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Pressure drop caused by a fire in a tunnel

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ABSTRACT

For many applications, one dimensional models of smoke motion are very useful. In spite of the limitation inherent to such models, they provide the ability to model a full tunnel system, even with ramifications, in a fully unsteady mode, with a very short computing time. However, these models need to have realistic evaluations of the various pressure drops which occur.

One of these pressure drops is due to the three dimensional effects of the fire source itself, with the bending and distortion of streamlines. In practical applications, there are mainly two methods which are used to model this pressure drop: either only the obstruction of the tunnel by the burning vehicle is taken into account, or an empirical formula is used. This formula may come from field measurements (see for example CETU (2003)) or CFD data (see for example Dutrieue & Jacques (2006)).

In the present paper, we recast results of obstruction models and empirical formulae in terms of dimensional analysis. We compare these estimations with data from a small scale experimental facility.

Keywords: Tunnel ventilation; Pressure drop; Fire; Throttling effect.

NOMENCLATURE

$B = \frac{g\mathcal{P}_c}{\rho_0 C_P T_0}$	Buoyancy created by the fire
b_s	radius of the plume at the source
$Cb = \frac{B}{gD_H^2 V}$	Non dimensional number associated with buoyancy
C_P	Specific heat of air
$c_1, c_2, \text{etc.}$	Numerical constants (see text)
D_H	Hydraulic diameter of the tunnel
$Fr = \frac{V}{\sqrt{g \frac{\Delta\rho}{\rho_0} D_H}}$	reduced Froude number
g	Acceleration of gravity
L	Length of the tunnel
\mathcal{P}_c	Convective heat release rate of the fire
$Re = \frac{D_H V}{\nu}$	Reynolds number

S	Cross section of the tunnel
T_0	Ambient temperature
V	Longitudinal velocity in the tunnel
W_s	Vertical velocity of the plume at the source
ΔH_{chimn}	Pressure drops or gains due to chimney effect
ΔH_{fans}	Pressure gain due to the fans
ΔH_{lin}	Linear pressure drops
ΔH_{sing}	Singular pressure drops
ΔH_{veh}	Pressure drops or gains due to vehicles
ΔP_a	Pressure difference at the portals
ΔP_f	Pressure drop due to the fire
λ_c	linear pressure drop coefficient in a rough duct
ν	Kinetic viscosity of air
ρ_0	Density of air at ambient temperature
$\Delta\rho$	Difference of ambient density with source density
Σ	Cross section of the vehicle in fire
$\xi_f = \frac{\Delta P_f}{\frac{1}{2}\rho_0 V^2}$	Pressure drop coefficient due to the fire
ξ_{ob}	Pressure drop coefficient due to obstruction

1 INTRODUCTION

In a tunnel with longitudinal ventilation, the motion of air may be understood in terms of pressures losses and gains:

$$\Delta H_{fans} = \Delta P_a + \Delta H_{lin} + \Delta H_{sing} + \Delta H_{veh} + \Delta H_{chimn}, \quad (1)$$

where ΔP_a is the pressure difference at the portal, ΔH_{lin} are the losses due to friction along the walls, ΔH_{sing} are the singular losses, i.e. due to local effects in the flow such as entry, outflow, section changes, etc., ΔH_{veh} are the gains or losses associated with the traffic, ΔH_{chimn} are the gains or losses associated with chimney effect and ΔH_{fans} are the gains due to the fans. One very specific singular pressure loss, denoted here ΔP_f , is due to the three dimensional effects of the fire source itself, which causes the bending and distortion of streamlines. The aim of the present paper is to discuss the computation of this term.

This effect was identified by engineers in charge of tunnel design long ago, and since then has been included in technical guidelines through empirical relationships (see for example [2] and previous editions of same document, e.g. the 1976 edition). However, before the update of tunnel ventilation regulations in the early 2000s following the Mont-Blanc fire, this term was often neglected compared with other terms such as the physical obstruction by the burning vehicle itself. This explains why this effect has been rarely studied in the literature.

An expression for this term is proposed in the aforementioned Dossier pilote des tunnels [2],

$$\Delta P_f = c_1 \frac{\mathcal{P}_c}{V D_H^2} \quad (2)$$

with \mathcal{P}_c the convective heat release rate of the fire, V the longitudinal velocity, D_H the hydraulic diameter of the tunnel, and $c_1 = 9 \cdot 10^{-5}$ a dimensionless constant. Eq. 2 is valid only if V is larger than the critical velocity and in particular this expression leads to absurd values for $V \rightarrow 0$.

