used the term heat release rate (HRR), but this is viewed as a misnomer by this author as the firepower has the same chemical production rate that would be attributed to a combustion-based power plant, and is not identical to the heat transferred in the reaction. Such misnomers have occurred throughout thermodynamics as represented in the terms: heat capacity, heat of vaporization and heat of combustion – all related to enthalpies. These misnomers might be attributed to remnants of the caloric theory of heat in which heat was viewed as being part of matter.

1.3 Fire Safety and Research in the Twentieth Century

At the start of the twentieth century there were significant activities in US fire safety. The National Fire Protection Association (NFPA) was founded in 1897 principally to address sprinkler use and its standardization. The Underwriter’s Laboratory (UL) was founded in 1894 by William H. Merrill to address electrical standards and testing. In 1904, Congress created the National Bureau of Standards (NBS), later becoming the National Institute of Standards and Technology (NIST) in 1987. After the Baltimore conflagration (1904), Congress directed NBS to address the structural fire safety of buildings. That program began in 1914 under Simon Ingberg, and had a profound influence on standards and testing dealing with structural fire protection over the next 60 years. It is noteworthy to consider the words of the NBS Director to Congress in 1914 when US fire losses were
reported at more than ten times those of Europe: ‘The greatest fire loses are in the cities having laws and regulations’ [11].

Sixty years later America Burning cited ‘One basic need is to strengthen the grounding of knowledge about fire in a body of scientific and engineering theory, so that real world problems can be dealt with through predictive analyses’ [1]. The result of that President’s Commission report led to the consolidation of the three existing fire programs at NBS at that time: building fire safety (I. Benjamin and D. Gross), fire research and fire fighting (J. Rockett and A. F. Robertson) and flammable fabrics (J. Clark and C. Huggett). The consolidation forged the Center for Fire Research (CFR) under John Lyons in 1974. It included the development of a library for fire science (M. Rappaport and N. Jason) – a necessity for any new research enterprise. The CFR program focused on basic research and important problems of that time. They involved clothing fabric and furnishing fire standards, the development of smoke detectors standards, floor covering flammability and special standards for housing and health care facilities. Its budget was about $5 million, with more than half allocated as internal NBS funds. It co-opted the NSF RANN (Research for Applied National Needs) fire grants program along with Ralph Long, its originator. This program was endowed solely for basic fire research at $2 million. Shortly after 1975, the Products Research Committee (PRC), a consortium of plastic producers, contributed about $1 million annually to basic research on plastic flammability for the next five years. This industry support was not voluntary, but mandated by an agreement with the Federal Trade Commission that stemmed from a complaint that industry was presenting faulty fire safety claims with respect to test results. This total budget for fire research at NBS of about $8 million in 1975 would be about $30 million in current 2004 dollars. Indeed, the basic grants funding program that originating from the NSF is only about $1 million today at NBS, where inflation would have its originally allocated 1974 amount at about $7.5 million today. Thus, one can see that the extraordinary effort launched for fire research in the 1970s was significant compared to what is done today in the US. While US fire research efforts have waned, international interests still remain high.

Fire research in the USA during the 1970s was characterized by a sense of discovery and a desire to interact with centers of knowledge abroad. For years, especially following World War II, the British and the Japanese pursued research on fire with vigor. The Fire Research Station at Borehamwood (the former movie capital of the UK) launched a strong research program in the 1950s with P. H. Thomas, a stalwart of fire modeling [12], D. Rasbash (suppression), M. Law (fire resistance) and D. L. Simms (ignition). The Japanese built a strong infrastructure of fire research within its schools of architecture, academia in general and government laboratories. Kunio Kawagoe was the ambassador of this research for years (about 1960 to 1990). He is known for contributions to compartment fires. Others include S. Yokoi (plumes), T. Hirano (flame spread), T. Wakamatsu (smoke movement), T. Tanaka (zone modeling), Y. Hasemi (fire plumes), T. Jin (smoke visibility), K. Akita (liquids) and H. Takeda (compartment fire behavior).

In Sweden, beginning in the early 1970s, Professor O. Pettersson engaged in fire effects on structures, fostering the work of S. E. Magnusson and founding the fire engineering degree program at Lund University. Vihelm Sjolin, coming from the Swedish civil defense program, provided leadership to fire researchers like Kai Odeen (compartment fires) and Bengt Hagglund (radiation, fire dynamics), and later directed a $1 million Swedish basic research program in fire during the 1980s. Today Sweden has strong fire research efforts at Lund University and at the SP Laboratory in Boras (U. Wickstrom and
B. Sundstrom). Programs remain active around the world: PR China (W. C. Fan), Finland (M. Kokkala and O. Keski-Rinkinen), France (P. Joulain and P. Vantelon) and the United Kingdom (G. Cox, D. Drysdale, J. Torero, G. Makhviladze, V. Molkov, J. Shields and G. Silcock) to cite only a few.

