Chapter 2
Fuel and Ventilation Controlled Fires

Abstract The effect of ventilation on fire development is one of the most important phenomena to understand in tunnel fire safety engineering. Ventilation controls the combustion process and is usually the phenomenon that engineers find most difficult to comprehend. Tunnel fires are considerably different from compartment fires in the way flashover occurs and develops; misconceptions about the effects of ventilation in tunnel fires are clarified in this chapter. The difference between fuel-controlled fires and ventilation-controlled fires is shown and explained. This chapter lays out the basics for understanding the role of ventilation interactions with other combustion phenomena and in fire development. This chapter is based partly on theory, but also includes experimental data obtained by the authors.

Keywords Ventilation control · Fuel control · Oxygen · Combustion

2.1 Introduction

The basic knowledge about fire physics in tunnels is derived from research in compartment or corridor fires. Major theoretical and experimental work was carried out in the 1950s and 1960s followed up by numerical applications in the 1980s and 1990s. This work provided the knowledge base for understanding fire physics and development in tunnel fires and has been used as a basis for many theoretical breakthroughs. This progression, of course, is due to the limited amount of basic fire research that has focussed solely on tunnel fires [1]. In the following sections, the effects of ventilation that are based on knowledge from compartment fires and which have been applied to tunnel fires are identified and explained wherever possible.

2.2 Fire Development in Building Fires

Fire development in compartments or enclosures inside buildings is usually divided into periods or stages. In textbooks [2, 3], four distinct time periods of the complete fire development process in compartments are usually identified. The fire starts

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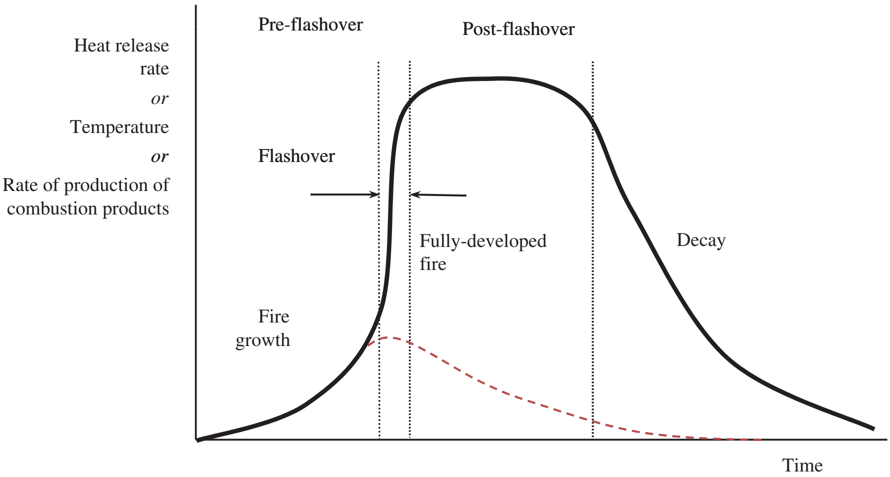

Fig. 2.1 Phases of a typical compartment fire [4]

with a *growth* period which either transitions to a rapid *flashover period* or, if that stage is not achieved, starts to decay and the fire ends. If flashover occurs, the fire becomes *fully developed* during the third period, with relatively constant conditions, before it starts to *decay* during the last period. This complete fire development is represented in Fig. 2.1 and is given as either heat release rate (HRR), temperature, or rate of combustion products as a function of time. Usually the growth period is defined as the *preflashover* stage, and the *post-flashover* stage includes the fully developed fire and the decay period. The fire development in tunnels cannot be described in the same way because the interactions with the enclosure differ considerably.

Traditionally, compartment fires are defined as either *fuel-controlled* or *ventilation-controlled*. In the growth period or the pre-flashover stage of a compartment fire there is sufficient oxygen available for combustion and the fire growth is entirely dependent on the flammability and configuration of the fuel. During this stage, the fire is defined as fuel-controlled. The fire after the growth period can either continue to develop up to and beyond a point at which interaction with the compartment boundaries becomes significant (flashover) or it can start to decay (dashed line in Fig. 2.1). There are two factors that determine the direction of the fire development: a lack of fuel will impede development; or the fire will become ventilation-controlled if there is enough fuel but the fire grows to a size dictated by the inflow of fresh air $(\dot{m}_a)$. The definition and mathematical expression of the difference between fuel- and ventilation-controlled fires will be given in Sect. 2.4.

