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Analysis of Fire Throttling in Longitudinally Ventilated Tunnels With a One-dimensional Model

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Abstract. Fire throttling is the increase in flow resistance due to a large fire in a longitudinally ventilated tunnel. Although the fire throttling effect has been been known and studied for tunnels over the last 40 years, there is not yet a consistent one-dimensional (1D) model that can describe this behaviour or a framework suitable for practical application. We propose a semi-empirical model, based upon pipe flow engineering principles, to describe this effect by separating the resistance to flow, or pressure loses in three parts: upstream of the fire, locally at the fire, and downstream of the fire. The proposed 1D model called TE1D is derived from a simple steady one-dimensional momentum balance in which a semi-empirical mean temperature distribution is assumed across the tunnel. We verify the model by comparing the pressures losses it predicts with those calculated in CFD simulations based on OpenFOAM and Fire Dynamics Simulator. The comparison shows good agreement between the CFD codes for the range of fires sizes considered from 5 to 50 MW and good agreement between TE1D and the CFD results with the proposed 1D model for fire sizes below 30 MW. However, for values above there are large discrepancies between the results obtained by the TE1D and CFD. We posit as a potential explanation that these differences are due to flow and temperature stratification which is not accounted for in the 1D model. The model using pipe flow principles allows engineers to adopt this model for design, together with other pressure losses considered in tunnel ventilation.

Keywords: Tunnel fires, Tunnel ventilation, Fire throttling, Pressure losses, Temperature distribution, CFD, FDS, OpenFOAM

List of Symbols

a	Subindex denoting values in the cold air zone upstream of the fire
f	Subindex denoting values in the flame zone at the fire
s	Subindex denoting values in the hot smoke zone downstream of the fire
Δp	Pressure losses [Pa]
F	Pressure losses due to friction [Pa]
1D	One-dimensional
3D	Three-dimensional

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HRR	Heat release rate [MW]
ρ	Density of air flow [kg/m^3]
u	Longitudinal velocity [m/s]
T	Temperature [K]
p	Pressure [Pa]
$\dot{m}$	Mass flow rate [kg/s]
A_T	Tunnel cross-sectional area [m^2]
c_p	Specific heat capacity at constant pressure [kJ/kg K]
D_h	Hydraulic diameter of tunnel [m]
h_t	Total heat transfer coefficient [kW/m^{2}K]
H	Height of tunnel [m]
L	Length of tunnel [m]
H_{eff}	Effective tunnel ceiling height [m]
$T_{\max}$	Maximum temperature on tunnel ceiling [K]
$\dot{Q}$	Heat release rate [W]
$\dot{Q}_c$	Convective heat release rate [W]
$\dot{Q}^*$	Non-dimensional heat release rate [-]
b_0	Radius of fire source [m]
v'	Non-dimensional ventilation velocity [m/s]
w^*	Characteristic plume velocity [m/s]
g	Gravitational acceleration [m^2/s]
ϵ	Relative surface roughness in the Moody diagram [−]
λ	Friction coefficient [−]
$\mathcal{F}$	Temperature decay function [−]
C_1	Empirical constant in formula for Δp_f [-]
C_2	Empirical constant in formula for Δp_f [s$^{1.9}$kg$^{0.2}$/m$^{2.6}$]

1. Tunnel Ventilation and the Fire Throttling Effect

Globally, tunnel infrastructure is part of a sector with over $ 700 billion dollars of investment in 2017 [1]. For long transport tunnels such as road and rail tunnels, a key component in managing fire safety is the provision of a tunnel ventilation system to manage not only vehicle emissions but also, more importantly, smoke and heat from a fire.

In most tunnels, longitudinal ventilation is preferred to transverse systems due to their comparatively easier design and construction. Longitudinal ventilation can be achieved via jet fans, ventilation shafts or nozzles providing significantly simpler construction compared to extended plenums and smoke ducts for transverse system. The design of a longitudinal ventilation system is a well studied topic including design fires, critical ventilation velocity, tunnel fire ventilation calculations and back-layering [2, 3].

In a longitudinally ventilated tunnel, the ventilation principle in a fire is to push air along the tunnel, usually in the direction of traffic travel so the upstream of the fire is kept free of smoke. See Fig. 1. When designing such systems, the various contributors of pressure losses, such as surface friction, traffic obstructions, tunnel geometry and incline need to be consider. Fire is a key influence in the design of longitudinal ventilation systems.

The size of a fire, and its influence in the airflow velocity required to create a smoke free area upstream of the fire is the well studied topic of critical ventilation velocity. Further, it has been known for over 40 years [4] that a fire in a closed

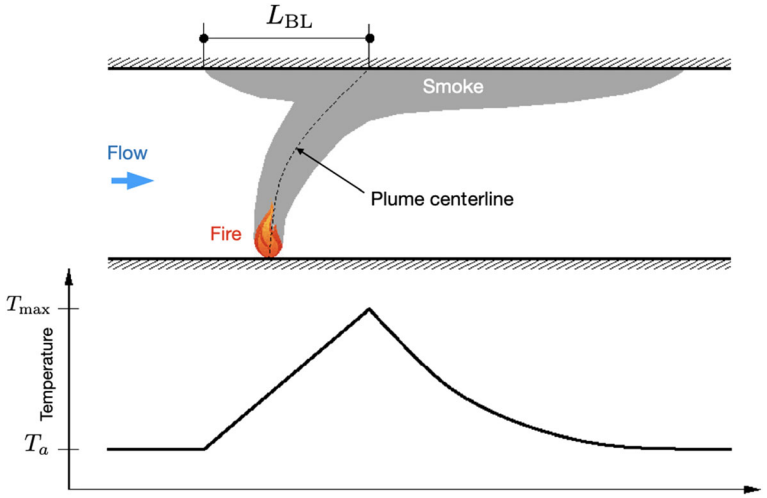


Figure 1. A tunnel fire in a longitudinally ventilated enclosed tunnel: notation (top) and an indicative steady-state temperature distribution (bottom). The distance L_{BL} represents back layering, and the length of the region where the average temperature increases from its ambient value to its maximum value. Note that in the following we will assume the maximum temperature is a point source, with $L_{BL} = 0$.

duct, e.g. a tunnel, results in pressure loss. The studies showed that the presence of a fire has a similar effect to that of a narrowing, or blockage, at the location of the fire. The terms *fire throttling* or *fire choking* used to refer to this effect may originate from the terminology employed to describe similar aerodynamic behaviour observed in internal flows within ducts and nozzles.