Enabled by ample funding, enthusiasm for problems rich in interdisciplinary elements and challenged by new complex problems, many new researchers engaged in fire research in the 1970s. They were led by Professor Howard Emmons (Harvard), who had been encouraged to enter the field of fire research by Professor Hoyt Hottel (MIT). They both brought stature and credibility to the US fire research interest. Emmons also advised the Factory Mutual Research Corporation (FMRC) on its new basic program in fire research. The FM program inspired by Jim Smith was to serve insurance interests – a significant step for industry. That spawned a remarkably prolific research team: R. Friedman, J. deRis, L. Orloff, G. Markstein, M. Kanury, A. Modak, C. Yao, G. Heskestad, R. Alpert, P. Croce, F. Taminini, M. Delichatsios, A. Tewarson and others. They created a beacon for others to follow.

Under NBS and NSF funding, significant academic research efforts emerged in the US at this time. This brought needed intellect and skills from many. It was a pleasure for me to interact with such dedicated and eager scientists. Significant programs emerged at UC Berkeley (C. L. Tien, P. Pagni, R. B. Williamson, A. C. Fernandez-Pello and B. Bressler), Princeton (I. Glassman, F. Dryer, W. Sirignano and F. A. Williams), MIT (T. Y. Toong and G. Williams), Penn State (G. M Faeth), Brown (M. Sibulkin), Case-Western Reserve (J. Tien and J. Prahl) and, of course, Harvard (H. Emmons and G. Carrier). Many students schooled in fire were produced (A. Atreya, I. Wichman, K. Saito, D. Evans and V. Babrauskas – to name only a few). All have made their mark on contributions to fire research. Other programs have contributed greatly: the Naval Research Laboratory (H. Carhart and F. Williams), FAA Technical Center (C. Sarkos, R. Hill, R. Lyon and T. Eklund), SWRI (G. Hartzell and M. Janssens), NRC Canada (T. Harmathy, T. T. Lie and K. Richardson), IITRI (T. Waterman) and SRI (S. Martin and N. Alvares). This collective effort reached its peak during the decade spanning 1975 to 1985. Thereafter, cuts in government spending took their toll, particularly during the Reagan administration, and many programs ended or were forced to abandon their basic research efforts. While programs still remain, they are forced into problem-solving modes to maintain funds for survival. Indeed, the legacy of this fruitful research has been the ability to solve fire problems today.

1.4 Outlook for the Future

In 2002 NIST was directed by Congress under $16 million in special funding to investigate the cause of the 9/11 World Trade Center (WTC) building failures. The science of fire, based on the accomplishment of the fertile decade (1975 to 1985), has increasingly been used effectively in fire investigations. The Bureau of Alcohol, Tobacco and Firearms (BATF), having the responsibility of federal arson crimes, has built the largest fire laboratory in the world (2003). The dramatic events of 9/11 might lead to a revitalized public awareness that fire science is an important (missing) element in fire safety regulation tenets. The NIST investigation could show that standards used
in regulation for fire safety might be insufficient to the public good. Students of this text will acquire the ability to work problems and find answers, related to aspects of the 1993 bombing and fire at the WTC, and the 9/11 WTC attacks. Some of these problems address issues sometimes misrepresented or missed by media reporting. For example, it can clearly be shown that the jet fuel in the aircraft attacks on the WTC only provided an ignition source of several minutes, yet there are still reports that the jet fuel, endowed with special intensity, was responsible for the collapse of the steel structures. It is generally recognized that the fires at the WTC were primarily due to the normal furnishing content of the floors, and were key in the building failures. It is profound that NIST is now investigating such a significant building failure due to fire as the mandate given by Congress to the NBS founding fire program in 1914 – 90 years ago – that mandate was to improve the structural integrity of buildings in fire and to insure against collapse.