Unfortunately, there are different interpretations and use of the terminology for fuel and ventilation control. This has resulted in a great confusion among the practicing engineers. A fuel-controlled fire, that is when there is enough oxygen to combust all the available fuel vapors in the enclosure, is also described as well ventilated, over ventilated, oxygen rich or fuel lean. A ventilation-controlled fire, that is when there is not enough oxygen available to combust all the fuel available inside the enclosure, is sometimes described as under ventilated, fuel rich or oxygen starved [4]. This can cause confusion for the reader, but as authors use different words to describe the same physical phenomena it is unavoidable and difficult to deal with. Due to this confusion it is very important to understand the basic difference of these two combustion modes. The term fuel and ventilation control will be used in this chapter.

For compartment fires the transition period between fuel- and ventilation-controlled fire is usually defined as the 'flashover'. Flashover means that everything that can burn inside a compartment starts to burn during this stage. The situation is shown in Fig. 2.1 as a sudden increase in the HRR. This can also be described as a sudden increase in gas temperature, production of yields of gases such as carbon dioxide (CO_2) or other well defined production terms.

2.3 Fire Development in Tunnel Fires

Tunnel fires are generally fuel-controlled as there are seldom restrictions to air access. Tunnels usually have two or more portals and therefore act as communicating spaces if no mechanical ventilation is installed. The fire is supplied with air due to pressure differences between the fire gases and the atmosphere and possibly the pressure difference between portals. This is represented by the diagrams on the left side in Fig. 2.2 for fuel-controlled compartment fires and tunnel fires. However, in severe fires such as the Mont Blanc, Tauern, and the St. Gotthard fire disasters [5] with multiple large vehicles involved, the supply of air was not enough to sustain complete combustion. This will result in a sudden increase in the production of carbon monoxide (CO) and all the oxygen (O_2) that is transported to the fire source could be consumed. This may not be the case if only one vehicle is burning, but will definitely occur when more vehicles are involved. This situation is represented by the picture on the right side in Fig. 2.2 for ventilation-controlled tunnel and compartment fires.

The way the air is supplied to the fire source is a key issue for these types of large fires. If there is a supply of fresh air between burning vehicles the fire will continue to develop as long as there is enough oxygen available. If the fire is supplied with air from one direction as in longitudinal ventilated tunnels, it is possible to estimate how much air is needed to sustain complete combustion.

Figure 2.3 shows the possible fire development in large tunnel fires such as the Mont Blanc and the Tauern fires where many large vehicles were completely consumed in the fire. In such large fires there are five different zones assumed [4]:

