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Tunnel ventilation modelling in sloped tunnels

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1. Introduction

Heavy good traffic by road has continually increased over many years and owing to population or environmental impact reasons, the actual number of road tunnels has grown in many countries. It must be remarked that, due to the sharp reduction of vehicle pollutant emissions, the ventilation of road tunnel is more and more determined by the need of controlling smoke in case of fire, especially when HazMat transportation is involved. Italy is the European Country with the highest number of road tunnel: the total length of existing and designed/under construction tunnels reaches nearly 1200 km. As shown in Table 1, the severity of tunnel unwanted events can be rather high. Moreover, recent tunnel accidents have evidenced the need of extending the conventional concept of "hazardous materials" to a broader range of transported goods and the relevance of prevention and limitation of consequences measures in case of fire in road tunnels.
It must be noticed that this risk is recognized in the European Community Directive 2004/54/CE dealing with the safety on the trans-European road network. According to the Directive, a mechanical ventilation system is required when the tunnel length exceeds 1000 m and the traffic exceeds 2000 vehicle per hour.
Longitudinal ventilation systems generally represent the best way to protect humans from fire and smoke exposure following an accident into a road tunnel of small/medium length. However, its application in the Trans-European road network is allowed in long tunnel (> 1000m) only if a complete risk assessment study is performed.

Table 1 High severity accidents in road tunnel from 1940.

Year	Tunnel	Length (m)	Fatalities	Injured people	Vehicle	Immediate acc. cause
1949	Holland (USA)	2250		66	23	Load loss
1978	Velsen (NL)	770	5	5	6	Collision
1979	Nihonzaka (Japan)	1045	7	2	173	Collision
1980	Sakai (Japan)	459	5	5	10	Collision
1982	Caldecott (USA)	1028	7	2	8	Collision
1983	Pecrile (Italy)	600	8	22	10	Collision
1986	L'armé (France)	1105	3	5	5	Collision
1987	Gumefens (CH)	340	2		3	Collision
1993	Serra Ripoli (Italy)	442	4	4	16	Collision
1994	Hugouenot (S. Africa)	6111	31	28	1	Engine failure
1995	Pfaender (Germany)	6719	53	4	4	Collision
1996	I. Femmine (Italy)	148	5	10	20	Collision
1999	M. Bianco (Italy)	11600	39		26	Fire after a leak
1999	Tauren (Austria)	6400	12		40	Collision
2003	Vicenza (Italy)		6	50		Roll Over

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The key design parameter is the so-called critical ventilation velocity, i.e. the minimum speed of the longitudinal ventilation avoiding the spread of the smoke produced by fire in the upstream direction (phenomenon known as “backlayering”). This technique was firstly applied by Thomas (1970) to study the effect of ventilation rate on tunnel fires; he suggested that the type of flow, along a transverse section of the tunnel, depends on the ratio between flotation forces and inertial forces. Quite a number of experiments were carried out subsequently by Oka and Atkinson (1995) to assess the effects of changes in the shape, dimensions and position of the fire source upon the ventilation speed. It was demonstrated by their works that, for fires developing considerable heat output and producing, as a consequence, flames that would exceed the tunnel’s height, the critical speed relation to heat output decreases progressively, until it becomes nil. A few experiments carried out by Wu and Bakar (2000) clearly prove that, for tunnels having the same height, the critical speed varies with its width; it is necessary, therefore to employ another characteristic length, i.e. the hydraulic radius, or hydraulic height of the tunnel. Notwithstanding the development of several studies on tunnel fire, based on empirical, phenomenological or CFD approaches, the effects of tunnel slope on smoke movement and its control still represent a main area of uncertainty. In a recent study (Palazzi et al., 2005), a mathematical model has been developed to calculate critical velocity, with reference to the worst situation of an hydrocarbon pool fire extended to the whole section of an horizontal tunnel. By solving mass, momentum and energy balances, a relatively simple expression of the critical ventilation velocity has been obtained, as a function of the tunnel height and of the most significant stoichiometric, thermal and fluid-dynamic parameters involved in the combustion. The maximum values of the critical ventilation velocity, calculated by means of the aforesaid expression, are in good agreement with the experimental ones and with those obtained by some more complex models proposed by other authors. This paper applies the same mathematical approach, with appropriate modifications, in order to obtain the critical ventilation velocity in case of a sloped tunnel. The experimental step of this study was performed in a laboratory scale-tunnel under natural ventilation, forced ventilation, presence/absence of obstacles and different tunnel slopes, up to a maximum angle corresponding to 6°.

