

# 1 An Introduction to Combustion in Organic Materials

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## 1.1 Introduction

Combustion is a process by which fuel and oxidizer react to produce a different set of chemical products and heat. The process is intimately linked to the nature of the fuel but also to different transport processes that define the characteristics of the combustion process. This chapter provides a brief and general description of the different processes and of commonly used nomenclature.

Discussing combustion of organic materials needs to start with simple definitions that enable the description of the main phenomena involved. Organic materials can be defined as carbon-based materials, which can be divided into natural materials and processed materials. Processed materials are those generated through some modification that alters the physical or chemical characteristics of the natural materials. Natural materials include vegetation, decomposed vegetation, coal or the large group known as hydrocarbons (oils, tars, etc.). Processed materials include timber, plastics, petrol and many other industrial products. It is important to emphasize that many inorganic materials will also combust, but these will not be discussed here.

From the combustion perspective natural or processed organic materials are no different; in both cases the combustion process can be described

as a chemical reaction that is defined by the following generic expression:



The 'fuel' being the organic material and the 'oxidizer' being oxygen extracted in most cases from air. Chemical reactions associated with combustion are exothermic, thus the products are released with a significant amount of energy. The specific energy (i.e. joules produced per kilogram of the material) tends to be extremely high when combustion processes are compared to other energy-generating mechanisms (electric batteries, fuel cells, etc.; Fernandez-Pello, 2002). Thus, combustion of organic fuels has been a preferred source of energy.

Combustion processes have been controlled for at least 100 000 years (Stahl, 1984; James, 1989) and humans have learnt to harness the energetic content of organic fuels for cooking, comfort and power. Until the industrial revolution combustion was poorly understood and was limited to controlled burning of natural fuels (i.e. coal, wood). The Industrial Revolution generated the first true understanding of combustion (Faraday, 1908), the massive use of organic fuels, and the first attempts to modify organic compounds to produce more efficient fuels (Frank, 2005).

Today, combustion of modified organic fuels represents more than 85% of the total worldwide energy production (Jacobson, 2009).

A different form of combustion is known as fire. Fire is the uncontrolled chemical oxidation of organic fuels that is generally associated with destruction. In fire, the heat of the combustion process serves to sustain the uncontrolled burning of any adjacent organic fuels. Fires occur in many forms and scales and are generally deemed as detrimental to humans, economies and the environment. Natural fires include peat, forest and underground fires (Rein, 2009) while infrastructure fires affect buildings of all natures and sizes (Torero and Rein, 2009).

To be able to discuss controlled or uncontrolled combustion of organic solids it is important to understand the fundamental underlying physical and chemical phenomena involved. The following sections will therefore present a brief discussion of combustion related processes.

## 1.2 The Reactive Zone

Given that combustion is an exothermic chemical reaction, it has to happen in a specific location. The location is given by the way reactants are delivered and by the local temperature. If the temperature is too low or in the absence of fuel or oxidizer combustion cannot occur, thus there are specific conditions that will sustain combustion. If adequate conditions are attained at a specific location the chemical reaction will proceed at a defined rate ( $\dot{\omega}'''$ ; 1/seconds). The dot denotes per unit time while the triple prime per unit volume. The rate is a function of the supply of reactants and the temperature as indicated by Equation 1.2:

$$\dot{\omega}''' = AY_{\text{F}}^n Y_{\text{O}}^m e^{-E/RT} \quad (1.2)$$

Equation 1.2 is a common way to represent typical combustion reactions and is one potential form of the family of Arrhenius type equations that describe the reaction rate on the basis of kinetic theory. This expression indicates that the

presence of oxygen and fuel is necessary with them appearing through their respective concentrations ( $Y_{\text{F}}$  is the concentration of fuel while  $Y_{\text{O}}$  is the concentration of oxygen). Both terms are dimensionless. The coefficients  $n$  and  $m$  are called the reaction orders and denote the sensitivity of the rate to each of the reactants. The exponential term brings the dependency on temperature. This term shows that the reaction rate will be very small unless the temperature reaches a threshold that makes the product  $RT$  comparable to the activation energy ( $E$ ). The constant  $R$  is the gas constant ( $R=8.314$  J/mol K) and  $T$  is the temperature in kelvin. The product  $RT$  represents the energy accumulated in the molecules as the temperature increases; thus when the temperature reaches a certain threshold the number of collisions induced by the increase in kinetic energy results in the breakdown of the molecules and the onset of the reaction. The rate will then continue to increase as the temperature increases. The term  $A$  (1/second) is just the constant of proportionality that links the reaction rate to the parameters controlling it.