- burnt out cooling zone
- glowing ember zone
- combustion zone

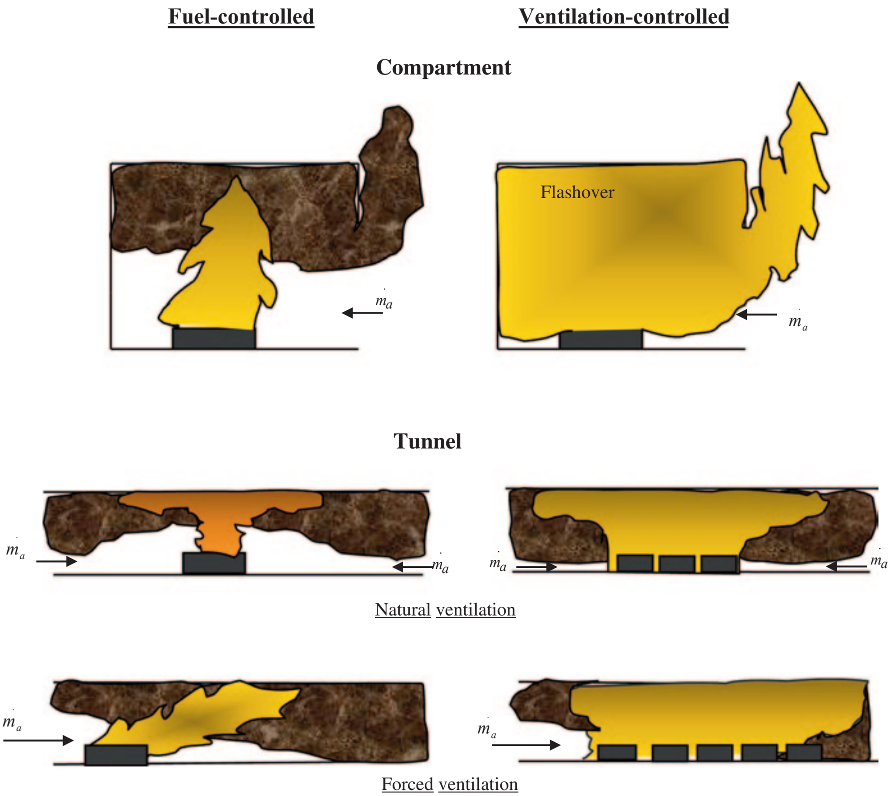

Fig. 2.2 Fuel-controlled (*left-side*) and ventilation-controlled fires in a compartment and a tunnel (*right-side*) with natural draught (*middle*) and forced ventilation (*lower*), respectively [4]. The *arrows* indicate the flow of fresh air

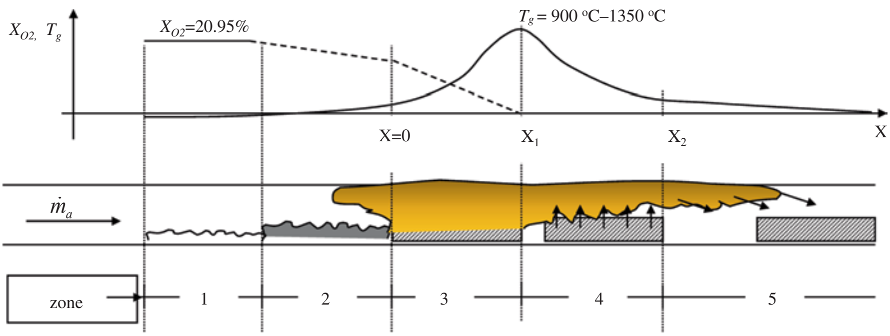

Fig. 2.3 Schematic representation of the burning process of a ventilation-controlled fire in a tunnel [4]

- excess fuel zone
- preheating zone

Figure 2.3 is based on the original work by de Ris [6]. Provided that there are enough large vehicles in the vicinity of the initial fire, these different zones move forwards in a dynamic manner. The most interesting zone is the ‘combustion zone’ involving the burning vehicles. The combustion zone starts at $x=0$ (see Fig. 2.3) and contains fully developed fires in numerous vehicles. Here, we assume that there is enough fuel-vapor and oxygen to support continuous combustion. Flames are observed throughout this zone. The gas temperature beyond $x=0$ increases rapidly until it reaches a peak value at $x=x_1$, that is just behind the combustion zone. At the same time, the oxygen supplied to the combustion zone is rapidly depleted. The explanation given by de Ris [6] on oxygen reduction was originally deduced for duct fires. De Ris’ explanation fits very well to a tunnel situation with numerous large vehicles placed close together, and where the fire can spread easily. The ‘excess fuel zone’, where all oxygen has been consumed in the combustion zone, starts at $x=x_1$. Fuel vaporises from the vehicles throughout this zone, although no combustion takes place here due to lack of oxygen. This will occur up to a point along the tunnel where the gas temperature has decreased to the fuel pyrolysis temperature. This temperature (at the surface of the material) can be assumed to be higher than 300 °C for the majority of solid materials. Beyond this point, that is point $x=x_2$ in Fig. 2.3, no vaporisation of the vehicles occurs. At the same time the hot gas flows into a so-called ‘preheating zone’ and exchanges heat with the tunnel walls and preheats the vehicles that have not yet started to burn within this zone.

Model scale tests carried out by Hansen and Ingason [7] verifies very well this process in longitudinal tunnel flows with multiple objects burning. The oxygen on the downstream side is virtually zero, and the CO production starts to increase significantly. The increase of CO production is the best indicator of a ventilation-controlled situation. This is discussed in more detail in Sect. 2.6.

There is a third mode of combustion conditions related to ventilation in buildings and tunnels. This is a mode of inerting (sometime called vitiation or mixing of vitiated air) of the fire source. This mode may be very important for fires in tunnels with natural ventilation. If the base of the fire source is completely surrounded by air that has high content of inerting gases (vitiated air) such as CO_2 it may self-extinguish. The inerting air, which is a mixture of air and combustion products, has usually about 13 % oxygen when the fire will self-extinguish (That is, flammability limits are exceeded) [8]. This limit is to some extent temperature dependent [9]. Increasing temperature tends to lower the flammability limits and thereby the concentration when the fire self-extinguishes. The temperature dependence is discussed in further detail in Sect. 2.7.