2. Experimental

Materials are described in detail in Palazzi et al., 2005, as concerns experimental runs carried out with the laboratory tunnel depicted in Fig. 1. The total length of the laboratory tunnel is 6.0 m, the internal radius is 0.15 m, the height from the floor is 0.2 m and the width at the floor level is 0.28 m. It should be noticed that the tunnel was equipped with an adjustable slope device, controlled by a digital laser level, within a slope range $0° \leq \theta \leq 6°$.

3. Theoretical

In case of fire in a tunnel, a longitudinal ventilation system is often operated in order to create, upstream of the fire, a smokeless area, essential for evacuation and rescue operations. If the ventilation rate is low, the fire smoke may propagate also upstream of the fire, contrary to the ventilation air flow, a phenomenon known as “backlayering”.

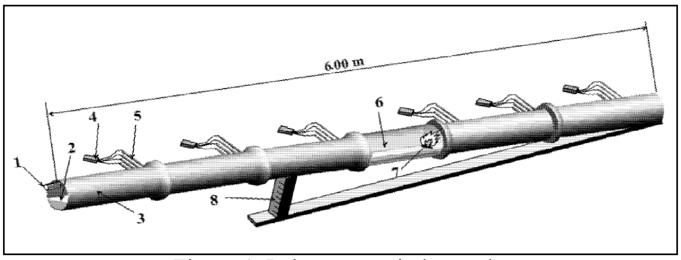

Figure 1. Laboratory wind tunnel
(1=longitudinal ventilation fan; 2=fire-proof floor; 3=fire-proof concrete tunnel; 4=data acquisition module; 5=stainless steel thermocouples; 6=Pyrex glass testing chamber; 7=fire source; 8=adjustable slope device)

The critical velocity, that is the minimum value capable of avoiding backlayering and thus force smoke to move only downstream, is, obviously, a determining value when designing ventilation systems. Palazzi et al., (2005) developed a model considering the main effects of a longitudinal tunnel ventilation system on the smoke flow, i.e., the momentum of the advecting smoke column involving a longitudinal component and the drag effect between the air conveyed by the ventilation system and the backlayering (see Fig. 2). The fresh air velocity depends on the parameters α, r and b, respectively connected to the stoichiometric, thermal and fuid-dynamic characteristics of the combustion process, as follows:

$$v_a = \alpha \frac{(r-1)^{1/2}}{r} \frac{1-b^2}{(1+3b)^{3/2}} (gH)^{1/2} \tag{1}$$

where:

$$r = \frac{\rho_a}{\rho_f} \quad (2) \qquad \alpha = \frac{\dot{m}_a}{\dot{m}_f} \quad (3) \qquad b = \frac{\dot{m}_{b2}}{\dot{m}_f} \quad (4) \qquad b = \frac{f}{1-f} \quad (5)$$

The last equation allows obtaining, as a function of the entrainment constant f, the value of b in connection of which backlayering becomes zero, just in the tunnel section where the fire starts. Generally speaking, the value of f is to be obtained on experimental basis. However, under the hypothesis that backlayering is comparable to a plane jet (Kunsch, 2002), we can assume that $f = 0.01 \div 0.04$. In particular, in backlayering absence ($b = 0$) and under the condition $r = 2$, the maximum value of the critical velocity results:

$$v_a = v_{ca,\max} = \frac{\alpha}{2} (gH)^{1/2} \tag{6}$$

The results obtained by the model are in good agreement with the ones presented by Oka and Atkinson (1995), Bendelius (1996) and Wu and Bakar (2000), when f is in the range $0 \div 0.1$. In order to consider the sloped tunnel configuration, the physical model was modified, as shown in Fig. 3. Consequently, the mathematical model was developed as described in the following paragraphs.