One of the earliest discussions of fire throttling by Greuer et al. [4] was published in 1973. The authors discussed their research on mine tunnels and suggested that when a fire is introduced in a tunnel, the presence of a fire results in additional head loss and pressure loss. A second notable publication by Hwang and Chaiken [5] published in 1978 discussed their research on the effect of a duct fire on the velocity of the air ventilation. This was followed by a publication in 1979 by Lee et al. [6] that documented small-scale duct fire experiments carried out to understand the effect of air flow in a duct fire.

The suggestions from these earlier researchers [4–6] indicate that the fire throttling effect is likely made of two main components: a localised flow resistance caused locally at the fire, and an increased resistance downstream of the fire.

Over the last 20 years, this issue has been detailed in various publications [7–10], and despite renewed interests in recent years [11–13], the literature describing this effect, including the understanding remains scattered and inconsistent. There have been several equations proposed to treat the fire throttling effect, and two of such equations are from CETU [7] and Dutrieue and Jacques [9] that consider the

pressure drop directly at the fire, but not downstream of the fire. These two equations are examined in later sections, namely eqs. (28–29).

Despite this, it is acknowledged at a fundamental level in the various publications [7–10], and certainly in design considerations [14], that the occurrence of the fire throttling effect has a material impact in practical applications.

This is because the increase in flow resistance due to the fire requires extra fans to achieve the required critical ventilation velocity [13]. Whilst there is a safety buffer in the sizing of the tunnel ventilation system by oversizing the fan capacity, this is typically in the region of 5% fan capacity. This represents a volumetric increase of 3 m^3 to 8 m^3/s in volume flow rate for a typical tunnel, and is inadequate to deal with any major losses that are not already accounted for in the design. Practitioners and tunnel designers will know it is impractical to simply increase the fan capacity by a larger margin because this would impact the sizing of the ventilation shaft in tunnel, and therefore the tunnel diameter, i.e. tunnelling cost. In a project, the sizing of the tunnel's diameter can make or break the capital expenditure of a project.

In this research, we aim to amalgamate the conjectures published to date, and distill the fire throttling effect into a concise description. This description is presented in a one-dimensional model based on pipe flow principles that aims to incorporate the effects of a fire. We achieve this in our one-dimensional model by identifying the zones in the tunnel impacted by the fire, and proposing a specific model for each of these zones.

Using this description, we then evaluate their contribution to the fire throttling effect, and this is achieved by comparing the pressure losses calculated by the one-dimensional model to those obtained via CFD simulations. CFD simulations are chosen to verify the one-dimensional model due to the lack of experimental data obtained from simultaneous measurements of pressure and temperature that would be required to validate it.

Our secondary objective is to provide a description of the fire throttling effect that forms the foundation for practical application, or for further research. This is one reason why the one-dimensional model is based on pipe flow principles, i.e. the same principles routinely used in the analysis and design of longitudinally ventilated tunnels.

2. 1D Modelling of Fire Throttling

Since the fire throttling effect is characterised by pressure losses, we will describe in this section a 1D model, based on the standard assumptions of pipe flow engineering theory [15], to calculate the pressure losses due to the fire in terms of the temperature distribution it generates along the tunnel.

For the sake of simplicity and ease of analysis, our modelling scenario is that of a single fire in a straight enclosed tunnel of constant section with only two openings: the entrance and exit portals. Flow quantities in the 1D model, such as flow velocity and pressure, are based on area-averaged values. As it is customary in

these 1D models [3], we assume the momentum balance of the flow in the tunnel to be the sum of independent contributions of the form

$$\sum_k \Delta p_k = 0 \tag{1}$$

where Δp_k represent pressure changes due to the various effects considered in the model. Terms of this form have been proposed to model the effect of wind, obstacles, wall friction, buoyancy, fans, inflow and outflow portals, and tunnel inclination amongst others.

This paper will focus on the terms that are the main contributors to pressure losses in a longitudinally ventilated tunnel in the presence of a fire. We will present and discuss formulations for those terms leading to the throttling effect, and assess their suitability by comparison with CFD results. In what follows we will consider only three independent contributions to the total pressure losses, Δp, namely

$$\Delta p = \Delta p_a + \Delta p_f + \Delta p_s \tag{2}$$

where the terms in the right-hand side denote the pressure losses in the cold air zone of the tunnel, Δp_a, the local pressure losses at the fire site, Δp_f, and the pressure losses in the zone filled with hot smoke downstream of the fire, Δp_s. The subindices a, f and s are shorthand for air, flame, and smoke, respectively. Δp_a and Δp_s are pressure losses distributed along the length of the tunnel whereas Δp_f is a localised pressure loss at the site of the fire.

3. Calculation of Pressure Losses

The calculation of the pressure losses in eq. (2) will utilize the notation of Fig. 2 in the following sections. This figure shows the domain split into three zones: a zone of cold air at the entrance of the tunnel upstream of the fire where we will assume the values of the flow variables are constant, a zone in the vicinity of the flame that will be assumed to be of negligible length compared to the length of the tunnel, and a zone of hot smoke downstream of the fire where its influence will be felt.

As stated in the previous section, our aim is to calculate the pressure losses corresponding to these three zones, i.e. Δp_a, Δp_f, and Δp_s, respectively.