There are mainly two situations where inerting may occur in tunnel fires. The first one is in very long tunnels (tens of kilometres) with natural ventilation and nearly no slope and where one can expect long back-layering distances. The back-flow of mixed air toward the fire may be highly inerted due to mixing of combustion products that are transported backward from the fire with fresh air flowing from the entrance toward the fire, see Fig. 2.4.

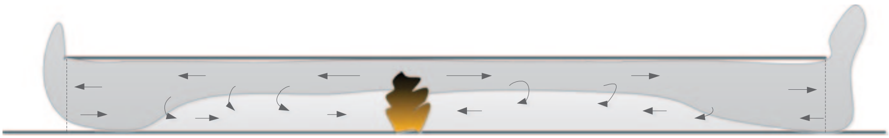

Fig. 2.4 Schematic representation of an inerted fire in a long tunnel. The *arrows* pointing toward the fire indicate inerted (vitiated) air flow

When this inerted air reaches the base of the fire it will affect the combustion efficiency. Depending on the degree of mixing and stratification of the airflow that reaches the fire source, different effects are observed. Currents with pure fresh air along the tunnel floor will usually supply the fire with sufficient oxygen to sustain combustion at the lower levels of the fire. At the upper/higher levels, some influences on the combustion efficiency may occur. Self-extinguishment due to inerted backflow is difficult to obtain in this situation, simply because the mixing of fresh air and combustion products is not efficient enough. The entire base of the fire has to be covered with inerted air of less than 13 % oxygen in order to obtain self-extinguishment.

Self-extinguishment in tunnels due to inerted air has been observed in experiments with a model scale tunnel but the experimental conditions were in these cases quite special [10, 11]. The fresh air was choked upstream of the fire by reducing the inlet area. As the fresh airflow was reduced, the degree of mixing upstream of the fire increased. At a certain critical area the fire self-extinguished due to the inerted air (< 13 % oxygen) created by the mixing of the backflow combustion products and inflowing fresh air.

When inerted air surrounds the fire source, and conditions reach the flammability limits, the fire will not produce much CO or smoke. The radiation levels decrease and some flames lifting from the fire source can be observed [10–12]. This has been observed in many fire tests by the authors. There is nothing which indicates that this would not occur in a similar situation in a tunnel fire, that is when the surrounding inerted air reaches the flammability limits, the flame volume, CO production, and soot production will decrease considerably.

The second condition where vitiation may occur is in a long tunnel with only one opening, such as a tunnel under construction or a mine tunnel. If no mechanical ventilation is present, or the ventilation is shut off after a fire, this could result in smoke and combustion gases redrawn back to the fire from either one or two directions, as it mixes with the fresh air coming in from the portal. This may result in self-extinguishment of the fire. This has not been reported from any real fires, but Lönnermark and Ingason [13], reported about this phenomena in model scale tests carried out using dead end tunnels with only one portal at a higher level than the dead end, where the fire source was located. The fire did not succeed to establish a circulating flow between the fire source and the portal, so the mixing backflow coming toward the fire source had less than 13 % oxygen when the fire self-extinguished. The combustion conditions were influenced prior to reaching the flammability limits and the HRR of the fire was reduced significantly compared to a fully ventilated fire.

2.4 Fuel or Ventilation Control in a Compartment Fire

In this section, the focus is on fully developed fires in a compartment. The parameters that govern whether the fire will go to flashover include the fire load, the dimensions of the compartment and the ventilation openings as well as the thermal properties of the surrounding walls. Flashover in a compartment has been explained as thermal instability caused by the energy generation rate increasing faster with temperature than the rate of aggregated energy losses [14]. Usually, this phenomenon occurs during a short period and results in a rapid increase of HRR, gas temperatures, and production of combustion products. After a flashover has occurred in a compartment, the rate of heat release will develop to produce temperatures of 900–1100 °C. The period after flashover is called the post-flashover stage or the fully-developed fire period, see Fig. 2.1. During this period, the HRR is assumed to be dictated by the oxygen flow through the openings and the fire is therefore defined as 'ventilation-controlled', see Figs. 2.2 and 2.5. The heat released depends upon the amount of air available within the compartment. The air mass flow rate through the opening, $\dot{m}_a$, can be expressed in general terms [15, 16] as:

$$\dot{m}_a = \delta \rho_a \sqrt{g} A_0 \sqrt{h_0} \tag{2.1}$$

where δ is a proportionality constant which is a weak function of temperature, ρ_a is the ambient density (kg/m^3), A_0 is the area of the opening (m^2) and h_0 is the height of the opening (m). The mass flow rate of the fresh air flowing into a compartment could be simply estimated using the classic enclosure fire theory.

