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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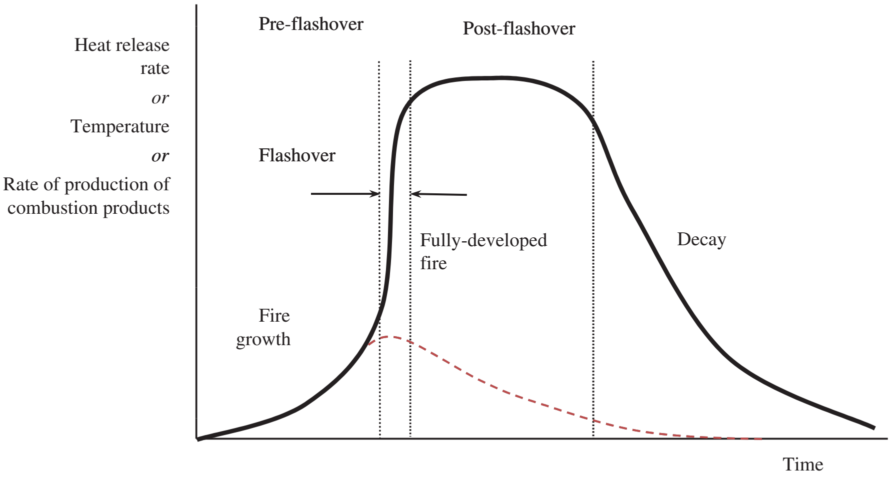

Fig. 2.1 Phases of a typical compartment fire [4]

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

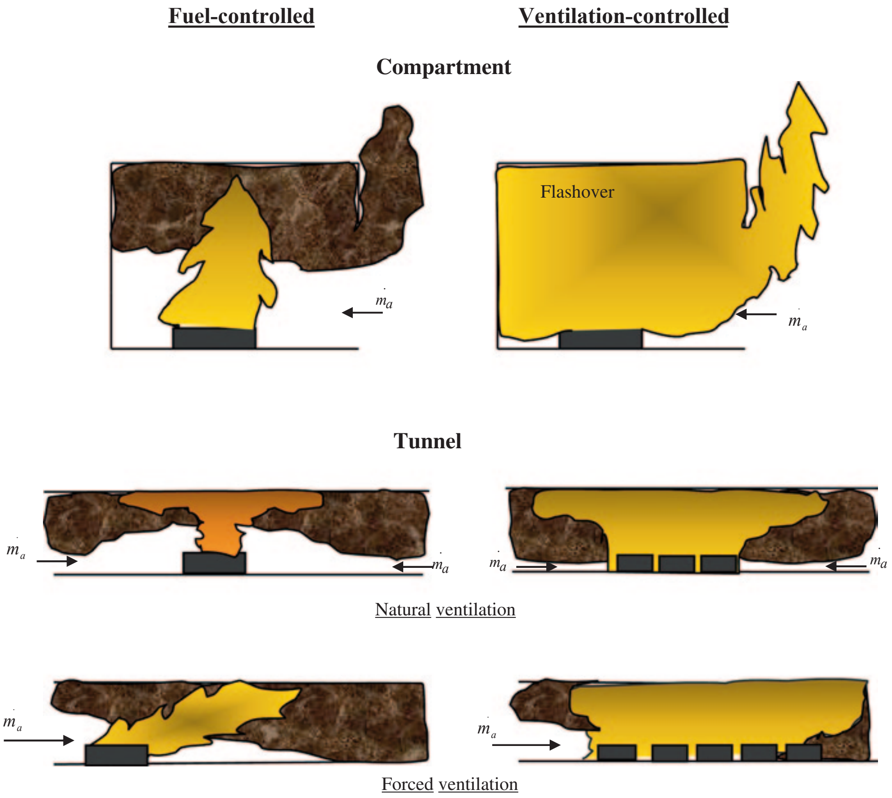

Fig. 2.2 Fuel-controlled (*left-side*) and ventilation-controlled fires in a compartment and a tunnel (*right-side*) with natural draught (*middle*) and forced ventilation (*lower*), respectively [4]. The *arrows* indicate the flow of fresh air