While much interest and action have been taken toward the acceptance of performance codes for fire safety in, for example, Japan, Denmark, Australia, New Zealand, the US and the rest of the world, we have not fully created the infrastructure for the proper emergence of performance codes for fire. Of course, significant infrastructure exists for the process of creating codes and standards, but there is no overt agency to insure that fire science is considered in the process. The variations in fire test standards from agency to agency and country to country are a testament to this lack of scientific underpinning in the establishment of regulations. Those that have expertise in fire standards readily know that the standards have little, if any, technical bases. Yet these standards have been generally established by committees under public consensus, albeit with special interests, and their shortcomings are not understood by the general public at large.

Even without direct government support or international harmonization strategies, we are evolving toward a better state of fire standards with science. Educational institutions of higher learning probably number over 25 in the world currently. That is a big step since the founding of the BS degree program in fire protection engineering at the University of Maryland in 1956 (the first accredited in the US). This was followed by the first MS program, founded by Dave Rasbash in 1975, at the University of Edinburgh. It is very likely that it will be the force of these programs that eventually lead to the harmonization of international fire standards using science as their underlying principles. This will likely be an uneven process of change, and missteps are likely; to paraphrase Kristian Hertz (DTU, Denmark): ‘It is better to use a weak scientific approach that is transparent enough to build upon for a standard practice, than to adopt a procedure that has no technical foundation, only tradition.’ Hopefully, this text will help the student contribute to these engineering challenges in fire safety standards. Fire problems will continually be present in society, both natural and manmade, and ever changing in a technological world.

1.5 Introduction to This Book

This book is intended to be pedagogical, and not inclusive as a total review of the subject. It attempts to demonstrate that the subject of fire is a special engineering discipline built on fundamental principles, classical analyses and unique phenomena. The flow of the
subject matter unfolds in an order designed to build upon former material to advance properly to the new material. Except for the first and last chapters, instruction should follow the order of the text. In my teaching experience, a one-semester 15-week, 45-hour course, covering most of Chapters 2 through 11, are possible with omission of specialized or advanced material. However, Chapter 11 on compartment fires is difficult to cover in any depth because the subject is too large, and perhaps warrants a special course that embraces associate computer models. The text by Karlsson and Quintiere, *Enclosure Fire Dynamics*, is appropriate for such a course (see Section 1.5.4).

The current text attempts to address the combustion features of fire engineering in depth. That statement may appear as an oxymoron since fire and combustion are the same, and one might expect them to be fully covered. However, fire protection engineering education has formerly emphasized more the protection aspect than the fire component. Figure 1.7 shows a flow chart that represents how the prerequisite

![Flow chart for subject material](image-url)
material relates to the material in the text. Standard texts can be consulted for the
prerequisite subjects. However, it is useful to present a brief review of these subjects to
impart the minimum of their facets and to stimulate the student’s recollections.

1.5.1 Thermodynamics

Thermodynamics is the study of matter as a macroscopic continuum. Mass is the tangible
content of matter, identified through Newton’s second law of motion, \( m = F/a \). A system
of fixed mass which could consist of a collection of different chemical states of matter
(species) must remain at a constant total energy if it is isolated from its surroundings. For
fire systems only internal energy \( (U) \) will be significant (excluding kinetic, electrical,
etc.). When a system interacts with its surroundings, the first law of thermodynamics is
expressed as

\[
U_2 - U_1 = Q + W \quad \text{or as a rate expression} \quad \frac{dU}{dt} = \dot{Q} + \dot{W} \quad (1.1)
\]

The internal energy changes from 1 to 2 and heat \( (Q) \) and work \( (W) \) are considered
positive when added to the system. Work is defined as the product of the resultant of
forces and their associated distances moved. Heat is energy transferred solely due to
temperature differences. (Sometimes, the energy associated with species diffusion is
included in the definition of heat.) The first law expressed in rate form requires the
explicit introduction of the transport process due to gradients between the system and
the surroundings. Despite these gradients implying nonequilibrium, thermodynamic
relationships are assumed to hold at each instant of time, and at each point in the
system.

The second law of thermodynamics allows us to represent the entropy change of a
system as

\[
dS = \frac{1}{T} dU + \frac{p}{T} dV \quad (1.2)
\]

This relationship is expressed in extensive properties that depend on the extent of the
system, as opposed to intensive properties that describe conditions at a point in the
system. For example, extensive properties are made intensive by expressing them on a
per unit mass basis, e.g. \( s = S/m \) density, \( \rho = 1/\nu, \nu = V/m \). For a pure system (one
species), Equation (1.2) in intensive form allows a definition of thermodynamic
temperature and pressure in terms of the intensive properties as

\[
\text{Temperature, } T = \left( \frac{\partial u}{\partial s} \right)_v \\
\text{Pressure, } p = \left( \frac{\partial s}{\partial v} \right)_u \quad (1.3)
\]