If we consider Fig. 2.5, we can integrate the total mass flow rate entering the enclosure by the following equation:

$$\dot{m}_a = \int_0^{h_1} C_d \rho_a w u(z) dz \tag{2.2}$$

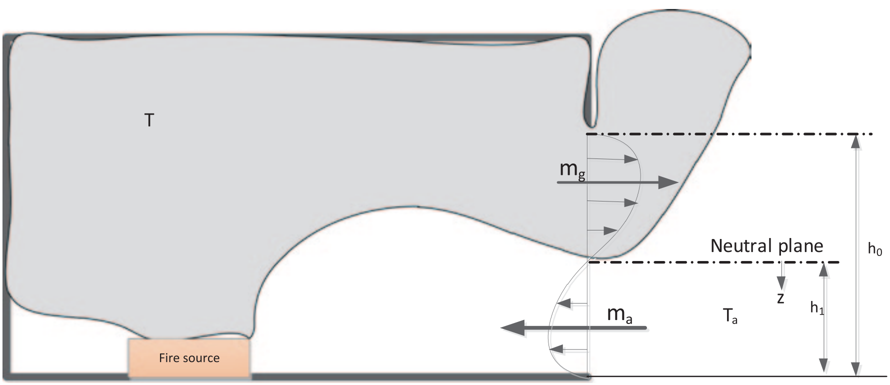

Fig. 2.5 Post-flashover in a compartment fire

where C_d is the flow coefficient, h_1 is the height from the neutral layer to the floor level and u(z) is the velocity as a function of height z, see Fig. 2.5. The *w* is the width of the opening (with the area A_0) which can be the door width. With aid of Bernoulli's equation we can obtain the following relationship for the horizontal velocity entering the enclosure:

$$u(z) = \sqrt{\frac{2g\Delta\rho}{\rho_a}}\sqrt{z} \tag{2.3}$$

where $\Delta\rho = \rho_a - \rho = \rho_a\left(1 - \frac{T_a}{T}\right)$. Introducing Eq. (2.3) into (2.2) yields the following equation:

$$\dot{m}_a = C_d \rho_a w \sqrt{\frac{2g\Delta\rho}{\rho_a}} \int_0^{h_1} \sqrt{z}\,dz \tag{2.4}$$

Integration of Eq. (2.4) yields the following equation:

$$\dot{m}_a = \frac{2}{3} C_d \rho_a w \sqrt{\frac{2g\Delta\rho}{\rho_a}} h_1^{3/2} \tag{2.5}$$

Karlsson and Quintiere [3] gives a correlation between h_1 and h_0:

$$h_1 = \frac{h_0}{1 + (\rho_a / \rho)^{1/3}} \tag{2.6}$$

Introducing Eq. (2.6) into Eq. (2.5) we yield the following relationship:

$$\dot{m}_a = \frac{2}{3} C_d \rho_a w h_0 \sqrt{2}\sqrt{g} \sqrt{\frac{\Delta\rho / \rho_a}{\left[1 + (\rho_a / \rho)^{1/3}\right]^3}} \sqrt{h_0} \tag{2.7}$$

Karlsson and Quintiere [3] have shown that the term $\sqrt{\frac{\Delta\rho / \rho_a}{\left[1 + (\rho_a / \rho)^{1/3}\right]^3}}$, which they define as *density factor*, can be approximated by a value of 0.214 in the case of fully developed fires in an enclosure, see Fig. 2.6.

Thus Eq. (2.7) can be simplified to:

$$\dot{m}_a = \frac{2}{3} 0.214 \sqrt{2} C_d \rho_a \sqrt{g} A_0 \sqrt{h_0} \tag{2.8}$$

where we use $wh_0 = A_0$. Eq. (2.8) can be rewritten and is identical to Eq. (2.1):