The magnitude of the activation energy ( $E$ ) will define the sensitivity of the reaction rate to temperature: the larger the value of  $E$  (high activation energy) the more sensitive the reaction rate is to variations of the reactants' temperature. Combustion reactions have very high activation energies, thus are extremely sensitive to temperature.

As the molecules of reactants combust to produce products they release energy. The energy produced per unit time and volume of reactants is denoted by  $\dot{Q}'''$  (joules/m<sup>3</sup>.s) and is given by Equation 1.3:

$$\dot{Q}''' = \rho \Delta H_{\text{C}} \dot{\omega}''' \quad (1.3)$$

where  $\Delta H_{\text{C}}$  is the heat of combustion or energy produced per kilogram of fuel (joules/kg<sub>FUEL</sub>) while  $\rho$  is the global density of the reactants. The heat of combustion depends on the organic fuel, and typical values are tabulated in most combustion books (Glassman and Yetter, 2008). Table 1.1 lists the heat of combustion of a small group of organic materials.

**Table 1.1** Representative heats of combustion ( $\Delta H_c$ ) of different organic materials.

Fuel	$\Delta H_c$ (MJ/kg <sub>FUEL</sub> )
Hydrogen	141.80
Propane	50.35
Gasoline	47.30
Paraffin	46.00
Kerosene	46.20
Coal (lignite)	15.00
Wood	15.00
Peat (dry)	15.00
PVC (Polyvinyl chloride)	17.50
PE (Polyethylene)	44.60

The energy produced is then transferred back to the products or lost to the environment. The fraction of the energy transferred to the products will define the temperature of the products and is normally referred to as the flame temperature,  $T_F$ . If the flame temperature is high enough then heat will be transferred to fresh reactants leading to a self-sustained reaction; if the temperature is too low then the reaction will have to be assisted by an external supply of energy.

Equation 1.2 shows clearly the requirements for a sustained reaction: fuel and oxidizer have to be delivered in sufficient quantities to maintain adequate concentrations, and the flame temperature has to be high enough to guarantee sufficient heat transfer to the reactants to achieve a high enough temperature that will result in a strong reaction rate. Thus, ignition requires the supply of reactants within the necessary concentrations (flammability limits) and a supply of energy to initiate the reaction and increase the reaction rate to a level where it becomes self-sustained (critical ignition energy). Extinction can be then achieved by precluding the arrival of either reactant or by enhancing heat losses so that the temperature of the flame decreases below the threshold that will enable sufficient energy production to self-sustain the reaction.

Combustion chemistry has been briefly discussed here using a simple approach; nevertheless, the complexity of this process can be significant, involving many reactions and different transport

processes (heat and mass). For a more detailed discussion the reader is directed to Glassman and Yetter (2008).

While combustion is a chemical reaction and thus the reaction rates are expressed in chemical terms, it is in many cases a process controlled by the transport of heat and mass. How fast the reactants reach the reaction zone determines the production of energy, and how fast the energy is transferred towards the reactants will determine the vigour of the reaction rate.

The simplest way to separate different forms of combustion is by specifying the mechanisms by which reactants reach the reaction zone. The first case is the premixed flame; in this case fuel and oxidizer are mixed in concentrations that are adequate for combustion to occur. Here, no mass transport is necessary and the reaction consumes the reactants as fast as the energy is transferred towards the unburnt gases. Thus the problem is dominated purely by heat transfer. The other extreme is the non-premixed flame; in this case fuel and oxidizer are separate and the energy produced is determined only by the rate at which reactants can be delivered to the flame. In this case the process is dominated purely by mass transfer, so many texts refer to non-premixed combustion as 'diffusion flames'. Premixed flames will require fuel and oxidizer to both be in the gas phase, and they are thus commonly used for burners and other controlled energy-generating processes such as engines or turbines. Non-premixed flames are typical of condensed-phase fuels (liquids or solids) where the fuel is supplied at a rate that is defined by the amount of energy delivered by the combustion reaction. This energy is what enables the phase of the fuel to change. Non-premixed combustion is typical in uncontrolled processes such as fires but can also be used in boilers, fireplaces and engines.