The distributed pressure losses in the tunnel contributing to the throttling effect are calculated through the pressure gradient calculated via the Darcy-Weisbach friction coefficient, λ, using the formula

$$\frac{dp}{dx} = \frac{1}{2}\frac{\lambda}{D_h}\rho u^2 \tag{3}$$

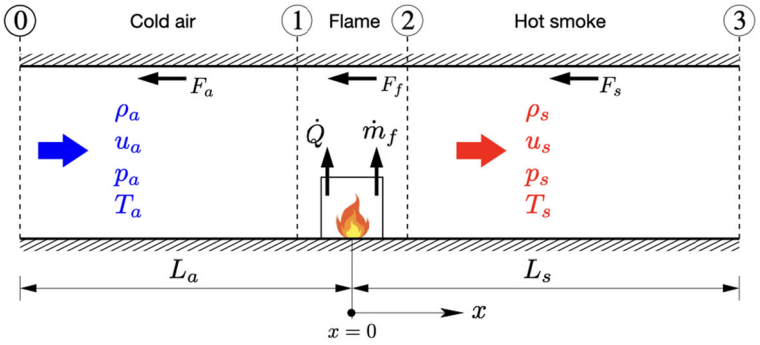


Figure 2. Notation for the calculation of the pressure losses.

where D_h is the hydraulic diameter of the tunnel cross section, and the friction coefficient $\lambda(\mathrm{Re})$ is given a function of the Reynolds number, Re, via the commonly used pipe flow engineering formulas [15]. Here we have adopted the explicit approximation to Colebrook's formula for the friction coefficient [16], namely

$$\lambda = \left\{ 2\log\left(\frac{\varepsilon}{3.715} + \frac{5.72}{\mathrm{Re}^{0.9}} \right) \right\}^{-2}; \quad 65 < \varepsilon\,\mathrm{Re} < 1300 \tag{4}$$

where ε is the relative surface roughness in the Moody diagram.

The additional distributed friction generated in the hot smoke zone is accounted for through changes in velocity due to temperature as proposed in references [17, 18]. For an enclosed tunnel of constant cross-sectional area, temperature corrections are obtained by a combination of the continuity and the perfect gas equations leading to

$$\rho u A = \text{cons.} \quad \& \quad \rho \mathrm{T} = \text{cons.} \quad \Longrightarrow \quad \frac{\mathrm{u}}{\mathrm{T}} = \text{cons.} \tag{5}$$

Therefore, if the distribution of temperature, $T(x)$, along the tunnel is known, equation (5) will be used to update densities and velocities according to

$$u(x) = u_a \frac{T(x)}{T_a}; \qquad \rho(x) = \rho_a \frac{T_a}{T(x)} \tag{6}$$

where the subindex a indicates again the (constant) values in the cold air zone in the tunnel. The form of the temperature distribution adopted in this work is described in the following section.

3.1. Temperature Distribution Along the Tunnel

As noted earlier, this calculation method for evaluating the pressure losses due to a fire relies upon specifying a temperature distribution. This section describes the temperature distribution adopted here.

Let x denote the coordinate along the length of the tunnel, in the direction of the incoming flow of air, with the fire source located at $x = 0$. We assume the minimum flow velocity is equivalent or greater than the critical ventilation velocity which allows us to neglect back-layering and plume deflection effects so that we can assume a temperature distribution of the form

$$T(x) = \begin{cases} T_a & x < 0 \\ T_s(x) & x \geq 0 \end{cases} \tag{7}$$

where T_a represents the (constant) temperature in the cold air zone upstream of the fire, and $T_s(x)$ represents the variation of temperature in the hot smoke zone downstream of the fire. The adopted form of $T_s(x)$ will be discussed in Sect. 3.4. Here we are assuming that the presence of the fire leads to a jump in temperature at $x = 0$ with $\Delta T = T_s(0) - T_a > 0$. The value of ΔT is a function of the fire heat release rate (HRR).

Note that, if required, the effects of back-layering and plume deflection could be incorporated in the temperature distribution through empirical formulas such as those proposed in references [19] and [20], respectively. For now, we will proceed on the basis there is negligible back-layering.

We will now proceed to describe how to calculate the three contributions to the pressure losses given such a temperature distribution.

3.2. Pressure Losses in the Cold Air Zone

Following the notation of Fig. 2 and using the assumed temperature distribution, the pressure losses, Δp_a, in the cold air zone ($0 \rightarrow 1$) are obtained by integrating the pressure gradient given by eq. (3) with constant temperature, T_a, and therefore constant velocity. The pressure losses Δp_a are given by

$$\Delta p_a = \frac{\lambda_a L_a}{2D_h} \rho_a u_a^2 \tag{8}$$

where λ_a denotes the constant friction coefficient in the cold air zone. In the comparison with CFD results that will follow in the verification of the method to be presented in Sect. 5, the value of the surface roughness ε in eq. (4) is selected to match the (constant) pressure gradient of the computed solution in the cold air zone. This calibration ensures the friction due to cold air flow is the same in the 1D model and the CFD simulation. We recognise there may be uncertainties in the CFD models, and this calibration mitigates this because by matching the friction in the cold region between the 1D model and the CFD simulation, we have certainty any discrepancy is due to the temperature only.

3.3. Pressure Losses Across the Fire

We obtain two alternative expressions of the localised pressure losses caused by the fire, Δp_f, through a conservation analysis using the control volume in the flame zone ($1 \rightarrow 2$) shown in Fig. 2. The first one relates Δp_f to the HRR of the fire, $\dot{Q}$, and the second one to the temperature jump across the fire. This temperature jump can be obtained from semi-empirical formulas such as the plume theory which will be described in detail later in this section. The subindex 2 in the following derivations will denote the values immediately upstream of the flame zone which we recall it is assumed to be of zero length. For instance, $\rho_2 = \rho_s(0)$ where $\rho_s(x)$ is the density in the hot smoke zone as illustrated in Fig. 2.

Denoting by $\dot{m}_f$ the mass flow produced by the fire, conservation of mass, or continuity, states that

$$A_T(\rho_a u_a - \rho_2 u_2) + \dot{m}_f = 0 \tag{9}$$

where A_T is the (constant) cross-sectional area of the tunnel. Balance of momentum can be expressed as

$$A_T(p_2 - p_a) + F_f = A_T(\rho_a u_2^2 - \rho_2 u_a^2) \tag{10}$$

where F_f is the pressure loss due to friction at the fire site. Finally the conservation of energy reads

$$\dot{Q} + \dot{m}_f c_p T_a = A_T c_p(\rho_2 u_2 T_2 - \rho_a u_a T_a) \tag{11}$$

where c_p is the specific heat capacity at constant pressure. Note in later sections we will only consider the contribution of the convective energy to the HRR $\dot{Q}$ following reference [3]. We neglect fire mass flow, i.e. $\dot{m}_f \approx 0$, with the assumption that fire size and the temperature are the main contributors to the fire throttling effect. The kinetic energy in the conservation of energy has been neglected on the basis that it is orders of magnitude smaller than the thermal energy [12]. The momentum source term due to buoyancy for the fire is neglected on the basis it is small compared to the momentum in the overall tunnel.