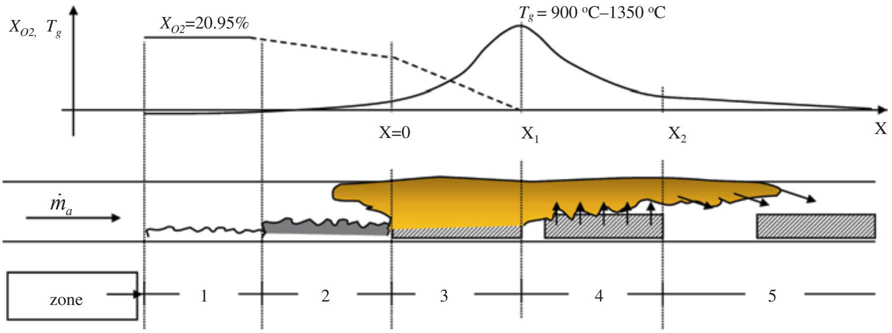

Fig. 2.3 Schematic representation of the burning process of a ventilation-controlled fire in a tunnel [4]

- 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.

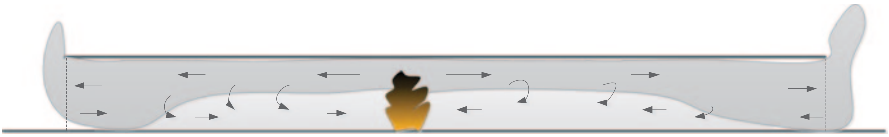

Fig. 2.4 Schematic representation of an inerted fire in a long tunnel. The *arrows* pointing toward the fire indicate inerted (vitiated) air flow

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:

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

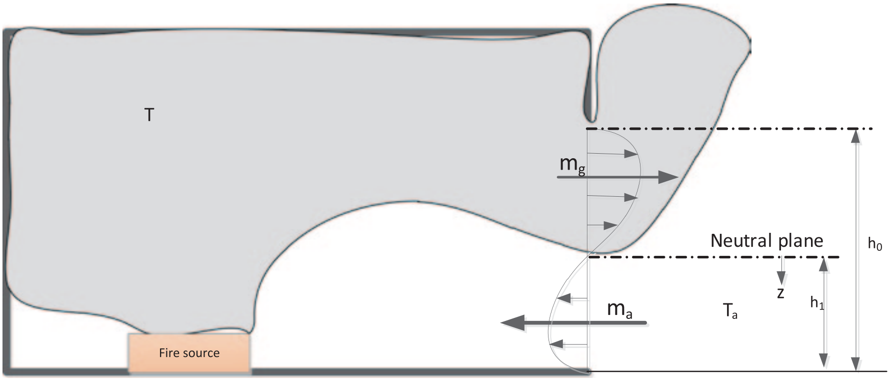

Fig. 2.5 Post-flashover in a compartment fire

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:

$$\dot{m}_a=\frac{2}{3}C_d\rho_a wh_0\sqrt{2}\sqrt{g}\sqrt{\frac{\Delta\rho/\rho_a}{\left[1+(\rho_a/\rho)^{1/3}\right]^3}}\sqrt{h_0} \tag{2.7}$$

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):

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

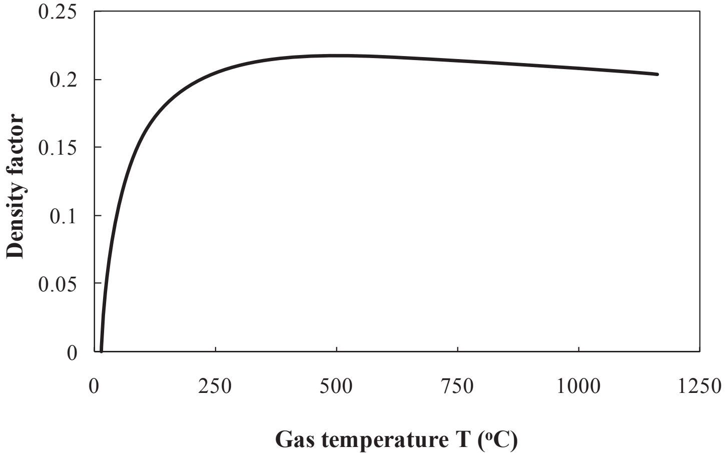

Fig. 2.6 The density factor as a function of the gas temperature inside the compartment

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 $\mathrm{m}^{-5/2}$) and 0.5 (kg/s $\mathrm{m}^{-5/2}$) 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 $(\delta\rho_a\sqrt{g} = 0.5\ \mathrm{kg/s\,m^{-5/2}})$ 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 the coach (assuming that all the oxygen in the entrained air is consumed within the coach) is burned outside the openings.