The thermodynamic pressure is equal to the mechanical pressure due to force at
equilibrium. While most problems of interest possess gradients in the intensive properties
(i.e. \(T, p, Y_i\)), local thermodynamic equilibrium is implicitly assumed. Thus, the equation of state, such as for an ideal gas

\[ p = \frac{RT\rho}{M} \]  

holds for thermodynamic properties under equilibrium, although it may be applied over variations in time and space. Here \(M\) is the molecular weight, \(\rho\) is the density and \(R\) is the universal gas constant. For ideal gases and most solids and liquids, the internal energy and enthalpy \((h = u + p/\rho)\) can be expressed as

\[ du = c_v \, dT \quad \text{and} \quad dh = c_p \, dT \]  

respectively \((1.5)\) where \(c_v\) and \(c_p\) are the specific heats of constant volume and constant pressure. It can be shown that for an ideal gas, \(R = c_p - c_v\).

### 1.5.2 Fluid mechanics

Euler expressed Newton’s second law of motion for a frictionless (inviscid) fluid along a streamline as

\[
\int_1^2 \rho \frac{\partial v}{\partial t} \, ds + \left( \rho \frac{v^2}{2} + p + \rho gz \right)_2 - \left( \rho \frac{v^2}{2} + p + \rho gz \right)_1 = 0 
\]  

\((1.6)\)

The velocity \((v)\) is tangent along the streamline and \(z\) is the vertical height opposite in sign to the gravity force field, \(g = 9.81 \, \text{N/kg} \) \((1 \, \text{N} = 1 \, \text{kg m/s}^2)\). For a viscous fluid, the right-hand side (RHS) is negative and in magnitude represents the power dissipation per unit volume due to viscous effects. The RHS can also be represented as the rate of shaft work added to the streamline or system in general.

Pressure is the normal stress for an inviscid fluid. The shear stress for a Newtonian fluid is given as

\[ \tau = \mu \frac{\partial v}{\partial n} \]  

\((1.7)\)

where \(\mu\) is the viscosity and \(n\) is the normal direction. Shear stress is shown for a streamtube in Figure 1.8. Viscous flow is significant for a small Reynolds number.

![Figure 1.8 Flow along a streamline](image-url)
(Re = \( \rho vl/\mu \)), where \( l \) is a characteristic length. Near surfaces, \( l \) might be thought of as the boundary-layer thickness where all of the viscous effects are felt and \( Re \) is locally small. However, if \( l \) is regarded as a characteristic geometric length, as the chord of an airfoil, \( Re \) might be found to be large. This means that the bulk flow away from the surface is nearly inviscid. Flows become unstable at large \( Re \), evolving into a chaotic unsteady flow known as turbulence. Turbulence affects the entire flow domain except very close to the surface, where it is suppressed and laminar flow prevails.

### 1.5.3 Heat and mass transfer

Heat can flow due to the temperature difference in two distinct mechanisms: (1) radiation and (2) conduction. Radiation is energy transfer by electromagnetic waves and possesses frequency (or wavelength). Radiant energy can be generated in many different ways, which usually identifies its application, such as radio waves, microwaves, gamma rays, X-rays, etc. These different forms are usually identified by their wavelength ranges. Planck’s law gives us the emitted radiation flux due to temperature alone as

\[
\dot{q}'' = \varepsilon \sigma T^4
\]

where \( \varepsilon \) is the emissivity of the radiating body, varying between 0 and 1. The emissivity indicates the departure of an ideal (blackbody) emitter. For solids or liquids under fire heating conditions, although \( \varepsilon \) depends on wavelength, it can generally be regarded as a constant close to 1. For gases, \( \varepsilon \) will be finite only over discrete wavelengths, but for soot distributed in combustion product gas, \( \varepsilon \) is continuous over all wavelengths. It is this soot in flames and combustion products that produces the bulk of the radiation. In general, for smoke and flames the emissivity can be represented for each wavelength as

\[
\varepsilon = 1 - e^{-\kappa l}
\]

The absorption coefficient \( \kappa \) depends in general on wavelength (\( \lambda \)). For large \( \kappa l \), \( \varepsilon \) approaches 1 – a perfect emitter. This limit generally occurs at turbulent flames of about 1 m in thickness.