A more detailed analysis was performed by Dutrieue & Jacques [3], where they used data from CFD simulation to propose the following expression:

$$\Delta P_f = c_2 \frac{\mathcal{P}_c^{0.8} V^{1.5}}{D_H^{1.5}} \quad (3)$$

with $c_2 = 41.5 \cdot 10^{-6} \text{ s}^{1.9} \text{ kg}^{0.2} / \text{m}^{2.6}$.

More recently, another group of workers from academia “rediscovered” the pressure drop caused by a fire under the name of “throttling effect” (see [6] and references therein). Note however that this last paper is somehow distorted by a lack of knowledge of the techniques used in the engineering community, and makes a slight confusion between the critical velocity and the means to achieve it through the sizing of the fans, by stating *in fine* that the critical velocity is modified by this throttling effect while they simply mean that the throttling effect leads to the need of more jet fan power to achieve the critical velocity.

The aim of the present paper is to propose a unified approach to estimate ΔP_f through a simple dimensional analysis, and to test this approach against the scarce available numerical and experimental data. Section 2 presents the dimensional analysis, section 3 presents the data used, including the small scale experiment. Section 4 discusses the results and section 5 is the conclusion.

2 DIMENSIONAL ANALYSIS

The expressions proposed above suffer both from being purely empirical. Here, as a starting point, we decided to proceed through dimensional analysis in order to have a better chance of getting close to physical understanding. Obviously, ΔP_f , by hypothesis, should depend on the heat release rate of the fire. However, since it is a purely fluid mechanics phenomenon, we decided to express the heat release rate in buoyancy units:

$$B = \frac{g \mathcal{P}_c}{\rho_0 C_P T_0}. \quad (4)$$

We now assume that we should have:

$$\Delta P_f = f(\rho_0, D_H, B, \nu, V, g \frac{\Delta \rho}{\rho_0}). \quad (5)$$

Note that g does not act directly as in a free surface flow, but through density differences, hence the use of $g \Delta \rho / \rho_0$ with ρ_0 the ambient density and $\Delta \rho$ the difference between the ambient density and the source density. This is 7 quantities for 3 units. We are left with 4 non-dimensional quantities. We take the reduced Froude number Fr , the Reynolds number Re and two specific numbers ξ_f and Cb :

$$Fr = \frac{V}{\sqrt{g \frac{\Delta \rho}{\rho_0} D_H}}, \quad Re = \frac{D_H V}{\nu}, \quad \xi_f = \frac{\Delta P_f}{\frac{1}{2} \rho_0 V^2}, \quad Cb = \frac{B}{g D_H^2 V}. \quad (6)$$

Note that ξ_f may be interpreted as a singular pressure drop coefficient associated with the fire source, and Cb is a non dimensional number scaling the heat release

rate of the fire with the aeraulic conditions in the tunnel. We now have the expression:

$$\xi_f = f(Cb, Fr, Re).$$

In real cases, Reynolds number is always large, and we assume that as soon the flow is turbulent, the dependence on Reynolds number is weak. We are then left with

$$\xi_f = f(Cb, Fr) \quad (7)$$

3 DATASETS

In order to go further than dimensional analysis, we decided to use two datasets, one from [3] based on CFD at real scale, and the other one from small scale experiment.

3.1 Data by Dutrieue & Jacques (2006)

The study by Dutrieue & Jacques (2006) [3] is based on 3D CFD simulations with a specific static pressure analysis to compute separately pressure drop of the fire. We used the figures in the paper to extract the results. Results of this extraction is given on figure 1 as a plot of ξ_f as a function of Cb . Error bars represents the uncertainties created by our data extraction process. Note that since calculating ξ_f is not a linear process, error bars are not symmetrical. From the data in the paper, it is hard to estimate the Froude number. With V of order 3 m/s, $D_H = 5.5$ m, $\frac{\Delta\rho}{\rho_0}$ of order 0.75, and assuming a flame temperature of 900°C, we get $Fr \sim 0.5$. From these data, we have