Bullen and Thomas [21] have showed that the amount of excess fuel burning outside the openings is mainly dependent on the fuel surface area and the ventilation factor $A_0\sqrt{h_0}$. Thus, assuming that this factor is relatively constant for this type of geometry (a train coach) the maximum HRR according to Eq. (2.11) was proposed by Ingason [20] to be multiplied by a factor of 1.72. Ingason [20] proposed a more general expression of Eq. (2.11), where maximum HRR in a train coach after flashover such as the one shown in Fig. 2.7 can then be estimated according to the following equation:

$$Q_{\max} \approx \eta 1500 A_0 \sqrt{h_0} \tag{2.12}$$

where η is a correction factor which may be determined from experiments. Li et al. found that this correction factor can vary considerably. The correction factor ranged from 0.67 to 1.7 and was found to be around 1.27 in full scale tests carried out with a commuter train inside a tunnel [19]. The work of Li et al. [19] will be presented in more detail in Chap. 6.

Example 2.1
What is the HRR of the burning train coach shown in Fig. 2.7? The coach windows are 1.0 m wide and 1.0 m high and there are seven windows on each side. The door opening is 1 m wide and 2 m high. The total opening area times the square root of the opening heights is 15.4 $\mathrm{m}^{5/2}$ $\left(\sum A_{0,window}\sqrt{h_{0,window}} + A_{0,door}\sqrt{h_{0,door}} = 15.4\ \mathrm{m}^{5/2}\right)$.

Solution: According to Eq. (2.11) the maximum HRR is equal to 23 MW. This means that if this coach were burning in a tunnel the total HRR inside the tunnel would be higher than 23 MW since fuel volatiles are burning outside the openings. This can be estimated by multiplying the value obtained using Eq. (2.12) by a constant of 1.7. Thus, the maximum HRR from the burning coach in Fig. 2.7 is estimated to be 40 MW. This estimated value could be conservative since the highest correction factor obtained from tests is used in the calculation.

2.5 Fuel or Ventilation Control in a Tunnel with Longitudinal Flow

Ingason [4] has developed a method to determine whether a tunnel fire is fuel or ventilation-controlled. According to the definition of fuel control (or well-ventilated), the oxygen or the oxidant is in unlimited supply and the rate of combustion is independent of the oxygen supply rate or mass flow rate of air. The HRR is then determined by the fuel supply rate or mass flow rate of the vaporised fuel. The combustion behavior is then similar to that of combustion in the open where access to air is unlimited. The combustion efficiency will be controlled by the local mixing of air and fuel.

A ventilation-controlled fire (or under-ventilated) is, in contrast, controlled by the oxygen supply and the rate of combustion or HRR becomes dependent on both air and fuel supply rates. The efficiency of combustion depends on the fuel supply rate relative to the oxygen supply rate. When precisely the necessary amount of oxygen is available to enable complete combustion one says that the mixture is "stoichiometric". The stoichiometric coefficient, r, which gives the mass ratio of air to fuel required for stoichiometric combustion of fuel to produce CO_2 and H_2O, can be obtained using the following equation by Ingason [4]:

$$r = \frac{137.8\left(a + \frac{b}{4} - \frac{c}{2}\right)}{12a + b + 16c} \tag{2.13}$$

where the letter index comes from a generic fuel ($C_aH_bO_c$). In order to demonstrate the use of Eq. (2.13) let us consider an example.

Example 2.2
How much air is required to completely burn 1 kg of propene, C_3H_6?

Solution: Here $a=3$, $b=6$ and $c=0$. With the aid of Eq. (2.13) we obtain the stoichiometric ratio, $r=14.7$. This means that 14.7 kg of air are required to completely burn 1 kg of propene.

There are many different ways of characterising the relationship between air (oxygen) supply and the fuel supply. Tewarson [22] define the fuel-to-air equivalence ratio, ϕ, as.

$$\phi = \frac{r\dot{m}_f}{\dot{m}_a} \tag{2.14}$$

where $\dot{m}_a$ is the mass flow rate of air (oxygen) supply, $\dot{m}_f$ is the fuel mass loss rate (fuel supply, in kg/s) and r is the stoichiometric coefficient for complete combustion obtained by Eq. (2.13). Beyler [23] defines the equivalence ratio ϕ as the normalized fuel to air ratio, which is the same as given by Tewarson.