2.1. Fire-smoke interactions

Making reference to Fig. 3, taking into account the tunnel slope, the mathematical model was developed, under following hypotheses: 1. Mechanical energy conservation during the transformations to which the smoke is subjected as time goes on (compression, expansion, kinetic energy variation, speed direction variation); 2. Smoke particles during the acceleration phase cover the maximum distance; 3. Negligible drag effect at the tunnel ceiling; 4. $v_b = v_z$

$$\frac{1}{2}\rho_b v^2 = (\rho_a - \rho_f) g \frac{H - H_{b2}}{2} \frac{1}{\cos\theta} \quad (7) \qquad v_b = v_z = v \cdot \cos\theta \quad (8)$$

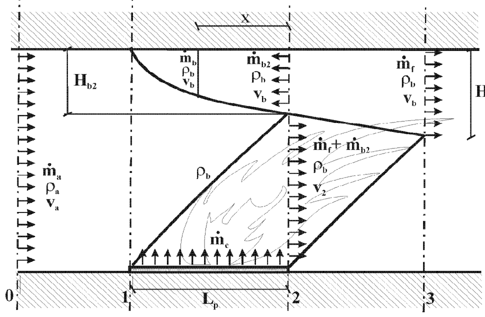

Figure 2. Physical model of fire and smoke in plane tunnel.

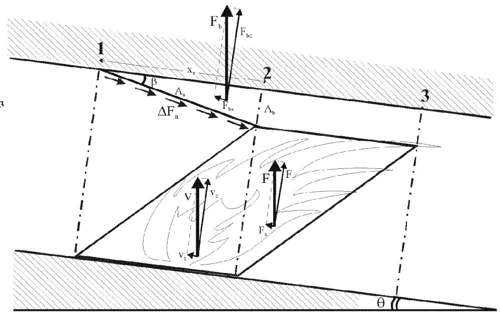

Figure 3. Physical model of fire and smoke in sloped tunnel.

Considering the horizontal component of the buoyancy, the momentum balance referred to the section 2-3 of the tunnel can be written as:

$$(\dot{m}_f + \dot{m}_{b2})v_2 - (\dot{m}_f - \dot{m}_{b2})v_2 - F_x = 0 \tag{9}$$

A complete description of the model is provided by following equations:

$$H_b = H\frac{A_{b2}}{A} \tag{10}$$

$$F_x = F\cdot\sin\theta = (\rho_a - \rho_b)V_{23}\cdot\sin\theta \tag{11}$$

$$V_{23} \cong L_p A \tag{12}$$

$$L_p = (H - H_{b2})\frac{v_2}{v_b} \tag{13}$$

$$\dot{m}_{b2} = \rho_b v_{b2} A_{b2} \tag{14}$$

$$\dot{m}_f + \dot{m}_{b2} = \rho_b v_2 (A - A_{b2}) \tag{15}$$

$$\dot{m}_a = \rho_a v_a A \tag{16}$$

Taking into account eqs. (2), (8) and (10), eq. (7) can be written as follows:

$$v_{b2} = (r-1)gH\left(1-\frac{A_{b2}}{A}\right)\cos\theta \tag{17}$$

Considering eqs. (10)÷(15), eq. (9) can be written as:

$$v_2^2 - v_2 v_{b2} + 2\frac{1}{A/A_{b2}-1}v_{b2}^2 - (r-1)gH\frac{v_2}{v_{b2}}\sin\theta = 0 \tag{18}$$