### 1.2.1 Premixed flames

Figure 1.1 shows a schematic of how a combustion reaction will propagate through a flammable mixture. The reactants (right) and products (left) are stationary and the chemical reaction ( $\dot{\omega}'''$ ) propagates at a velocity  $U$ . The velocity is determined

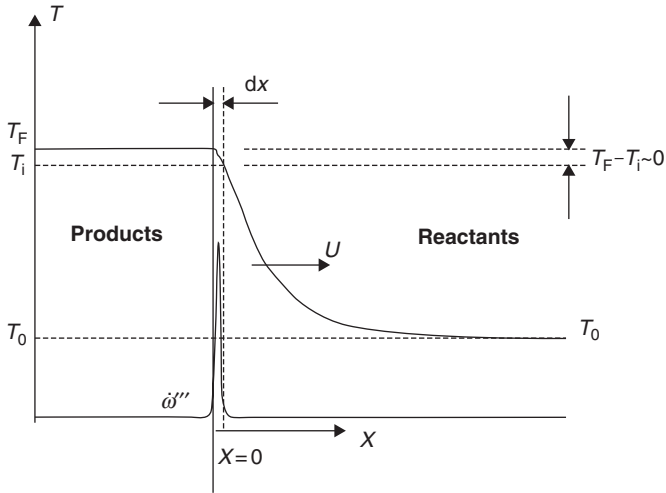


Fig. 1.1 Schematic of a propagating premixed flame.

by the transport of heat from the products at the flame temperature,  $T_F$ , to the reactants at ambient temperature ( $T_0$ ). The reaction is concentrated in a very thin region ( $dx$ ) (written as a differential because it is a small length) bounded by total consumption of the reactants (left) and the ignition temperature,  $T_i$  (right). As explained before, the reaction is concentrated in a thin region because combustion reactions have typically high activation energies, and thus are very sensitive to temperature. Instead, preheating can occur through a much wider region, thus it is common to assume that the ignition and flame temperatures are very similar. As the reaction propagates the hot products expand. The thermal expansion can dissipate slower than the speed of the reaction front, in which case there will be no pressure build-up and the result will be a deflagration. If the expansion is violent and the reaction (i.e. heat transfer) cannot proceed fast enough then a pressure front will develop behind the reaction resulting in an explosion or a detonation (Lewis and von Elbe, 1937).

For premixed flames the main parameter of concern is the flame propagation velocity,  $U$ . The first theoretical treatment that provided a flame propagation velocity,  $U$ , is due to Mallard and Le Châtelier, described in Le Châtelier's '*Cours de chimie industrielle*' at *École des Mines* (1897) and later formalized by Lewis and von Elbe (1937).

The flame propagation velocity is controlled mainly by heat transfer ahead of the flame. Heat transfer is influenced by the nature of the flow field (laminar vs turbulent), the thermal properties of the mixture, and radiative heat losses from the hot gases towards the environment. In Figure 1.1 the hot gases are shown at constant temperature thus heat losses are being ignored. In reality the hot gases will cool behind the flame.

### 1.2.2 Non-premixed flames

Figure 1.2 shows a schematic of a non-premixed flame. The fuel comes from the right with an initial concentration of  $Y_{F,i}$  while the oxidizer comes from the left with an initial concentration of  $Y_{O,i}$ . As they approach the flame zone,  $dx$ , fuel and oxidizer are transported towards the flame where they will be consumed, while products move away from the flame diluting fuel and oxidizer. Mass transport mechanisms could be diffusion or convection, and the mass flux of reactants towards the flame dominates the reaction and energy release rates and therefore determines the flame temperature. Heat transfer from the flame, especially radiation, will also affect the flame temperature, thus ignition and extinction become a complex function of mass and heat transfer to and from the flame.

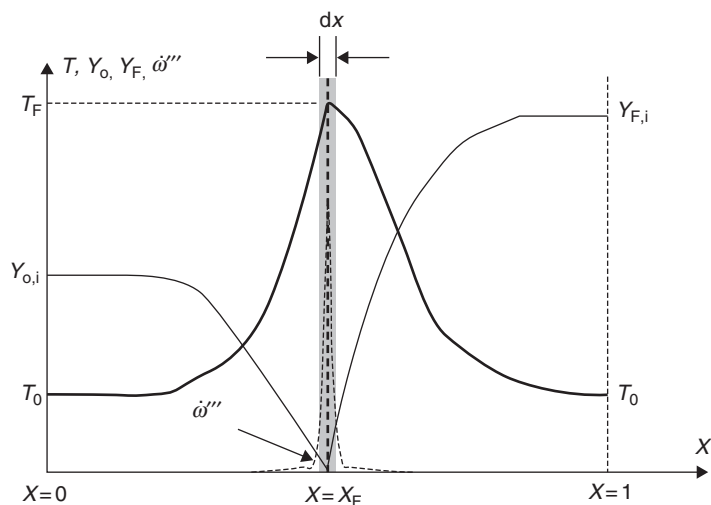


Fig. 1.2 Schematic of a non-premixed flame.