$$\dot{m}_a = \delta \rho_a \sqrt{g} A_0 \sqrt{h_0} \tag{2.9}$$

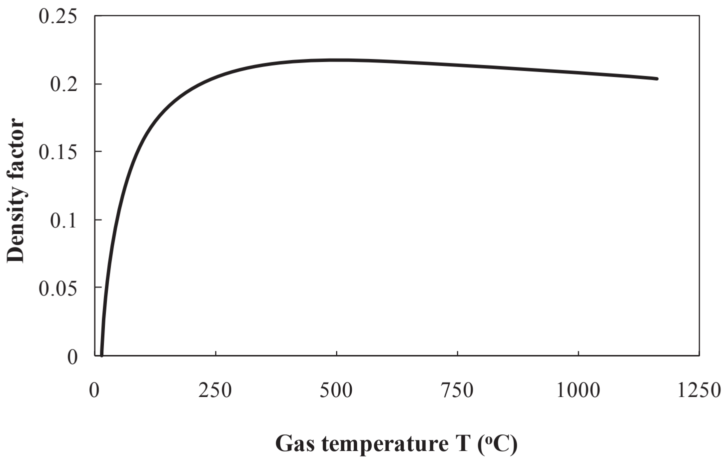

Fig. 2.6 The density factor as a function of the gas temperature inside the compartment

where $\delta = \frac{2}{3} C_d \sqrt{2} \sqrt{\frac{\Delta\rho / \rho_a}{\left[1 + (\rho_a / \rho)^{1/3}\right]^3}}$. This means that for a fully developed fire, δ is a weak function of the gas temperature. The value of δ has been estimated to be either 0.13 [16] or 0.14 [15], respectively, for postflashover fires. Assuming that C_d is equal to 0.7 and the density factor is 0.214, we obtain $\delta = 0.14$ using the equation for δ. The value of $\delta\rho_a\sqrt{g}$ in the preflashover case (fuel-controlled) is 0.3 (kg/s m$^{-5/2}$) and 0.5 (kg/s m$^{-5/2}$) in the postflashover (ventilation-controlled) case assuming the density, ρ_a, is equal to 1.22 kg/m^3 and g equal to 9.81 m/s^2. For the postflashover this can be written as:

$$\dot{m}_a = 0.5 A_0 \sqrt{h_0} \tag{2.10}$$

The term $A_0\sqrt{h_0}$ is better known as the 'ventilation factor' and originates from Bernoulli's equation applied to density flow through a single opening [2].

Assuming that each kg of oxygen used for combustion produces about 13.1×10^3 kJ [17, 18] and that the mass fraction of oxygen (Y_{O_2}) in air is 0.231 we can approximate the maximum HRR that is possible *inside* a compartment during the ventilation-controlled stage. If we use the values given earlier in combination with Eq. (2.1), that is $13.1 \times 10^3 \times 0.231 \times \dot{m}_a$ where $\dot{m}_a = \delta\rho_a\sqrt{g} A_0 \sqrt{h_0}$, we obtain the maximum HRR, $\dot{Q}_{max}$ (kW), within the compartment ($\delta\rho_a\sqrt{g} = 0.5$ kg/s m$^{-5/2}$) as [4]:

$$\dot{Q}_{max} \approx 1500 A_0 \sqrt{h_0} \tag{2.11}$$

According to all text book literature, all the oxygen entering the compartment is assumed to be consumed within the compartment. This assumption has been challenged by Li et al. [19] as they pointed out that it is impossible to consume all

Fig. 2.7 A fully developed fire in a train coach (photo Tomas Karlsson)

the oxygen that enters the compartment inside the compartment itself. It was stated that the maximum HRR can be estimated based on full consumption of the oxygen flowing in through the openings multiplied by a correction factor, which depends on the heat absorbed by the fuel surfaces and the fuels available. The heat absorbed by the surfaces is proportional to the heat of combustion and inversely proportional to the heat of pyrolysis. In summary, Li et al. [19] concluded that although these types of fires are normally called ventilation-controlled fires, they are also closely related to the type and configuration of the fuels inside the compartment, that is they are in some way also fuel controlled because much of the combustion process occurs outside the openings in fully developed fires.

Ingason [20] explains this in a slightly different way, purely based on the earlier view that in a flashover situation all the oxygen is consumed inside the compartment. This includes the assumption that the rate at which air enters the compartment is insufficient to burn all the volatiles vaporising within the compartment and the excess volatiles will be carried through the opening with the outflowing combustion products (That is, all oxygen is consumed and unburned fuel will leave the compartment). This is normally accompanied by external flaming in the vicinity of the opening as shown in Fig. 2.7.

Ingason [20] reported that this phenomenon becomes important when one wishes to estimate the maximum HRR in a 'postflashover' steel body train coach located *inside* a tunnel. Equation (2.10) may underestimate the maximum HRR within the tunnel if excess volatiles are burned outside the train coach. Model scale tests (1:10) of a fully developed fire in a train coach showed that the maximum heat release when all windows were open was on average 72 % higher than the value obtained according to Eq. (2.11) [20]. This means that 42 % of the total fuel vaporised within

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