From eqs. (4), (14) and (15), it results:

$$\frac{(A-A_{b2})}{A_{b2}} = \left(1+\frac{1}{b}\right)\frac{v_{b2}}{v_2} \quad\Rightarrow\quad A_{b2} = A\cdot\left(1+\frac{1+b}{b}\frac{v_{b2}}{v_2}\right)^{-1} \tag{19}$$

By combining eqs. (17) ÷(19), it is possible to obtain the expressions of v_{b2} , v_2 and A_{b2} as a function of the other tunnel parameters. At last, by means of eqs. (3) and (16), the expression of v_a:

$$v_a = \alpha\frac{(r-1)^{1/2}}{r}(gH)^{1/2}\cdot\varphi(b,\theta) \tag{20}$$

A full description of the function $\varphi(b,\theta)$ can be analytically obtained; however, in the explored range $0 \le \theta \le 6°$, $0.01 \le b \le 0.04$ it results $\varphi(b,\theta) \cong 1$. Furthermore, the rather complicated analytical expression produces results that are not supported by experimental data on the influence of θ on v_a. Therefore, the modified behaviour of backlayer mainly accounts for the dependence of the critical ventilation velocity in a sloped tunnel. A theoretical insight into the details of the backlayer is developed in the following paragraph.

2.2. Backlayering

Under the hypothesis that, in a sloping tunnel, the buoyancy on backlayer be balanced by the drag enhancement between the opposite draughts (backlayer and cold air) (see Fig. 2): $$F_{bx} = \Delta F_{ax} \quad (21)$$

where: $$F_{bx} = (\rho_a - \rho_b) g \sin\theta \cdot V_b \quad (22) \qquad V_b = \frac{1}{2} A_b x_e \quad (23)$$

Generally speaking, in a macroscopic balance, the drag force acting on a draught can be expressed in the form: $F_a = f_a S K$, being f_a a drag coefficient, S a characteristic area and K the characteristic kinetic energy (Bird et al, 1962). Adopting this approach, it results: $$\Delta F_{ax} = f_a A_a \Delta K_a \cos\beta \quad (24)$$

$$A_a = A_b / \sin\beta \quad (25) \qquad \Delta K_a = \frac{1}{2} \rho_a \left[(v_a + \Delta v_a)^2 - v_a^2 \right] \quad (26)$$

By substituting eqs. (22) ÷ (26), into eq. 21), one can write:

$$(\rho_a - \rho_b) g \sin\theta \frac{1}{2} A_{b2} x_e = f_a \frac{A_{b2}}{\sin\beta} \frac{1}{2} \rho_a \left(\Delta v_a^2 + 2 v_a \Delta v_a \right) \cos\beta \quad (27)$$

$$\Delta v_a^2 + 2 v_a \Delta v_a = \frac{1}{f_a} (r-1) g H_{b2} \sin\theta \quad \Rightarrow \quad \frac{\Delta v_a}{v_a} = (1 + \gamma \sin\theta)^{1/2} - 1 \quad (28)$$

where: $$\gamma = \frac{(r-1) g H_{b2}}{f_a v_a^2} \quad (29)$$

Considering that $b \cong 10^{-2}$, following approximations can be made:

$$H_{b2} = H \frac{b(1-b)}{1+3b} \cong bH \quad (30) \qquad v_a^2 \cong \frac{\alpha^2}{r^2} (r-1) g H \quad (31)$$

So that, from eq. (29), it follows: $$\gamma \cong \frac{r^2}{\alpha^2} \frac{b}{f_a} \quad (32)$$

Assuming that $r = 2$ and $\alpha = 0.94$ (hexane), as reported in Palazzi et al., 2005; and taking into account that $f_a \cong f \cong b$, it follows that $\gamma \sin\theta <<< 1$, then:

$$\frac{\Delta v_a}{v_a} \cong \frac{1}{2} \gamma \sin\theta = k \sin\theta \propto \theta \quad (33)$$

The calculated values of v_a show a fairly good agreement with experimental results obtained at laboratory scale, under the operative conditions explored, i.e. sloping angle $0° \le \theta \le 6°$ (Fig. 4). Further experimental runs are needed to investigate a broader range of angles and to validate the following theoretical approach. By virtue of eq. (33), one can write:

$$v_{a\theta} = v_a + \Delta v_a = v_a (1 + k \sin\theta) \quad \Rightarrow \quad v_{a\theta} = \alpha \frac{(r-1)^{1/2}}{r} (gH)^{1/2} (1 + k \sin\theta) \quad (34)$$

In follow-up experimental and theoretical studies on medium slope effect, the involved phenomena will be addressed in more detail.