The fuel-to-air equivalence ratio, ϕ, can be used to determine whether a fire is fuel-controlled or not. In the case when the fuel-to-air equivalence ratio ϕ is less than one, $\phi < 1$, then the fire is assumed to be fuel controlled (well-ventilated). When the fuel-to-air equivalence ratio, ϕ, is equal to one ($\phi = 1$), the combustion process is stoichiometric (complete combustion). In the case when the fuel-to-air equivalence ratio, ϕ, is larger than one, (That is, $\phi > 1$) then the fire is assumed to be ventilation-controlled (under-ventilated).

2.5.1 Fuel Control

When the fire is fuel-controlled ($\phi < 1$), the HRR is directly proportional to the fuel mass loss rate, $\dot{m}_f$. The chemical HRR, $\dot{Q}$ (kW), which is directly proportional to the fuel mass loss rate, $\dot{m}_f$ (kg/s), can then be calculated using the following equation:

$$\dot{Q} = \dot{m}_f \chi \Delta H_c \tag{2.15}$$

where ΔH_c is the net heat of complete combustion (kJ/kg), that is in which the water produced is in the form of a vapour. In fires the combustion of fuel vapours is never complete, and thus the effective heat of combustion ($\Delta H_{c,eff} = \chi \Delta H_c$) is always less than the net heat of complete combustion (ΔH_c). Further, the combustion efficiency χ is the ratio of the effective heat of combustion to net heat of complete combustion, that is, $\chi = \Delta H_{c,eff} / \Delta H_c$ [24] (Tewarson [24] refers to the 'effective heat of combustion' as the 'chemical heat of combustion'). The fuel mass loss rate is sometimes expressed as the fuel mass loss rate per unit area of fuel (A_f), $\dot{m}_f''$, which means that $\dot{m}_f$ can be replaced by $\dot{m}_f'' A_f$ in Eq. (2.16).

2.5.2 Ventilation Control

If the fuel-to-air mass ratio is larger than the stoichiometric value, $\phi > 1$, then the fire is defined as ventilation-controlled and the HRR, $\dot{Q}$, is directly proportional to the mass flow rate of air, $\dot{m}_a$, (That is, proportional to the oxygen supply) available for combustion. Sometimes, but not always, we can simplify this by saying that the oxygen concentration in the gases flowing out of the compartment or the tunnel portal is essentially zero. One notable exception is ventilation-controlled fires in large compartments with small openings (That is, no flashover). There are different methods to determine the HRR for the ventilation-control conditions. The simplest is the following equation, which assumes complete combustion and that all the supplied air, $\dot{m}_a$, is consumed:

$$\dot{Q} = \dot{m}_a \frac{\Delta H_c}{r} \tag{2.16}$$

where the ratio $\Delta H_c / r$ is nearly constant for most carbon based material [18]. The energy release per kg of air consumed is approximately 3000 kJ/kg. If all the oxygen were consumed, the energy released would correspond to 13×10^3 kJ/kg of oxygen consumed. This can be derived by dividing the ratio $\Delta H_c / r$ with 0.231 which is the mass fraction of oxygen in air. This number is well known from calorimeter measurements in fire laboratories [25] which use the average value of 13.1×10^3 kJ/kg when calculating the HRR based on gas measurement and mass flow rates of combustion gases in a hood system.

2.5.3 Determination of Combustion Mode

The combustion mode is important to know. There are different ways to obtain that. In order to make a simple estimation of the combustion mode, that is determine whether the fire is fuel-controlled, stoichiometric or ventilation-controlled in a tunnel, we can combine Eqs. (2.14) and (2.15), and assume $\chi = 1$, to give:

$$\phi = \frac{\dot{Q}}{3000\dot{m}_a} \tag{2.17}$$

Equation (2.17) assumes that not all the air is necessarily consumed. Depending on the value of ϕ the degree of combustion efficiency is determined. If we assume stoichiometric combustion, that is ϕ becomes equal to 1, then the mass flow rate to obtain a complete combustion is

$$\dot{m}_a = \frac{\dot{Q}}{3000} \tag{2.18}$$

This equation can also be written as:

$$\dot{Q} = 3000\dot{m}_a \tag{2.19}$$

where $\dot{Q}$ is now in kW. This equation is of interest to estimate the fire size in a train coach with airflow $\dot{m}_a$ through windows and door openings. It can also be used to estimate how large a fire can become in a tunnel with a longitudinal flow, assuming good ventilation conditions around the fire source. If we have a tunnel with a cross-sectional area A (m^2) and we have a longitudinal centreline air flow $u\,(m/s)$ at an ambient temperature of 293 K.

$$\dot{Q} = 3130uA \tag{2.20}$$

where $\dot{Q}$ is in kW and a flow coefficient C_d of 0.87 for a longitudinal flow in tunnel is assumed.