The other mode of heat transfer is conduction. The conductive heat flux is, by Fourier’s law,

\[
\dot{q}'' = -k \frac{\partial T}{\partial n} \approx k \frac{\Delta T}{l}
\]

For laminar conditions of slow flow, as in candle flames, the heat transfer between a fluid and a surface is predominately conductive. In general, conduction always prevails, but in the unsteadiness of turbulent flow, the time-averaged conductive heat flux between a fluid and a stationary surface is called convection. Convection depends on the flow field that is responsible for the fluid temperature gradient near the surface. This dependence is contained in the convection heat transfer coefficient \( h_c \) defined by

\[
\dot{q}'' = -k \left( \frac{\partial T}{\partial n} \right)_s \equiv h_c (T - T_s)
\]
Convection is primarily given in terms of correlations of the form

\[ Nu \equiv \frac{h_c l}{k} = C Re^{n} Pr^{m} \quad \text{or} \quad Nu \equiv \frac{h_c l}{k} = C Gr^{n} Pr \]  

(1.12)

where the Grashof number, \( Gr \), replaces the \( Re \) in the case of natural convection, which is common to most fire conditions. The Grashof number is defined as

\[ Gr \equiv \frac{\beta g (T - T_s) l^3}{\nu^2} \]  

(1.13)

where \( \beta \) is the coefficient of volume expansion, \( 1/T \) for a gas, and \( Pr \) is the Prandtl number, \( c_p \mu/k \). These correlations depend on the nature of the flow and the surface geometry.

Mass transfer by laminar (molecular) diffusion is directly analogous to conduction with the analog of Fourier’s law as Fick’s law describing the mass flux (mass flow rate per unit area) of species \( i \) due to diffusion:

\[ \rho_i V_i = \dot{m}_i^{\prime\prime} = -\rho D \frac{\partial Y_i}{\partial n} \]  

(1.14)

where \( V_i \) is the diffusion velocity of the \( i \)th species, \( \rho \) is the mixture density and \( D_i \) is the diffusion coefficient and \( Y_i \) is the mass fraction concentration of the \( i \)th species. The corresponding analog for mass flux in convection is given in terms of the mass transfer coefficient, \( h_m \), as

\[ \dot{m}_i^{\prime\prime} = h_m (Y_i - Y_{i,s}) \]  

(1.15)

The convective mass transfer coefficient \( h_m \) can be obtained from correlations similar to those of heat transfer, i.e. Equation (1.12). The Nusselt number has the counterpart Sherwood number, \( Sh \equiv h_m l/D_i \), and the counterpart of the Prandtl number is the Schmidt number, \( Sc = \mu/\rho D \). Since \( Pr \approx Sc \approx 0.7 \) for combustion gases, the Lewis number, \( Le = Pr/Sc = k/\rho D c_p \) is approximately 1, and it can be shown that \( h_m = h_c/c_p \).

This is a convenient way to compute the mass transfer coefficient from heat transfer results. It comes from the Reynolds analogy, which shows the equivalence of heat transfer with its corresponding mass transfer configuration for \( Le = 1 \). Fire involves both simultaneous heat and mass transfer, and therefore these relationships are important to have a complete understanding of the subject.

### 1.5.4 Supportive references

Standard texts on the prerequisites abound in the literature and any might serve as refreshers in these subjects. Other texts might serve to support the body of material in this text on fire. They include the following combustion and fire books:


References


Problems

1.1 You may have seen the History Channel documentary or other information pertaining to the making of the World Trade Towers. Write a short essay, no more than two pages, on how you would have protected the Towers from collapse. You are to use practical fire safety technology, supported by scientific reasoning and information. You need to specify clearly what you would have done to prevent the Towers from collapse, based on fire protection principles, and you must justify your position. You can use other sources, but do not prepare a literature report; I am looking for your thinking.

1.2 Why do fire disasters seem to repeat despite regulations developed to prevent them from occurring again? For example, contrast the recent Rhode Island nightclub fire with the infamous Coconut Grove and Beverly Hill Supper Club fires. Can you identify other fires in places of entertainment that were equally deadly?

1.3 Look up the significant people that contributed to the development of fire science. Pick one, and write a one-page description of the contribution and its significance.
1.4 Examine the statistics of fire. Is there any logical reason why the US death rate is among the highest and why Russia’s increased so markedly after the fall of the Soviet Union?

1.5 The Oakland Hills fire in 1991 was a significant loss. Is the repetition of such fires due to earthquakes or the interface between the urban and wildlife domains? What is being done to mitigate or prevent these fires?

1.6 How does science enter into any of the codes and standards that you are familiar with?