$$\xi_f \approx 5.7 \cdot Cb \quad (8)$$

or, with a slightly better approximation

$$\xi_f \approx 5.6 \cdot Cb^{0.9} \quad (9)$$

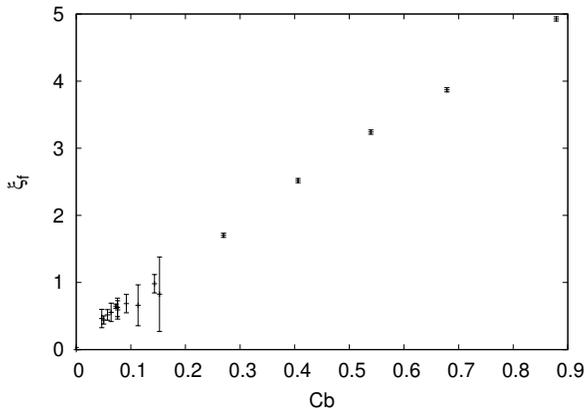


Figure 1: Data extracted from [3] and plotted with non dimensional numbers used in the present paper.

3.2 Data from small scale experiment

Experiments were performed in a reduced-scale model (figure 2) of length $L = 8.9\text{ m}$, width $W = 0.36\text{ m}$ and height $H = 0.185\text{ m}$. The side walls are made of toughened glass which permit visualisation of the flow. The releases of buoyant fluid are mixtures of air and helium, whose flow rates were controlled independently and measured by two flowmeters. To visualise the flow, the buoyant mixture is seeded with nebulised oil and lit with a laser sheet emitted by a lens installed at the inlet of the tunnel. Note that the mass of oil added to seed the buoyant release is a tiny fraction of the total mass injected at the source and thus does not affect the density of the mixture. The longitudinal ventilation is imposed by a fan at the end of the tunnel. The flow rate within the tunnel is measured by means of a hot-wire anemometer placed within a Venturi tube at the inlet, providing a spatially averaged velocity over the tunnel section in the range $0.11 \leq V_c \leq 1.15\text{ m s}^{-1}$. Pressure upwind and downwind the buoyant source were measured by means of two pressure taps connected to a micromanometer.

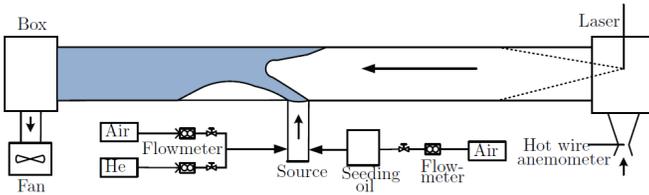


Figure 2: Schematic of the experimental set-up.

The fire is modelled through a plume, which is characterised by its modified source Richardson number Γ_s (we use here a modified notation compared with [1]),

$$\Gamma_s = \frac{5}{8\alpha} \frac{\Delta\rho}{\sqrt{\rho_0\rho_s}} \frac{gb_s}{W_s^2}. \quad (10)$$

The experimental apparatus allows a large range of plume Richardson numbers, representative of typical values for fire plumes. For the present work, we retained only cases when it takes values from 0.1 to 6.

Assuming a form

$$\xi_f = c_4 \cdot \frac{Cb}{Fr^\mu}, \quad (11)$$

data from the small scale model experiment suggest $c_4 = 1.43$ and $\mu = 0.74$ (see figure 3).

Note that, in the experiment, the reduced Froude number Fr varies on a relatively short range (from about 1 to about 2). The effect of this variation is therefore weak. Consequently, the simpler approximation

$$\xi_f \approx 1.84Cb \quad (12)$$

is nearly as good in terms of experimental results as eq. 11, as can be seen in figure 4.

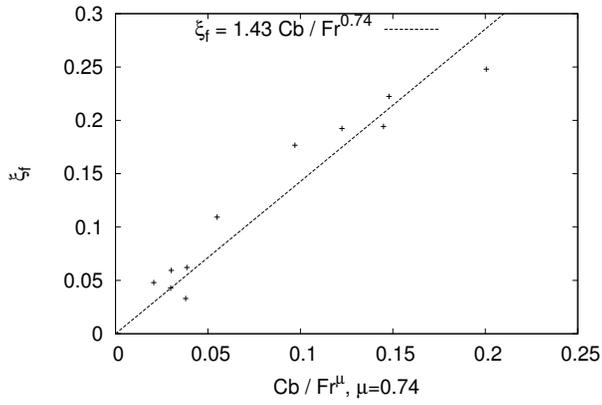


Figure 3: Data form the small scale model experiment assuming $\xi_f = c_4 \cdot \frac{Cb}{Fr^\mu}$.