In some cases, it is of interest to know how much oxygen is left after the combustion assuming that all the fuels are consumed. The mass fraction of unreacted oxygen or air passing the fire can be estimated using the following equation [4]:

$$\beta = \frac{\dot{m}_a - \dfrac{\dot{Q}}{3000}}{\dot{m}_a} \tag{2.21}$$

Here, it is assumed that not all the air ($\dot{m}_a$) is consumed by the fire. The use of Eqs. (2.17) and (2.21) is illustrated by Example 2.3.

Example 2.3
Assume a fire is burning in a Heavy Goods Vehicle (HGV) in a tunnel which is 6 m high and 10 m wide and having longitudinal ventilation inside the tunnel with a centreline velocity of 2 m/s. The fire is estimated to reach a peak HRR of 150 MW. Is the fire ventilation-controlled or fuel-controlled when the fire becomes 150 MW? The air density within the tunnel is $\rho_a = 1.2$ kg/m^3. What is the largest fire that can exist in the tunnel before it becomes ventilation-controlled?

Solution: First we calculate the mass flow rate of air; $\dot{m}_a = 0.87 \times 1.2 \times 2 \times 6 \times 10 = 125 \text{ kg/s}$*, where 0.87 is the flow contraction coefficient* *for tunnel flow. Equation (2.17) gives* $\phi = 150000/(3000 \times 125) = 0.4$. *This value is less than 1 and therefore the fire is fuel-controlled* ($\phi < 1$). *This also means that unreacted air is passing the combustion zone. The mass fraction of unreacted air can be obtained with Eq. (2.21);* $\beta = (125-(150\,000/(3000)))/125 = 0.6$. *This means that 60% of the available oxygen in the airflow remains unreacted and 40% has been consumed in the fire. Using Eq. (2.20) we find that the fire cannot be larger than* $3130 \times 2 \times 6 \times 10 = 375{,}000$ *kW (375 MW), unless it becomes ventilation-controlled. If we put 375,000 kW into Eq. (2.21) we get* $\beta = 0$ *which implies that all oxygen has been consumed in the fire.*

When the oxygen concentration at a given distance downstream of the fire in a forced ventilation flow is essentially zero, the fire gradually changes from fuel-controlled ($\phi < 1$) to ventilation-controlled fire ($\phi > 1$).

Ingason [4] proposed to use the ratio of mass flow of CO and CO_2 as an indicator of a ventilation-controlled fire. This can be expressed as the ratio $\dot{m}_{CO}/\dot{m}_{CO_2}$. When the values of the ratio begin to increase considerably, $\dot{m}_{CO}$ is the parameter that increases fastest, which indicates that there is not enough oxygen to combust all the available fuel. Tests in nontunnel environments showed that the ratio $\dot{m}_{CO}/\dot{m}_{CO_2}$ increases exponentially as the fire become ventilation-controlled for both diffusion flames of propane and propylene and wood crib fires [24]. Tewarson [26] investigated this thoroughly and presented a correlation between the ratio $\dot{m}_{CO}/\dot{m}_{CO_2}$. Tewarson [26] was able to show that wood crib fires become ventilation-controlled when the ratio $\dot{m}_{CO}/\dot{m}_{CO_2} > 0.036$ and gas diffusion flames become ventilation-controlled when this ratio is greater than 0.1. Ingason [4] proposed the following equation for $\dot{m}_{CO}/\dot{m}_{CO_2}$

$$\frac{\dot{m}_{CO}}{\dot{m}_{CO_2}} = \frac{M_{CO} X_{CO}}{M_{CO_2} X_{CO_2}} = 0.636 \frac{X_{CO}}{X_{CO_2}} \tag{2.22}$$

as an indicator for combustion mode where X is the volume concentration (or mole fraction) and M is the molecular weight (M is 28 g/mol for CO and 44 g/mol for CO_2). Thus, the limits for ventilation control when using this equation are $X_{CO}/X_{CO_2} > 0.057$ for wood cribs and 0.157 for gas diffusion flames.