Separately, we are assuming that the friction losses at the location of the fire are negligible since the length of the fire location is small compared to the length of the tunnel, namely $F_f \approx 0$ These three assumptions simplify the calculation methods. We can obtain the pressure losses due to changes in temperature caused by the presence of the fire in two alternative ways.

First, combining eqs. (9) and (10), the pressure losses can be written as

$$\Delta p_f = p_2 - p_a = \rho_a u_a^2 \left(1 - \frac{u_2}{u_a}\right) \tag{12}$$

and substituting the ratio of velocities by the ratio of temperatures via eq. (5), noting that $T_2 = T_s(0)$, we obtain the pressure losses as

$$\Delta p_f = \rho_a u_a^2 \left(1 - \frac{T_s(0)}{T_a}\right) \tag{13}$$

The temperature $T_s(0)$ can be calculated using the plume theory method as described in the later part of this same section. This version of the equation and calculation method is referred to as the *plume theory method*.

An alternative calculation of the pressure losses incorporates eqs. (9) and (10) into the energy eq. (11), together with eq. (5), to get

$$\frac{\dot{Q}}{A_T c_p} = \rho_a u_a^2 \frac{T_a}{u_a} - \rho_2 u_2^2 \frac{T_s(0)}{u_2} = \frac{T_a}{u_a}\left(\rho_a u_a^2 - \rho_2 u_2^2\right) = \frac{T_a}{u_a}\Delta p_f \tag{14}$$

The final expression of the pressure losses as a function of the HRR, $\dot{Q}$, is

$$\Delta p_f = -\frac{\dot{Q} u_a}{c_p A_T T_a} \tag{15}$$

This equation will be referred to as the *energy equation method*.

For the plume theory method in eq. (13), the value of the temperature jump due to the fire, $\Delta T = T_s(0) - T_a$, can be calculated in two alternative ways.

The first one follows the suggestion by Ingasson [3] to estimate the *average* temperature at the fire source as originating from the convective part of the HRR. From the control volume analysis carried out earlier, and replacing $\dot{Q}$ by its convective contribution $\dot{Q}_c$, namely

$$\Delta T = -\frac{\dot{Q}_c}{\dot{m}\, c_p} \tag{16}$$

where $\dot{m} = \rho_a u_a A_T$ is the mass flow of air in the tunnel. The convective HHR, $\dot{Q}_c$, is often assumed to be $\dot{Q}_c = 2/3\,\dot{Q}$ [3] which is the value that we will adopt here[1].

The second one is obtained from a semi-empirical formula for the *maximum* temperature at the fire, T_{max}, derived via the axisymmetric fire plume theory proposed by Li [19] as follows.

According to McCaffrey's fire plume theory [22], the maximum ceiling temperature can be assumed to be flame temperature when the fire is sufficiently large and impinges on the tunnel ceiling. In other words, maximum ceiling temperature should be a constant. This constant value was found to be approximately 1350°C based on several tunnel fire experiments [3].[2]

[1] The HRR ratio, $\dot{Q}_c/\dot{Q}$, is not constant in general. For instance, the Austrian code RVS 09.02.31 [21] recommends a value of the HRR ratio of 0.85 for 5 MW fires and of 0.75 for 30 MW to 50 MW fires, suggesting that the ratio should be, at least, a function of $\dot{Q}$ since as a larger fire causes higher temperature and more radiation.

[2] We recognise the value of 1350°C is high, given it is the maximum temperature and that a lower representative value of 900°C has been reported in other fire plume and flames studies. We proceeded with 1350°C [23] as we will show later on this provides an upper bound value when compared to CFD models.

Relating interaction of fire plume and ventilation flow is a crucial consideration in application of fire plume theory. Therefore, a dimensionless ventilation velocity, v', was defined [3] where both ventilation velocity, u_a, and characteristic plume velocity, w^*, can be correlated according to

$$v' = \frac{u_a}{w^*} \quad w^* = \left(\frac{g\,\dot{Q}}{b_0\,\rho_a\,c_p\,T_a} \right)^{1/3} \tag{17}$$

where b_0 is the equivalent radius of the fire source, and g is the gravitational acceleration.

In this model, the maximum *ceiling* temperature increment, $\Delta T = T_{\max} - T_a$, is given in $^\circ C$, by two separate formulas depending on the value of the non-dimensional ventilation velocity, v', namely

$$v' \leq 0.19 \quad \Delta T = 17.5 \frac{\dot{Q}^{2/3}}{H_{\text{eff}}^{5/3}} \tag{18}$$

$$v' > 0.19 \quad \Delta T = \begin{cases} \dfrac{\dot{Q}}{u_a\, {b_0}^{1/3}\, {H_{\text{eff}}}^{5/3}} & T_{\max} < 1350 \\ 1350 - T_a & T_{\max} > 1350 \end{cases} \tag{19}$$

Finally we will obtain $T_s(0)$ using the convective part contribution of the HRR, i.e. substituting $\dot{Q}$ by $\dot{Q}_c$, in the calculation the value of $T_{\max}$ in the formulas above. Note that $T_{\max}$ is the value of the temperature at the ceiling, given that we use it here as a proxy for the smoke temperature in all the perimeter of the tunnel section, we could expect pressure losses obtained with this parameter to be an upper bound.

3.4. Pressure Losses in the Hot Smoke Zone

The pressure losses, Δp_s, in the hot smoke zone ($2 \rightarrow 3$) are calculated by integrating the pressure gradient once the velocity is written in terms of the temperature, according to eq. (6), as

$$\Delta p_s = \frac{1}{2} \frac{\rho_a u_a^2}{T_a D_h} \int_0^{L_s} \lambda_s T_s(x)\, dx \tag{20}$$

Here we will consider the friction coefficient in the hot smoke zone, λ_s, to be dependent on the velocity and thus on the temperature, therefore we will have $\lambda_s(x)$. This means that the pressure gradient in the hot smoke zone, $\frac{dp_s}{dx}$, will not be constant but a function of x of the form

$$\frac{dp_s}{dx} = \frac{dp_a}{dx}\frac{\lambda_s T_s}{\lambda_a T_a} = C_a \lambda_s T_s \tag{21}$$

where C_a is a constant. This expression, that relates the slopes of the pressure losses in the cold air and hot smoke zones of the tunnel, will be useful in analysing the results to be presented and discussed in Sect. 5. Note we have simplified this description by considering the deceleration of the flow and hence the recovery of static pressure to be negligible. For a longitudinally ventilated tunnel designed to minimise smoke back-layering, smoke is expected to be diluted (cooled) over a short distance from the fire, and therefore the temperature distance (cooling to the tunnel wall) over the remaining distance of the tunnel is not expected to be significant.