The structure and characteristics of non-premixed flames have been studied extensively, with the first theoretical description presented by Burke and Schumann (1928). The main parameter of interest is the location of the flame. To establish the location of an axisymmetric gas flame with an oxidizer co-flow, Burke and Schumann (1928) required a series of assumptions of which the most important is that the chemistry is infinitely fast and therefore all fuel and oxidizer is consumed at the flame location. As illustrated in Figure 1.2, the concentration of fuel in the oxidizer zone is zero as well as that of the oxidizer in the fuel zone. This approach was later formalized using a compounded variable (Shvab-Zel'dovich variable; Williams, 1985) that enables the solution of mass and energy transport equations through a single scalar (mixture fraction). Further studies of non-premixed flames have emphasized details of transport and chemistry; nevertheless the original mixture fraction analysis is still extensively used.

### 1.3 Fuel Generation

So far the discussion has concentrated on gas-phase combustion processes. In the case of premixed flames the fuel is delivered into the gas phase

and mixed to guarantee a flammable mixture. In non-premixed flames the fuel can either be delivered in the gas phase (e.g. in a Bunsen burner) or it can be generated through a phase change process from a condensed fuel. This section will discuss the latter.

Organic solids and liquids have the potential to produce gas-phase fuels that can feed premixed or non-premixed flames. The production of the gas-phase fuel is sustained by the supply of heat. When heat is delivered to a condensed fuel its temperature increases until gas-phase products start emerging (Drysdale, 1998). If the condensed fuel is a liquid (and for some solids) the gasification process does not include any chemical changes and follows basic thermodynamic laws of thermal equilibrium between phases. Given an ambient temperature and pressure, gasification will aim to attain an equilibrium partial pressure of fuel at the gas side of the fuel surface (the Clausius–Clapeyron relation), the rate at which this equilibrium condition is attained is defined by the net heat supplied for gasification and the rate at which the gas-phase fuel is removed from the surface by convection or diffusion. Detailed explanation of the gasification of liquid fuels is provided by Drysdale (1998) or the Society of Fire Protection Engineers' Handbook (SFPE, 2009).

Most organic fuels undergo chemical changes when changing phase; this process is called pyrolysis. The pyrolysis process is a chemical reaction whose rate is generally described in a similar manner as a combustion reaction. Thus Arrhenius type formulations with high activation energies (Equation 1.2) are the norm when describing pyrolysis chemistry.

The process of pyrolysis can be extremely complex and, depending on the fuel and heating characteristics, can follow distinctly different paths. These paths can be a compendium of numerous reactions, which can be sequential or compete against each other. Furthermore, the chemical pathways followed can be strongly influenced by the presence of oxygen, as indicated in Equation 1.2.

It is important to note that while degradation of some fuels will show dependency on the oxygen concentration many others will not (Hirata *et al.*, 1985; DiBlasi, 1993). In those cases  $m$  in Equation 1.2 is assumed to be zero.

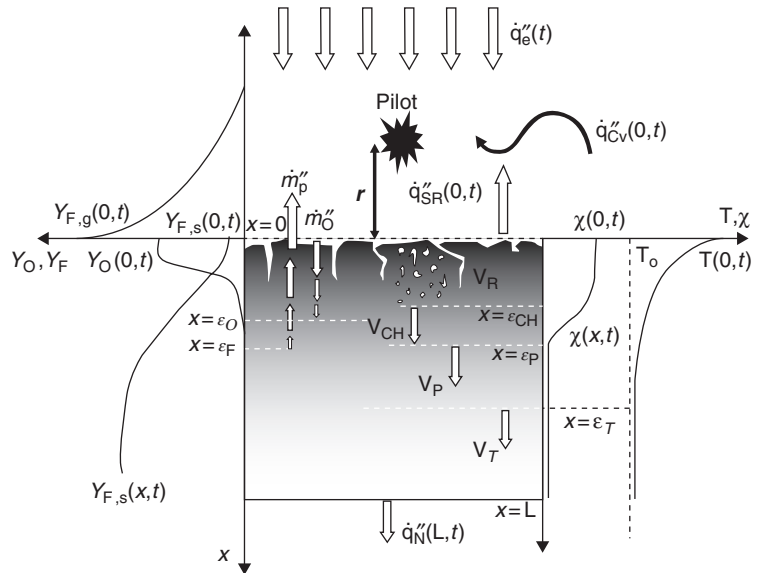
The chemical pathways leading to the pyrolysis of most solid organic fuels are fundamentally incomplete inasmuch as the constants associated with the equations that will serve to quantify the rate of each reaction step are unknown. Many studies have evaluated reduced chemical mechanisms (i.e. only including the main reaction rate-limiting steps) for the pyrolysis of different solids (Horrocks *et al.*, 2000) but there is still great uncertainty on the chemical pathways, the number of steps required and the constants associated with them. Thermo-gravimetric analysis (TGA) has been used in the past to establish reduced chemical reaction mechanisms as well as the associated constants. TGA deduces the kinetic constants of chemical reactions by measuring the rate of a reaction (mass loss) as a function of the controlled heating of a fuel. The principles behind TGA studies and some applications to materials relevant to fire are presented in SFPE (2009).