Hansen and Ingason [7, 27] performed fire tests in a 10 m long model-scale tunnel (1:15) where the longitudinal flow varied as well as the amount of fuel (number of wood pallet piles) used in the tests. The HRRs from the fire when four piles of scaled wood pallets were burned varied from 454 to 504 kW. For a single pile, the HRR was about 150 kW. The velocity in the tunnel was 0.3, 0.6, and 0.9 m/s, respectively and the cross-sectional area was 0.24 m^2. The maximum size of a fire that can exist, as calculated using Eq. (2.20): $3130 \times 0.6 \times 0.24 = 451$ kW before it becomes ventilation-controlled. This is very close to the HRR measured in the tests. This means that the fire, when spreading to all four of the wood pallet piles, should be ventilation-controlled and some increase in the CO production should be expected.

Therefore, analysis of not yet published information on gas concentrations from one test is included and discussed. Test number 11 of the test series in question was selected for the analysis. The peak HRR was measured to be 464 kW. In full scale

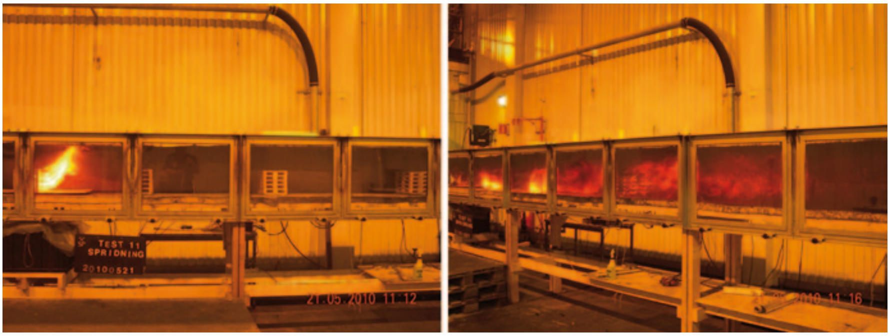

Fig. 2.8 Reduced scale tests using scaled wood pallets. This is test number 11, presented by Hansen and Ingason [7, 27]

this corresponds to HRR of 404 MW, which is a very large tunnel fire. This would correspond to two to four HGV vehicles burning at the same time. In Fig. 2.8 photos of the test setup are shown. The photo to the left shows test number 11 shortly after ignition of the first wood pallet pile. The longitudinal ventilation rate was 0.6 m/s, which corresponds to 2.32 m/s in full scale. The free-space distance between the first pile and the second one was 0.7 m, between the second and the third 0.9 m and between the third and the last one 1.1 m. Multiplying these lengths with the scale factor of 15 gives the full scale free space lengths 10.5, 13.5, and 16.5 m, respectively. In the photo to the right, we see that the fire has spread to all the wood pallet piles used in the test 11. The gas concentrations (O_2, CO_2, and CO) were measured on the downstream side 8.75 m from the entrance of the tunnel and approximately 2 m from the last pile. In Fig. 2.9, results of the gas concentration measurements at the ceiling height (0.9×H) are shown.

It is of interest to investigate the ratio X_{CO}/X_{CO_2} in order to determine if the fire is ventilation-controlled. From the graph in Fig. 2.9 (time equal to 423 s), we obtain a CO concentration of 2.0 %, a CO_2 concentration at the corresponding time of 19 % and the O_2 is only 0.5 % (essentially zero). This means that the ratio X_{CO}/X_{CO_2} is 2/19 = 0.105, which is higher than 0.056 given earlier for wood. In summary, we can say that this exercise with the test data indicates that Eqs. (2.17) to (2.22) are good indicators of the conditions in a tunnel with a longitudinal ventilation flow.

Although one should calculate the average values of O_2, CO_2, and CO based on numerous points over the tunnel cross-section, this was not possible as the only additional measuring point was the CO measuring point at half the tunnel height in the tests. The value of CO at the corresponding time was 2 %. The CO_2 instrument at the same position had only a measurement range from 0–10 %, and there was no O_2 measurement available at this height and length position. However, there was a thermocouple tree at the same position with five measuring points. These measurements show that there was very little variation in the temperature over the cross-section. Thus, one can conclude that the values shown in Fig. 2.9 are quite representative for the entire cross-section. Therefore, the theory that the condition for a ventilation-controlled fire is defined by $X_{CO}/X_{CO_2} > 0.056$ for wood is confirmed.