The temperature distribution in the hot smoke zone ($x \geq 0$) is considered as below. The adopted form of the temperature distribution, $T_s(x)$, in the hot smoke zone ($x \geq 0$) is defined as

$$T_s(x) = T_a + (T_s(0) - T_a)\,\mathcal{F}(x) \tag{22}$$

where the effect of the fire is assumed to be localised and represented as a sudden jump of temperature $\Delta T = T_s(0) - T_a$, and the decay of the temperature upstream of the fire is represented by the function $\mathcal{F}(x)$.

The temperature decay function $\mathcal{F}(x)$ could be modelled using heat transfer assumptions as suggested by Ingason [3] and calculated as the solution of the heat equation, i.e.

$$\mathcal{F}(x) = \exp\left(-\frac{h_t \pi D_h}{\dot{m} c_p} x\right) \tag{23}$$

which illustrates how the temperature decays as we move away from the fire in the direction of the flow. Note that h_t is the heat transfer coefficient (kW/m^{2}K), πD_h represents the wetted perimeter of the whole tunnel cross-section (m) and x is the distance from the fire along the tunnel (m).

Alternatively, one could adopt an empirical exponential form to fit an expression to experimental or field tunnel temperature data such as

$$\mathcal{F}(x) = 0.57\,\exp\left(-0.13\frac{x}{H}\right) + 0.43\,\exp\left(-0.021\frac{x}{H}\right) \tag{24}$$

where H is the height of the tunnel. This decay function has been generated from large-scale fire experiments [24] in tunnels, and the equation is documented in reference [3]. Equation 24 is used as a representative temperature profile that can be adopted in 1D calculations. This equation was chosen as it was derived from both the Runehamar and Memorial Tunnel fire tests and is found [3] to fit well to the experimental data. We acknowledge there may be more realistic or suitable temperature profiles that could be used. An investigation of the effect of different tem-

perature profiles is outside the scope of this paper, but incorporating them in future analyses should be straightforward.

4. Summary of the Pressure Losses Calculations in the TE1D Framework

This section collects the formulas, presented in the previous sections, for the calculation of the pressure losses along the tunnel due to the throttling effect. These calculations, which will be employed in the 1D code TE1D[3] framework, proceed as follows.

In the cold air zone of the tunnel upstream of the fire ($x < 0$) the pressure losses are given by

$$\Delta p_a = \frac{\lambda_a}{2D_h}\rho_a u_a^2 (L_a - x) \tag{25}$$

At the location of the fire $x = 0$, the localised pressure loss is calculated in two alternative forms. The approach based on the energy equation writes the pressure losses across the fire in terms of the HRR, $\dot{Q}$, as

$$\Delta p_{f,e} = -\frac{\dot{Q} u_a}{A_T T_a c_p}, \tag{26}$$

Alternatively, we could use eq. (13) with $T_s(0) = T_{\max}$ as per eq. (22), leading to

$$\Delta p_{f,p} = \rho_a u_a^2 \left(1 - \frac{T_s(0)}{T_a}\right) \tag{13}$$

This formula refers to ceiling temperatures and this is somewhat inconsistent with the use of area-averaged quantities in the one-dimensional theory in which this framework is based. We will see however in Sect. 5 that the values obtained this way provide an upper limit boundary of Δp_f. In the following, we will refer to eq. (13) as the plume theory method and to eq. (26) as the energy equation method.

In the hot smoke zone, the pressure losses are calculated as

$$\Delta p_s = \frac{1}{2}\frac{\rho_a u_a^2}{T_a D_h}\int_0^x \lambda_s(t) T_s(t)\, dt \tag{27}$$

Given that the friction coefficient λ_s in the hot smoke zone will be in general a function of the location t through the velocity, that varies along the tunnel due to

[3] The TE1D (pronounced as TED) framework is available as a MATLAB code and can be obtained from the Zenodo repository [25].

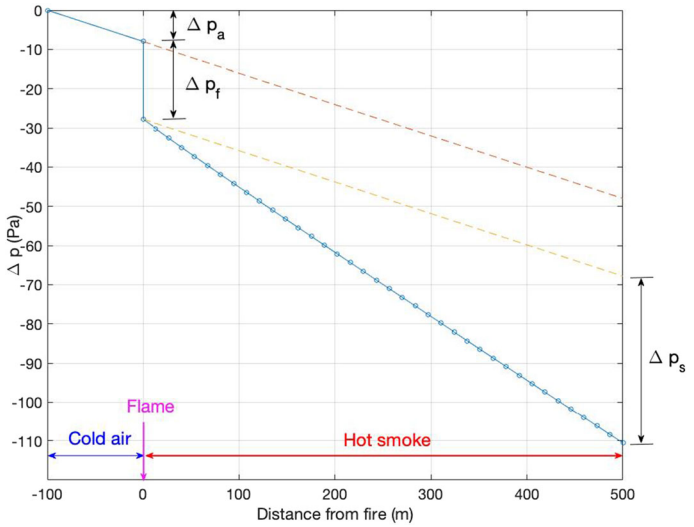


Figure 3. Schematic of the three contributions to the pressure losses along the tunnel: Δp_a (cold air), Δp_f (flame), and Δp_s (hot smoke). The pressure losses due to the fire throttling eect are $\Delta p_f + \Delta p_s$.

temperature changes as stated in eq. (6), numerical integration will be required to evaluate the integral in eq. (27).

An indicative sketch of the three contributions to the total pressure losses in the tunnel is depicted in Fig. 3.

5. Verification of the TE1D Framework Via Comparison to CFD Simulations

This section verifies the results from the 1D theory by comparison with CFD simulations obtained with OpenFOAM [12] and FDS 6.7.6 [26]. The objective of this comparison is to verify the consistency of CFD, and its suitability as a reference for the verification of the one-dimensional model, by considering two independently carried out simulations.