Despite the generalized use of TGA data, there is increasing recognition that pyrolysis reaction pathways are sensitive to the heating rate. The correlation of mass loss with kinetic constants used to interpret TGA data requires heating rates

of the order of 1 to 20°C/min, which is generally an order of magnitude slower than heating rates typical of any combustion process. Thus, recent studies have established methodologies that use complex models together with standard test methods and advanced optimization techniques to establish reaction schemes and their associated constants (Lautenberger *et al.*, 2006). Although these procedures allow exposure of the materials to heating rates typical of combustion and obtaining of comprehensive sets of constants they have only been applied to a limited number of materials. Currently, methodologies that use combinations of optimization techniques, models and tests remain research tools and are not widely used.

Before flaming ignition can occur, fuel in the gas phase needs to be produced. Solid materials that are not susceptible to spontaneous ignition (Drysdale, 1998) will show very little evidence of chemical reactions at ambient temperatures, thus can be deemed as inert. The reaction rates associated with pyrolysis can be considered negligible and therefore the material will not follow any transformation. As the temperature increases the reaction rates increase and the solid fuel starts changing. Given the temperature distribution within the material, the rates of decomposition are a function of  $x$ , with a greater production of pyrolysates close to the surface and lesser production at depth (Figure 1.3).

Local production of fuel is not the only important variable. The gas-phase fuel produced might be the result of a combination of pyrolysis and oxidation reactions, thus its composition might include large quantities of fully oxidized compounds such as carbon dioxide (CO<sub>2</sub>), partially oxidized gases such as carbon monoxide (CO) and other molecules that can have all levels of partial oxidation. Therefore, together with the reaction rates, the mass fraction of inert gases needs to be subtracted leaving the remaining reactive gases. As an example, Kashiwagi and Nambu (1992) studied the degradation products of cellulosic paper showing that there is a significant presence of inert gases like water vapour, fully oxidized gases like CO<sub>2</sub>, partially oxidized products like CO, and fuel like CH<sub>4</sub> and H<sub>2</sub>.



**Fig. 1.3** Schematic of the different processes occurring as a material undergoes degradation prior to ignition induced by an external source of heat.

There are scant data available on the degradation products of most organic combustible materials; therefore, the mass fraction of flammable gases present in the local products of degradation will be described here by means of a single variable,  $Y_{F,s}(x,t)$ , which represents a global contribution of all compounds that can be further oxidized. Figure 1.3 represents  $Y_{F,s}(x,t)$  as an increasing function with a minimum at the surface ( $Y_{F,s}(0,t)$ ). This is based on the assumption that where there is a greater presence of oxygen there are greater levels of oxidation.

Oxygen can migrate inside a fuel resulting also in an in-depth distribution ( $Y_O(x,t)$ ) that reaches ambient values at the surface ( $Y_O(0,t)$ ). In-depth oxygen and fuel diffusion is controlled by the structure of the solid. Some materials are highly permeable and allow unrestricted transport of species in and out of the solid. For other materials oxidation will occur only very close to the surface and could be potentially neglected. The permeability of the fuel can be a function of many variables including the degradation and consumption of the material and has received very little attention in the combustion literature. In the absence of a well-defined permeability

function, here a simple variable associated with the fuel permeability ( $\chi(x,t)$ ) will be introduced and assumed to describe in a generic manner the fraction of the fuel produced that can flow through the solid material. It has to be noted that  $\chi(x,t)$  is not strictly a permeability function but a combination of permeability, porosity and any fractures within the material. The permeability according to Darcy's law is a constant of proportionality that links the pressure gradients to the flow velocity in a homogeneous material. Here the material will have a more complex and heterogeneous structure. The permeability of the fuel has been found to be critical in the development of forest fires (Bartoli *et al.*, 2011) and peat fires (Rein, 2009; see also Chapter 2).

Oxygen and fuel concentrations will be controlled by the local permeability and by production/consumption rates, and thus indirectly by the temperature distribution ( $T(x,t)$ ). This makes it necessary to treat them independently; therefore two independent variables emerge,  $\epsilon_F(t)$  and  $\epsilon_O(t)$ . The former represents the region where fuel is being produced while the latter represents the region where oxygen is present in relevant quantities.