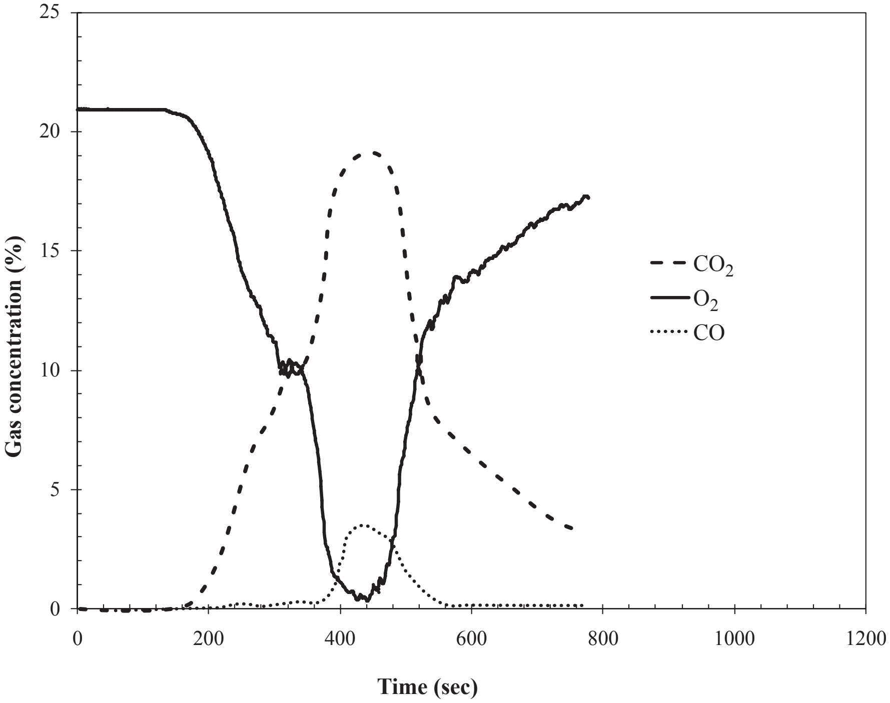

Fig. 2.9 The measured gas concentrations of O_2, CO_2, and CO 8.8 m from the entrance of tunnel for test number 11 in Hansen and Ingason [7, 27]

If there were additional wood pallet piles present in the tests, those piles would simply not ignite, at least not until the first piles have burned out. Due to the extremely high temperatures, these additional piles would continue to generate pyrolysis gases in accordance to the description given in Fig. 2.3.

This test really confirms how tunnel fires with longitudinal flow become ventilation-controlled. This is almost an extreme situation, and in order to obtain it one needs many large vehicles inside the tunnel and the fire must spread between them.

There is a misconception among engineers and scientists that when the oxygen concentration becomes lower than the flammability limits the fire will become ventilation-controlled or under-ventilated. That would mean that when the oxygen concentration is close to 13 %, the fire will not become larger and the size of the fire is governed by the air flow toward the fire. This is simply not true as has been shown earlier, both theoretically and experimentally. One may speculate that, in a case in which the second, third, or the fourth pile, or a vehicle in a real situation, is surrounded by oxygen concentrations lower than 13 %, the fire may self-extinguish or become ventilation-controlled. This explanation would not hold simply because the surrounding gas temperature is also a governing parameter for the combustion process. As in a combustion engine, a tunnel fire can burn until all the oxygen has been consumed as shown by test 11. This requires that the ventilation conditions and the surrounding gas temperature are suitable.

2.6 Effects of Vitiation on the Combustion Process

It is a well-known fact that a diffusion flame in an inerted environment will extinguish before consuming all the available oxygen from the surrounding atmosphere at ambient gas temperature or at least relatively low gas temperatures. It is also well known that if the surrounding gas temperature increases, the amount of oxygen that can be consumed will increase. This would establish a theorem that there is a correlation between the surrounding gas temperature and the level of oxygen at which the fire will self-extinguish. It is also known that as the conditions get closer to these limits, production of soot and CO decreases. This contradicts the idea of ventilation control, as one would expect an increase in the production of these parameters.