Briefly, FDS, or Fire Dynamics Simulator [26] is an open source CFD package based on incompressible LES, or large-eddy simulation, modelling and that is widely used by the tunnel ventilation community for fire and smoke modelling in research and practical applications. FDS is the primary simulation tool used in this paper. The OpenFOAM simulations have been carried out with FireFOAM, which is an application specifically designed for fire modelling, using a compressible LES model. More details on the FireFOAM simulations cited in this paper can be found in the work by Riess [12].

We have used CFD simulations because there is a lack of suitable experimental or field data from real fires with measurements of both pressure loss and tempera-

ture distribution along the tunnel which would be required for validating the simulation and analysis of the throttling effect.

Although some experimental and field data exist separately for either pressure or temperature[4], to the best of our knowledge, there is no data available for both in the same configuration. Tunnel fire experiments remain limited, and we take this opportunity to encourage development of more tunnel fire experiments especially considering the large number of new tunnel infrastructure to be built in the future [32].

5.1. FDS vs OpenFOAM Comparison

We have compared the FDS 6.7.6 results to those modelled independently by Riess [12] using OpenFOAM. The FDS simulations model a 34 MW fire in a 600 m long rectangular tunnel at 10 m (w) $\times$ 5.2 m (h) with a surface roughness of 2.5 mm. A methane fire is located at 100 m from the inflow portal, and the tunnel is longitudinally ventilated with an air velocity of 4 m/s. A uniform grid of 0.2 m is used noting the large fire sizes being modelled and therefore the grid is considered to be adequate. Adiabatic surface is used and is considered reasonable noting the simulations are run to reach steady state. The pressure profile in the FDS models are measured at fixed intervals as mean values across the cross section area of the tunnel.

The results in Fig. 4 show a reasonable agreement between the pressure losses calculated by OpenFOAM and FDS. The small discrepancies observed can be attributed to the difference in the method employed to measure the pressure drop. We have specifically chosen FDS 6.7.6 because its pressure solver has been modified to prevent the appearance of unphysical oscillations in the modelling of fires in long tunnels reported in previous versions [33, 34].

The subsequent three sections describe the evaluation of the terms Δp_a, Δp_f and Δp_s in the TE1D framework and verify them by comparing their values against those obtained in CFD simulations.

5.2. Calibration of the Term Δp_a

The value of the pressure losses, Δp_a, in the cold air zone upstream of the fire, depends on the surface roughness coefficient, ε, in the friction factor given by eq. (4). Here we choose the value of ε that matches the pressure gradient in the cold air zone calculated by the TE1D model to the pressure gradient in both CFD simulations. Figure 4 shows that both CFD models produce the same pressure gradient in the cold air zone.

5.3. Verification of the Term Δp_f

This section compares the CFD results with those obtained using the energy and plume equations in the TE1D framework, i.e. eqs. (13) and (26) respectively, and with the semi-empirical formulas:

[4] See for instance references [24, 27– 31] to name but a few.

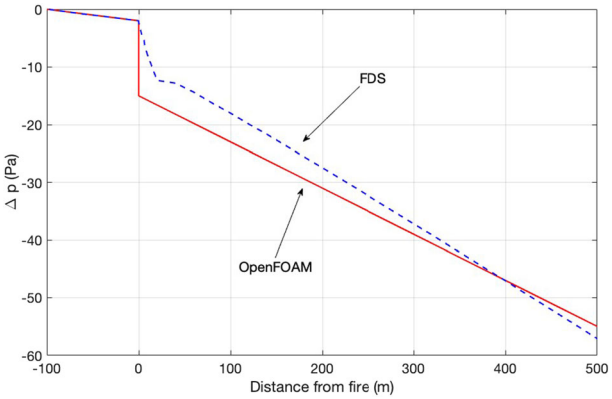


Figure 4. Comparison between the pressure losses calculated with FDS and OpenFOAM for a 34 MW fire.

$$\Delta p_f = C_1 \frac{\dot{Q}_c}{u \cdot D_h^2} \tag{28}$$

$$\Delta p_f = C_2 \frac{\dot{Q}_c^{0.8} \cdot u^{1.5}}{D_h^{1.5}} \tag{29}$$

where C_1 and C_2 are empirical constants, $\dot{Q}_c$ is the convective component of the fire HRR, u is the airflow velocity, and D_h is the hydraulic diameter of the tunnel cross section.

Formulas (28–29) have been proposed by CETU [7] and Dutrieue and Jacques [9] respectively, and their empirical constants C_1 and C_2 have values $C_1 = 9 \times 10^{-5}$ and $C_2 = 41.5 \times 10^{-5}$ $s^{1.9}kg^{0.2}/m^{2.6}$.

Figure 5 shows a comparison of the values of Δp_f for different fire sizes calculated by TE1D, the semi-empirical formulas (28–29), FDS and OpenFOAM [12]. The main differences are the fire size and the ventilation velocities of the rectangular and arched tunnel profiles.

By considering the plume method and the energy method as an upper and lower bound, the comparison shows the TE1D prediction is within this boundary compared to CFD models. In practical applications where there can be uncertainties, in particular early on the project where 1D method is most likely used, we recommend if TE1D is used to predict Δp_f, that TE1D plume theory is used. This is because the over prediction of the pressure drop will provide a level of safety buffer, and as per Fig. 5, TE1D energy equation under predicted the pressure drop when compared to the OpenFOAM values [12].

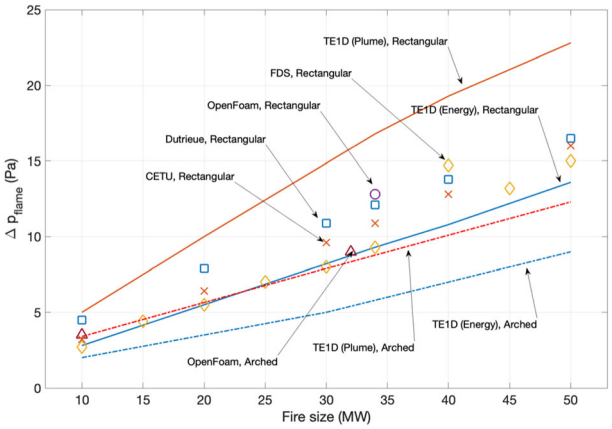


Figure 5. Comparison of the pressure drop Δp_f calculated using the TE1D energy and plume theory methods with values calculated by FDS and OpenFOAM and by using two semi-empirical formulas proposed in the literature [7, 9]. Arched tunnel sections included to provide additional comparison.