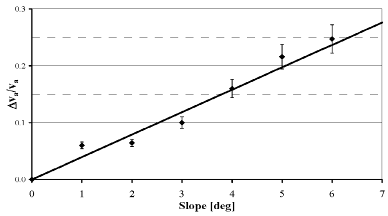

Figure 4. Measured and calculated increase of velocity vs.tunnel slope

Table 2. Nomenclature

A	Area of section 2 ($A=A_2+A_{b2}$), m^2	$\dot{m}_a$	Air mass flow rate, kg·s^{-1}
A_a	Contact area backlayering/cold air draughts, m^2	$\dot{m}_{b2}$	Backlayering mass flow rate (section 2), kg·s^{-1}
A_b	Backlayering area, m^2	$\dot{m}_f$	Smoke mass flow rate, kg·s^{-1}
A_{b2}	Backlayering area (section 2), m^2	r	Ratio air to smoke densities, -
b	Ratio backlayering to smoke flow rates, -	v	Vertical velocity in acceleration region, m·s^{-1}
f	Entrainment const.: smoke into fresh air flow, -	v_a	Air velocity, m·s^{-1}
f_a	Drag coefficient, -	v_{a0}	Air velocity in sloped tunnel, m·s^{-1}
F	Generation term in acceleration region, kg·m·s^{-2}	v_{b2}	Backlayering velocity (section 2), m·s^{-1}
ΔF_a	Cold air draughts, kg·m·s^{-2}	v_{ca}	Maximum value of critical velocity, m·s^{-1}
F_{bx}	Parallel comp. of backlayer buoyancy, kg·m·s^{-2}	v_z	Orthogonal component of velocity, m·s^{-1}
F_x	Parallel component of F, kg·m·s^{-2}	V_{23}	Volume between section 2 and 3, m^3
g	Acceleration of gravity, m·s^{-2}	V_b	Backlayering volume, m^3
H	Tunnel height, m	x_e	Distance at which backlayering becomes 0, m
H_b	Backlayering height, m	α	Ratio air to smoke flow rates, -
H_{b2}	Backlayering height (section 2), m	γ	Parameter defined by eq. 32
k	Parameter defined by eq. 33	ρ_b	Backlayering density, kg·m^{-3}
K_a	Air kinetic energy, kg m^2·s^{-2}	ρ_f	Smoke density, kg·m^{-3}
L_p	Pool diameter, m	θ	Slope of the tunnel, deg

3. Conclusions

Longitudinal ventilation systems can represent an optimal way to protect humans from fire and smoke exposure following an accident into a road tunnel of small/medium length. To avoid backlayering, i.e., the smoke spread in the upstream direction, a minimum speed of longitudinal ventilation is required, the so called critical ventilation velocity. This work develops a mathematical model to obtain the critical ventilation velocity in the case of a sloped tunnel. The resulting expression, experimentally validated in the range of low tunnel slope, indicates that the required ventilation is very sensitive as regards the involved buoyancy effects. In particular, if the road rises in the downstream direction, a slope of some few degrees could theoretically make useless the longitudinal ventilation, as protective measure against the smoke. Furthermore, the developed model is easily adaptable to the evaluation of the critical ventilation velocity when dealing with geometrical conditions different from the here studied ones e.g.: tunnel of different geometry, fire not extended to the whole section of the tunnel, obstacle presence in the tunnel, high sloping tunnels.

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