Beyler [28] has established a correlation between these critical conditions that depend on the surrounding gas temperature and the oxygen concentration. Beyler simply assumed that the critical adiabatic flame temperature governs the extinction of the fire. During adiabatic conditions, it is known that the energy released by combustion of the available oxygen in the surrounding air will raise the bulk gas temperature of the surrounding air by an amount equal to:

$$\dot{Q} = \dot{m}_a c_p (T_f - T) \tag{2.23}$$

where c_p is the average specific heat of gas over a given temperature range.

We can rearrange Eq. (2.16) as follows:

$$\dot{Q} = \dot{m}_a \frac{\Delta H_c}{r} = \dot{m}_a 3000 = Y_{O_2} \dot{m}_a 13100 \tag{2.24}$$

If we use the relationship $\dot{m}_{O_2} = \mathrm{Y}_{O_2} \dot{m}_a = X_{O_2} \frac{M_{O_2}}{M_a} \dot{m}_a$ where Y is mass fraction and M is mole mass (g/mol), and put it into Eq. (2.24) and combine it with Eq. (2.23) we obtain:

$$X_{O_2} = \frac{M_a}{M_{O_2}} \frac{c_p (T_f - T)}{13100} \tag{2.25}$$

If we assume the average c_p over the temperature range of interest (300–1700 K) is equal to 1.1 kJ/(kg K), and a critical adiabatic flame temperature of 1700 K as proposed by Beyler [28] for most hydrocarbon fuels, and use M_a=28.95 g/mol, M_{O_2}=32 g/mol, we will obtain a correlation using the relationship between the surrounding gas temperature and the oxygen concentration in % that indicates the oxygen level at which the fire would self-extinguish:

$$X_{O_2} = 0.0076(1427 - T) \tag{2.26}$$

Here T is given in °C. In Fig. 2.10, Eq. (2.26) is plotted as function of the temperate in °C.

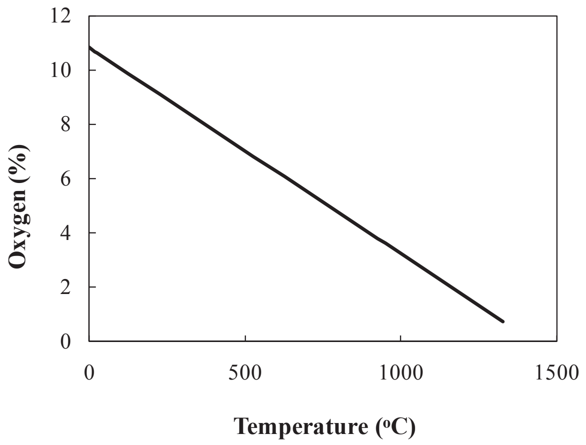

Fig. 2.10 The correlation between the critical oxygen volume concentration and the critical gas temperature according to Eq. (2.26)

This correlation can be used to estimate the effects of inerted air on fires in tunnels with longitudinal or natural ventilation. If we use the temperature measured in Hansen and Ingason [7, 27] on the downstream side of the fire, the highest temperatures measured in Test 11 were about 950 °C. This would mean that the lowest oxygen contents would be about 3.6 %, which is higher than those measured in the fire tests, that is, a value less than 1 %. The use of Eq. (2.26) is very valuable in order to better understand the fire physics in tunnels with longitudinal ventilation. In tunnels with natural ventilation and recirculating mixed or inerted air, the temperatures are lower in the combustion zone, and therefore one should expect higher levels of oxygen before it starts to affect the HRR. Most likely, there are also 3D local effects in this process, which is difficult to estimate and calculate in a one dimension process.

2.7 Summary

The chapter gives an overview of different effects of ventilation on the combustion process. It explains the differences between a fuel-controlled (well-ventilated) fire and a ventilation-controlled (under-ventilated) fire. A comparison between compartment fires and tunnel fires is given in order to explain the physical meaning of the terms fuel and ventilation control. A third condition was also introduced, namely the effects of inerting, which in some aspects can be classified as under-ventilated fire. This appears to be more important than earlier thought, as in naturally ventilated tunnels this may become an important phenomenon. The effects of the surrounding temperature on the vitiation or inerting effect of the mixing air are also shown.

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