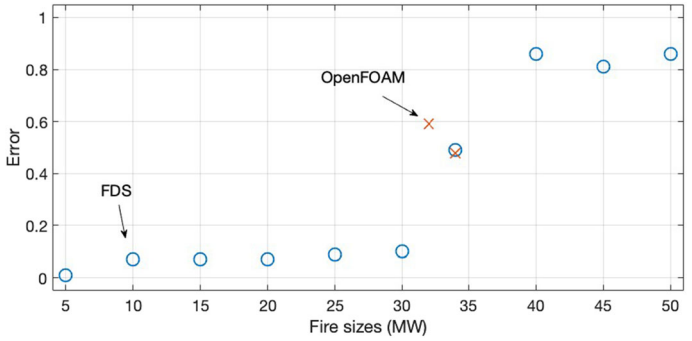


Figure 6. Comparison of error of TE1D to FDS and OpenFOAM [12]. The error is calculated as $|1-\epsilon|$ where ϵ is the ratio of the slopes calculated using TE1D and CFD.

5.4. Verification of the Term Δp_s

The simulations of the pressure losses in the hot smoke zone show that the pressure gradient is approximately constant for all the fire sizes considered. Therefore, to verify the 1D model we have compared the values of the pressure gradient obtained by TE1D with those evaluated using FDS and OpenFOAM [12] for different fire sizes. Figure 6 shows the relative error of the value of the pressure gradient in TE1D with respect to the CFD value, which is used as reference, for a range HRR. Note that the eqs. (28–29) proposed by CETU [7] and Dutrieue and Jacques [9] respectively only account for localised pressure losses at the fire and therefore have not been used for comparison here.

The comparison in Fig. 6 shows for a fire size under 30 MW, the error is tolerable when viewed from a preliminary design for practical application perspective. The results show beyond 30 MW, the error increases significantly. Keeping in mind the only variable here is the fire size with the velocity and tunnel geometry remain consistent, we postulate temperature alone, when it comes to a larger fire size, is not the critical contributor to pressure loss in the hot smoke zone.

To confirm this, using the FDS model we obtained the average of the temperature distribution in the hot smoke zone downstream of a 34 MW fire, and derived a fitted temperature curve given by $T_s(x) = T_a + 107\, e^{(-0.019x)}$. The corresponding pressure drop Δp_s is calculated using this fitted temperature distribution and it is shown in Fig. 7.

The results in Fig. 7 show with the fitted temperature curve, the slope is marginally steeper, i.e. closer to the steeper FDS slope, but the difference is negligible. This supports our suggestion for a larger fire the temperature is not the main contributor to the pressure loss in the Δp_s region.

Recall eq. 21 that relates to the slopes of the pressure losses in the cold air and hot smoke zones of the tunnel. Figure 8 shows the slopes for different fire sizes. The results show the effect of the additional pressure losses due to the increased temperature reduces materially at about 150 m away from the fire, which does not explain the significant difference in the slope shown in Figs. 6 and 7 for the bigger fires.

This is further reinforced by the plot in Fig. 9. This figure that shows that if temperature were the main contributor, we would expect the λT curve to show a much larger difference between the TE1D temperature and the FDS fitted temperature curve, as opposed to a negligible difference in the region of 5 to 6 observed here.

The analysis so far shows with TE1D, the increased friction due to changes in velocity (increased in temperature) is sufficient to capture the effect of the fire for smaller fire sizes. However for larger fire sizes beyond 30 MW, the increase in temperature alone does not fully account for the pressure loss due to the fire throttling effect in the hot smoke region, Δp_s.

As suggested by Riess [12], temperature stratification and the resultant shear stress to the tunnel walls appears to play a significant contribution to pressure loss in the Δp_s region. Figure 10 shows a comparison of the 2D velocity profile and smoke stratification for a small and a large fire, where the large fire can be seen to have much greater temperature stratification at the ceiling level.

Based on the above, this means for a 1D model and a large fire, e.g. beyond 30 MW, the increased temperature alone downstream of the fire is not the main contributor to the pressure loss. We surmise that a 1D model, when there is a sufficiently large fire where significant stratification is expected to occur, cannot capture the 3D effect of a fire, which is the bigger contributor to the pressure loss. This means when dealing with scenarios where large fires or where significant stratification are expected, additional corrections are required for a 1D model to correct for the prediction of pressure loss downstream of the fire, or Δp_s. One

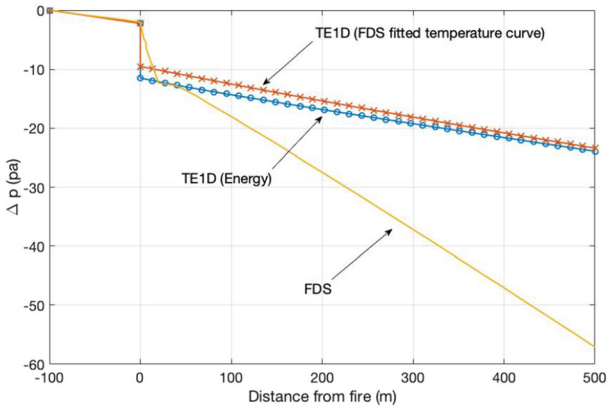


Figure 7. Comparison of the slope between TE1D derived temperature curve, and FDS fitted temperature curve to FDS model result for a 34 MW fire.

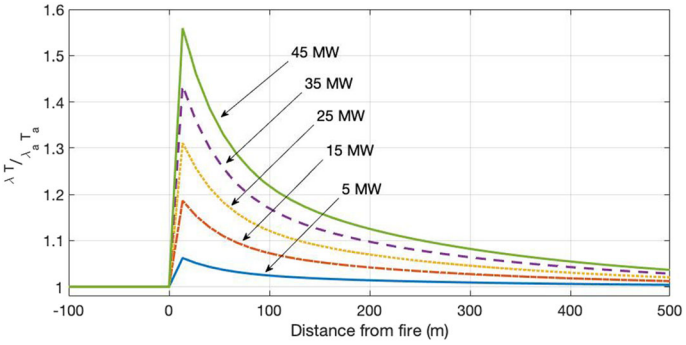


Figure 8. Comparison of $\frac{\lambda T}{\lambda_a T_a}$ for 5, 15, 25, 35 and 45 MW fires.

example of a correction is proposed by Riess [12]. Alternatively, CFD models should be used in these scenarios.