If all the reactions occurring can be represented in an Arrhenius form (Equation 1.2) then the local mass production,  $\dot{m}_p''(x, t)$ , can be summarized into a function of the form:

$$\dot{m}_p''(x, t) = Y_{F,s}(x, t) \sum_{i=1}^{i=N} \left[ A_i Y_O^{m_i}(x, t) Y_F^{n_i}(x, t) e^{-E_i/RT(x,t)} \right] \quad (1.4)$$

where the summation is not truly a sum of all the different  $N$  reaction steps but just some global combination of them that includes sequential and competitive reactions.

To obtain the total fuel production at the surface per unit area ( $\dot{m}_p''(0, t)$ ) it is necessary to integrate Equation 1.4 across the entire depth including the permeability function described above. It is important to note that fuel produced in-depth does not have to come out, and in many cases pressure increases within the fuel structure can be observed. A common manifestation of trapped fuel is the formation of bubbles. Figure 1.4 shows a sectioned sample of plastic where bubbles generated by heating from the top can be clearly seen. The effects of permeability and pressure are combined in a complex manner to define the flow within the porous medium. This remains an unresolved problem; thus the use of a simple variable such as  $\chi(x, t)$  is justified.

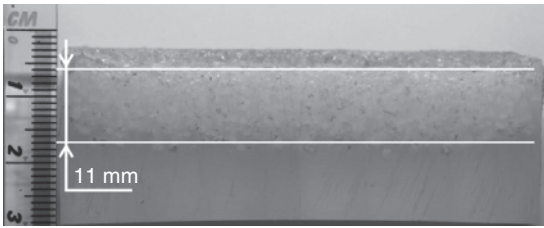


Fig. 1.4 Vertical sections of a clear plastic sample showing the bubble layer depth. The sample was exposed to a heat flux level of 20 kW/m<sup>2</sup> for 35 minutes with a conical heater. The image corresponds to a section of the sample where heat was imposed at the top. The layer between the lines is filled with bubbles while the layer below is transparent.

Once enough fuel is produced a flammable mixture can be generated in the gas phase and combustion can proceed as described in previous sections. The heat feedback from the flames will sustain the production of fuel and if enough fuel is produced then combustion will be self-sustained. If the heat does not produce enough fuel then the flame will have to be assisted by an external source of heat. The ratio of heat produced to the heat needed to sustain combustion of a condensed fuel is called the mass transfer number, or  $B$  number (Drysdale, 1998), and can be represented in its simplest form by Equation 1.5:

$$B = \frac{\dot{Q}_{\text{Feedback}}}{\dot{Q}_{\text{Pyrolysis}}} \quad (1.5)$$

Where all losses are neglected,  $\dot{Q}_{\text{Feedback}}$  is the energy from the flame delivered to the fuel surface and  $\dot{Q}_{\text{Pyrolysis}}$  is the energy required for the fuel to emerge in the gas phase. Theoretically, if  $B > 1$  then the reaction will be self-sustained and if  $B < 1$  it is necessary to deliver an external supply of heat to assist the combustion process. In combustors used for energy production it is essential that the fuel has  $B > 1$  while in fires it is only necessary that one of the fuels has a  $B > 1$  to support the combustion of all other fuels. In fires, it is typical that a single item such as a sofa or mattress made out of fuels that have mass transfer numbers much greater than one (e.g. polyurethane, cotton, nylon) sustains the combustion of other fuels that will naturally not burn on their own (e.g. wood, PVC). In some cases fuels that cannot sustain combustion can be induced to burn in a self-sustained manner just by placing and igniting several pieces together so that each piece delivers sufficient heat feedback to maintain the others' burning (e.g. wood burning in a fireplace). Although the concept is simple its application is very complex and it requires a detailed understanding of heat and mass transfer processes.

A common example that illustrates the importance of the  $B$  number and its complexity in the





Fig. 1.5 Burning candle. For a colour version of this figure, see Plate 1.1.

combustion of organic fuels is the candle. This example was used by Faraday in his famous Christmas lecture of 1861. Figure 1.5 shows a familiar picture of a candle where the presence of a glowing wick is clear. Solid wax will not burn in a self-sustained manner unless there is a wick. The energy feedback from the combustion of the wax is not sufficient to produce enough fuel ( $B < 1$ ) unless a mechanism is established to enhance the recovery of the energy and compensate for the energy required for the phase change of wax from solid to gas. The wick is this mechanism. The wick allows the melted wax from the candle to move upwards (capillary forces between the liquid and the solid fibres) and spread through the wick. This enhances the surface area that receives heat from the combustion reaction and thus enhances fuel production; the larger the wick, the greater the fuel produced and the larger the flame. At some point the production of fuel will be sufficient for the flame to be sustained.