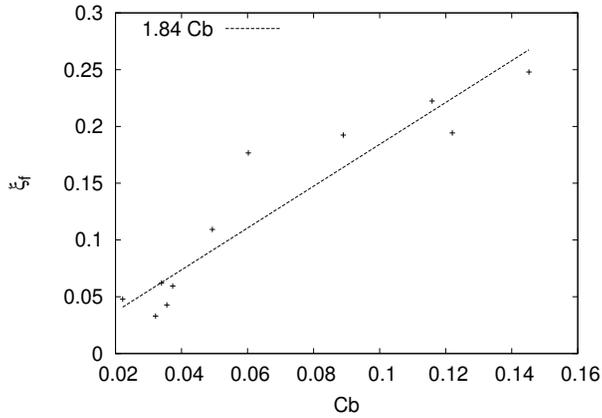


Figure 4: Data form the small scale model experiment assuming $\xi_f = c_3 \cdot Cb$.

4 DISCUSSION

The analysis of the data presented in the previous section shows that, at first approximation, the non dimensional head losses can be expressed in the form:

$$\xi_f \approx c_3 Cb \quad (13)$$

with c_3 ranging from 1.84 (small scale model) to 5.7 [3]. This expression can be easily compared to that presented in [2] (eq. 2), which can be recast in the form:

$$\xi_f = 2c_1 \frac{C_P T_0}{V^2} Cb. \quad (14)$$

For $V = 3\text{m/s}$, we have $2c_1 \frac{C_P T_0}{V^2} \approx 5.4$, which is close to the value of c_3 from [3]. This is quite remarkable, since eq. 2 was proposed with no knowledge of [3] and of present data.

The remaining questions are what values are given from these formulation in case representative of real situations, and how these value compares with other sources of pressure drop. We therefore decided to consider the specific case of a tunnel of hydraulic diameter $D_H = 8\text{m}$ in which we have first a 30 MW fire (large heavy good vehicle fire) with longitudinal velocity 3 m/s, and then a 200 MW fire (very large heavy good vehicle fire) with longitudinal velocity of 4 m/s. First, the total heat release rate is converted into the convective heat release rate by removing 30 % of it. This leads to $B = 540\text{ m}^4/\text{s}^3$ for a heat release rate of 30 MW and $B = 3550\text{ m}^4/\text{s}^3$ for a heat release rate of 200 MW. We obtain $Cb = 0.28$ for a heat release rate of 30 MW and $V = 3\text{ m/s}$ and $Cb = 1.42$ for a heat release rate of 200 MW and $V = 3\text{ m/s}$. Therefore, these two cases (large heavy good vehicle fire and very large heavy good vehicle fire) correspond to values of the same order and larger than the ones studied in [3], and larger but not by orders of magnitudes to the ones studies in the small scale experiment presented here. For these two cases, predictions of ξ_f through the 4 models presented in the present paper are given in table 1.

Table 1: Values of Cb and ξ_f for the two cases discussed in the text. ξ_f is computed using 4 formulations given in the left column of the table.

	Case 1 $\mathcal{P}_c = 20\text{MW}$ $V = 3\text{m/s}$ $Cb \approx 0.28$	Case 2 $\mathcal{P}_c = 133\text{MW}$ $V = 4\text{m/s}$ $Cb \approx 1.42$
eq. 2	$\xi_f \approx 1.7$	$\xi_f \approx 4.9$
eq. 3	$\xi_f \approx 1.2$	$\xi_f \approx 4.8$
eq. 13, $c_3 = 5.7$	$\xi_f \approx 1.7$	$\xi_f \approx 8.6$
eq. 13, $c_3 = 1.84$	$\xi_f \approx 0.5$	$\xi_f \approx 2.6$

The values of ξ_f from table 1 may be compared with the linear pressure drop coefficient along the tunnel $\frac{L}{D_H} \lambda_c$. For a 1000 m long tunnel with $D_H = 8\text{ m}$ and $\lambda_c = 0.02$ (see [2]), we get $\frac{L}{D_H} \lambda_c = 2.5$.