Conversely, we have now identified a threshold value where 1D model, e.g. TE1D, holds up reasonably well for fire sizes up to 30 MW. We acknowledge the cases tested in this research may not be universal, and that a parametric study considering the tunnel geometry and other variables that impact the stratification beyond fire sizes should be considered.

That said, from a practical application perspective, especially for the early stages of a project where speed of computation matters more and that designers are only interested in an approximate tunnel ventilation requirement, 1D models such as TE1D can be considered to estimate the impact of fire throttling effect, in particular for smaller fire sizes, e.g. 5 MW to 15 MW that reflects a typical passenger car or metro train design fire sizes.

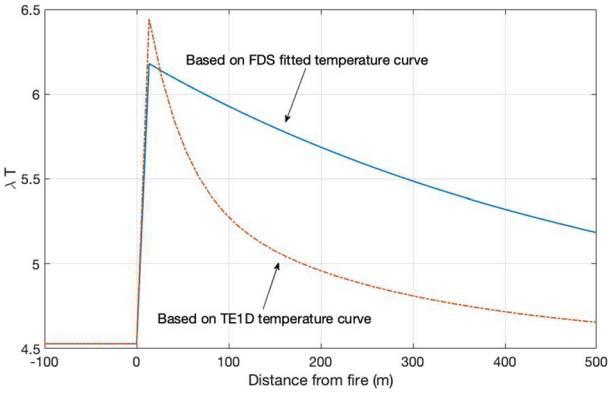


Figure 9. Comparison of λT using TE1D temperature curve and FDS fitted temperature curve for a 34 MW fire.

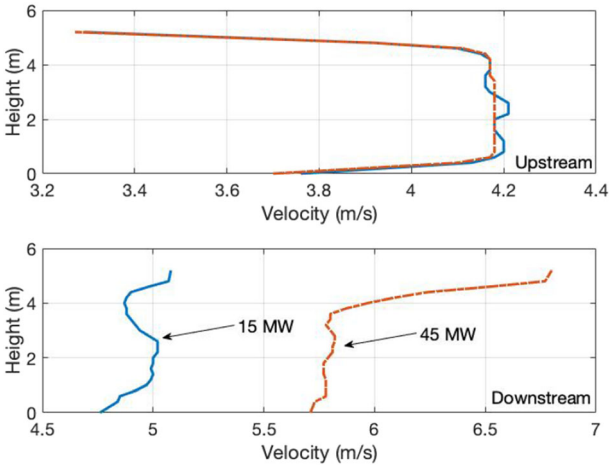


Figure 10. Comparison of the stratification downstream of the fire for a small and a large fire. Minor fluctuations in the upstream velocity profile for 15 MW fire are due to the data collection.

6. Conclusions

In this research, we have firstly amalgamated the previously fragmented understanding of fire throttling. We do this by using a one dimensional model. The model, implemented in the code TE1D, analyses the contributions to the pressure losses caused by the fire by splitting the tunnel length downstream from the fire into flame and hot smoke zones, and using the temperature distribution along the tunnel to account for the effect of the fire on pressure losses. The 1D model used here is based on a longitudinally ventilated tunnel, with adequate velocity such that back-layering can be minimised.

With the 1D model established, we then compared the prediction using this model to CFD models for varying fire sizes from 5 to 50 MW. The comparison shows the 1D model holds up well (within the predictions between TE1D Plume and Energy methods) in predicting the localised pressure drop at the fire location across the varying fire sizes. For the region downstream of the fire, the comparison shows 1D model predicts reasonably (approximately 10% error) for fire sizes up to 30 MW, and subsequently under predicts the pressure losses for large fire sizes beyond 30 MW.

By using a temperature curve derived from the CFD model, we have shown for larger fire sizes, the increase in temperature alone is not the main contributor for the pressure losses downstream of the fire. We believe the 3D effect of temperature stratification and the resultant stratification of shear stress effect on the tunnel wall could be a main contributor to the pressure loss. Additional corrections are needed to the 1D model to account for the full impact of the fire throttling effect for a larger fire beyond 30 MW where significant stratification is expected to occur.

For smaller fire sizes, we believe 1D model can be used in particular for earlier stages of design where engineers needed to prioritise approximating the fan thrust needed to overcome the losses expected in a tunnel.

We acknowledge the calculation methods presented here rely heavily on CFD models. It is well-known that the availability of only a small number of experiments and fire tests to validate CFD models is a challenge that the tunnel fire safety community has faced for a long time [33]. Unlike a safety critical but simple problem, the calculation of pressure losses is safety critical in the design of a tunnel ventilation system, and the presence of the fire throttling effect complicates the calculations.

With a safety critical and complex problem, this issue requires significantly more investment including tunnel fire tests to better understand the fire throttling effect, and to provide better validation benchmark. We strongly believe the tunnel fire safety community needs to continue promoting the importance of fire experiments to support better model validation, in particular as these computational methods are now the primary tools for tunnel fire safety design.

This article has gathered and analysed some of the ideas and methods proposed in the available literature to model the throttling effect with a view to gain a better understanding of the phenomenon and the limitations of these methods, and to develop a one-dimensional framework (our TE1D code) as a starting point for practitioners and researchers to build upon when considering the fire throttling effect.

We conclude with a quote from George Box: *All models are wrong, but some are useful*. This is a reminder on the importance to understand the limitations of models, including 1D models prior to using them. Furthermore, it is our belief that improved, more accurate, models would be developed and validated if full scale tunnel fire tests relevant to the fire throttling effect were to be performed and the acquired data made available to researchers and practitioners in the fire ventilation community.

Acknowledgements

Preliminary explorations of the ideas presented in the paper were carried out by Kuan Lin as part of his final year project [35]. His valuable contribution to the work described in this paper is gratefully acknowledged.

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