### 1.3.1 Heterogeneous combustion of organic fuels

While wax illustrates an extreme where surface area enhancement represents the mechanism for heat recovery that increases the mass transfer number above unity ( $B > 1$ ), the wick also provides an illustration of a different form of combustion that occurs in the solid phase. This form of combustion is called heterogeneous combustion because fuel and oxidizer are not in the same phase. Commonly the fuel will be in the solid phase while the oxidizer will be in the gas phase. Other commonly used terms for heterogeneous combustion are glowing, smouldering, embers, etc. (Rein, 2009).

The tip of a wick is formed by a large amount of loose fibres that are no longer impregnated by fuel. In the absence of the wax, the fibres burn and the wick is consumed. The end of the tip emerges outside the flame region (Figure 1.5), thus it is directly exposed to the air. The very large surface area provided by the fibres enables fast diffusion of oxygen towards the fibres' surface resulting in exothermic oxidation of the solid fuel before it can pyrolyze and change phase. Many natural and processed materials will sustain heterogeneous combustion under the right conditions. In some cases heterogeneous combustion will coexist with gas-phase flames. Very good examples of this are organic fuel beds typical of forest fires. Figure 1.6a shows a sample of pine needles arranged in a manner so that they form a porous medium with enhanced surface area for oxygen diffusion. If air flows through the bed then heterogeneous combustion can occur within the bed. In most cases gaseous fuel will also be produced resulting in a flame (Figure 1.6b). Timber also has the potential for both forms of combustion. In the case of timber an enhancement of the external supply of heat will result in pyrolysis dominating over diffusion and homogeneous combustion (Figure 1.7a). Whereas for low heat fluxes diffusion dominates, the flame disappears and glowing remains (Figure 1.7b). It is important to note that the porous nature of the fuel retains heat therefore heterogeneous

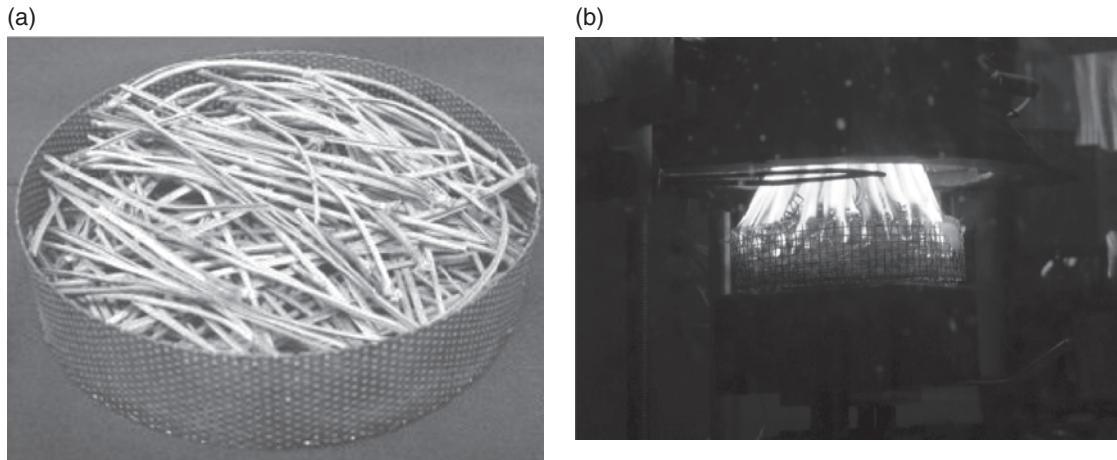


Fig. 1.6 (a) A bed of pine needles. (b) A burning bed of pine needles with homogeneous and heterogeneous combustion.