Values of ξ_f may also be compared with pressure drop coefficient associated with the obstruction caused by the geometry of the vehicle in fire,

$$\xi_{ob} = c_5 \left(\frac{S}{S - \Sigma} \right)^2, \quad (15)$$

with c_5 which depends on the shape and size of the obstacle. However, classical references (e.g. [4]) do not include this shape of obstacles. Based on the case of a diaphragm [4, §4.13], we may take as a first approximation

$$c_5 \approx \left(\frac{\Sigma}{S} + \sqrt{\frac{\Sigma}{2S}} \right)^2 \quad (16)$$

leading to

$$\xi_{ob} \approx \left(\frac{\Sigma}{S} + \sqrt{\frac{\Sigma}{2S}} \right)^2 \cdot \left(\frac{1}{1 - \Sigma/S} \right)^2. \quad (17)$$

Figure 5 gives values of ξ_{ob} from eq. (17). For a typical heavy good vehicle and a typical (relatively small) tunnel, we have $\Sigma \approx 12 \text{ m}^2$ and $S \approx 50 \text{ m}^2$ and therefore $\frac{\Sigma}{S} \approx 0.24$. On the other hand, for a very high blockage ratio that occurs in an underground train tunnel, one may have $\Sigma \approx 20 \text{ m}^2$ and $S \approx 25 \text{ m}^2$ and therefore $\frac{\Sigma}{S} \approx 0.8$. We can conclude that for heavy good vehicle fires, ξ_f is not small compared to ξ_{ob} and should be taken into account. On the other hand, for a very high blockage ratio such as can occur in an underground train tunnel, it is fully acceptable to neglect ξ_f .

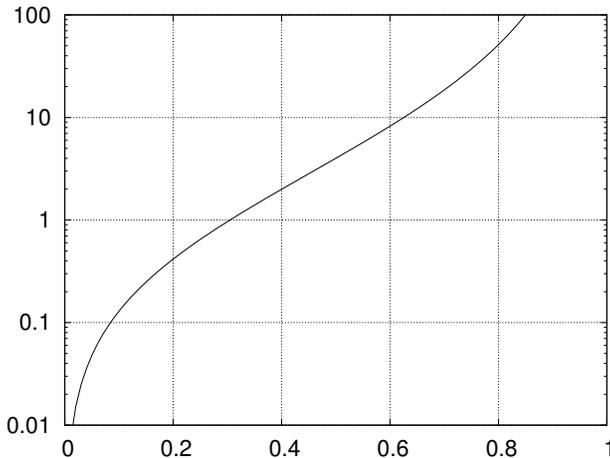


Figure 5: Values of ξ_{ob} as a function of Σ/S from eq. (17).

5 CONCLUSION

In the present paper we investigated the pressure drop caused by the fire. After a review of expressions in literature, we performed a dimensional analysis. It appears that a very simple law then comes from known pressure drop data, namely $\xi_f = c_3 C b$ with c_3 from 1.84 to 5.7, the lower value coming from small scale experiment and the upper value from CFD and fully compatible with empirical formulation of [2].

A more precise analysis should take into account the effect of the Froude number. However, its variations are generally weak, and its effect is barely visible in the present study.

For engineering purposes, the link between approximation of ξ_f and safety depends on the ventilation strategy. For longitudinal ventilation, where it is aimed to reach at least a given value, safety is to overestimate ξ_s , and the authors of this study recommend to take $\xi_s = 6Cb$. On the other hand, for transverse ventilation, where a low velocity is aimed at, safety is to underestimate the value of the coefficient, and the value 0 is satisfactory.

REFERENCES

- [1] Carlotti, P. and Hunt, G.R., An entrainment model for lazy turbulent plumes. *Journal of Fluid Mechanics*, **811**:682-700, 2017, doi:10.1017/jfm.2016.714.
- [2] CETU (Centre d'études des tunnels), Dossier pilote des tunnels – Ventilation. *CETU*, <http://www.cetu.developpement-durable.gouv.fr/ventilation-a575.html>, **ISBN 2-11-084740-9**, 2003.
- [3] Dutrieue, R. and Jacques, E., Pressure loss caused by fire in a tunnel. *proceedings of the 12th International Symposium on Aerodynamics and Ventilation of Tunnels*, BHRGroup, **12** 77-84, 2006.
- [4] Idel'cik, I.E., Mémento des pertes de charge. *Eyrolles ed., Paris*, 1986.
- [5] Technical Committee 5 Road Tunnels – World road association, Fire and Smoke Control in Road Tunnels. *PIARC / AIPCR publisher*, **ISBN 2-84060-064-1**, 1999.
- [6] Vaitkecius A., Carvel R., and Colella, F., Investigating the throttling effect in tunnel fires. *Fire Technology* **52** 1619-1628, 2016.