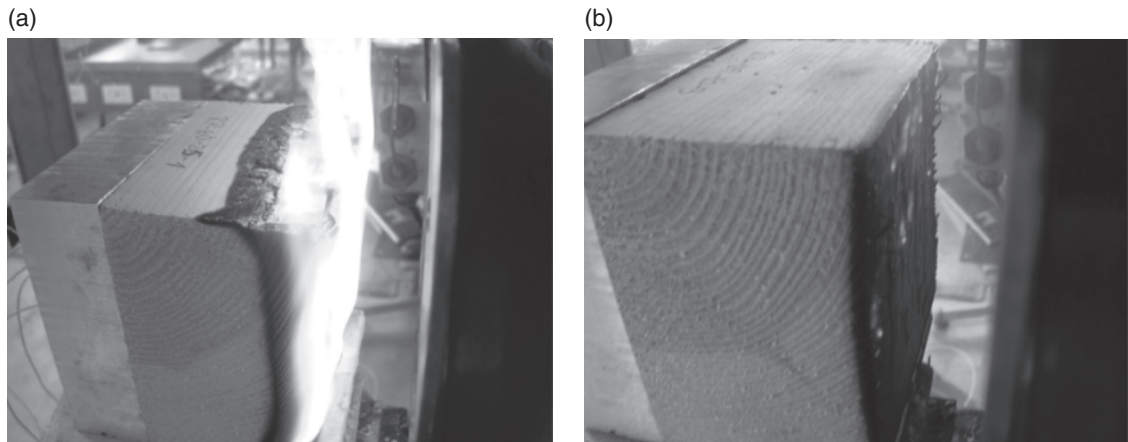


Fig. 1.7 (a) A piece of timber subject to a high heat flux resulting in flaming. (b) A piece of timber subject to a low heat flux resulting in heterogeneous combustion. For a colour version of this figure see, Plate 1.2.

combustion can occur under conditions (low heat input, low oxygen or fuel concentrations) that will not sustain flames.

#### 1.4 Summary

The combustion of organic fuels is a chemical reaction that results in the generation of products and heat. The nature of the process is controlled

by heat and mass transfer and can result in very different forms of combustion. The different transport mechanisms provide the basis to forms of combustion that include a wide range of commonly used terms such as detonations, explosions, deflagrations, fires, glowing, embers or smouldering. The nature of the fuel, natural or processed, will also play an important role in the nature of the combustion process. The main process linked to the fuel is the transformation of

the condensed-phase material into gases that in the presence of oxygen will combust.

### References

- Bartoli, P., Simeoni, A., Biteau, H., Torero, J.L. & Santoni, P-A. (2011) Determination of the main parameters influencing forest fuel combustion dynamics. *Fire Safety Journal* **46**: 27–33.
- Burke, S.P. & Schumann, T.E.W. (1928) Diffusion flames. *Industrial and Engineering Chemistry Research* **20**: 998–1004.
- Di Blasi, C. (1993) Modeling and simulation of combustion processes of charring and non-charring solid fuels. *Progress in Energy and Combustion Science* **19**: 71–104.
- Drysdale, D.D. (1998) *An Introduction to Fire Dynamics*. John Wiley & Sons, Ltd.
- Faraday, M. (1908) *The Chemical History of a Candle: A Course of Lectures Delivered Before a Juvenile Audience at the Royal Institution*. William Crookes (ed.), Chatto & Windus, London.
- Fernandez-Pello, A.C. (2002) Micropower generation using combustion: issues and approaches. *Proceedings of the Combustion Institute*, **29**: 883–98.
- Frank, A.F. (2005) *Oil Empire: Visions of Prosperity in Austrian Galicia*. Harvard Historical Studies, Harvard University Press.
- Glassman, I. & Yetter, R.A. (2008) *Combustion*, 4th edn. Academic Press.
- Hirata, T., Kashiwagi, T. & Brown, J.E. (1985) Thermal and oxidative degradation of poly(methyl methacrylate): Weight loss. *Macromolecules* **18**: 1410–18.
- Horrocks, A.R., Gawande, S., Kandola, B. & Dunn, K.W. (2000) *Recent Advances in Flame Retardancy of Polymeric Materials*. Business Communications Co., Norwalk, CT.
- Jacobson, M.Z. (2009) Review of solutions to global warming, air pollution and energy security. *Energy and Environmental Science* **2**: 148–73.
- James, S.R. (1989) Hominid use of fire in the lower and middle Pleistocene. *A review of the evidence. Current Anthropology* **30**: 1–26.
- Kashiwagi, T. & Nambu, H. (1992) Global kinetics constants for thermal oxidative degradation of a cellulosic paper. *Combustion and Flame* **88**: 345–68.
- Lautenberger, C., Rein, G. & Fernandez-Pello, A.C. (2006) The application of a genetic algorithm to estimate material properties for fire modeling from bench-scale fire test data. *Fire Safety Journal* **41**: 204–14.
- Lewis, B. & von Elbe, G. (1937) Theory of flame propagation. *Chemical Reviews* **21**: 347–58.
- Rein, G. (2009) Smouldering combustion phenomena in science and technology. *International Review of Chemical Engineering* **1**: 3–18.
- SFPE (2009) *Handbook of Fire Protection Engineering*, 4th edn. Society of Fire Protection Engineers.
- Stahl, A.B. (1984) Hominid dietary selection before fire. *Current Anthropology* **25**: 151–68.
- Torero, J.L. & Rein, G. (2009) Physical parameters affecting fire growth. In Wilkie, C.A. & Morgan, A.B. (eds) *Fire Retardancy of Polymeric Materials*, 2nd edn. CRC Press, Taylor & Francis, pp. 43–74.
- Williams, F.A. (1985) *Combustion Theory*, 2nd edn. Benjamin Cummings Publishing Company.

