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AN ANALYTICAL MODEL TO SOLVE THE VENTILATION PROBLEM IN SLOPED TUNNELS

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The risk connected to tunnel transportation depends on external and intrinsic factors, as well as on the presence of tunnel safety devices. In this paper, firstly it is presented a tunnel risk characterization framework, suitable to be applied to existing road infrastructures. Secondly, the longitudinal ventilation problem in both plane and sloping tunnels is faced, so to allow a quantitative comparison between equipped or non-equipped alternative tunnels. Longitudinal ventilation systems generally represent the best technology to protect humans from fire and smoke exposure following an accident into a road tunnel of small/medium length. 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 the applicative phase of this work, reference is made to the worst situation of an hydrocarbon pool fire extended to the whole section of a sloped 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 subsequent preliminary experimental investigation of this research was performed in a laboratory scale-tunnel under natural ventilation, forced ventilation and different tunnel slopes, up to a maximum angle corresponding to 6°.

1. TUNNEL RISK CHARACTERIZATION

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. 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. One very important point to be underlined, in terms of harm to people and existing safety measures, is that in many of the accidents with fatalities or injuries there were no evacuation possibilities, e.g.. no emergency exits or ventilation system.
As well known risk is a triplet combination of event, probability and severity. By the analysis of representative scenarios in terms of number of fatalities, injuries and material damage it is possible to perform the consequence quantification. The risk connected to tunnel transportation depends on external factors (e.g. heavy vehicle traffic load, vehicle characteristics, material transported) and intrinsic factors (e.g.: tunnel geometrical dimensions (length, height, section, slope, pavement transverse gradient) and tunnel safety devices (smoke control, detection and alarm systems; water supply, anti-deflagration materials in electric rooms).). It must be noticed that fire risk in tunnel is recognized in the European Community Directive 2004/54/CE dealing with the safety on the trans-European road network. Governments have set rules and regulations to enhance safety in new tunnels by establishing technical requirements such as: explosion resistant tunnel structure, explosion safe drainage of liquid releases, evacuation safe ways and fire-proof refuges, smoke and fire detection systems, tele-video surveillance and monitoring connected to a control

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room, antifire equipments, alarm and ventilation systems, safe radio-communication systems, traffic stopping devices at the entry of the tunnel, appropriate safety simulations. Ideally, the effect of these requirements should be quantified by determining the number of people that can escape safely from the accident site inside the tunnel, for each relevant scenario. Unfortunately, existing tunnels are usually not properly equipped to reduce and mitigate the risk connected to Haz Mat transportation. In selecting the optimal transportation strategy, in order to mitigate the connected risk, it is essential the evaluation (by means of idoneous risk indices) of the hazards connected to different types of tunnels, on alternative routes. In addition, to consequence evaluation it is advisable to evaluate also following items:
self-rescue possibility, i.e., the ability of the people in the vicinity of the accident to safe themselves;
controllability, i.e., keeping the disaster consequences limited by emergency response services.
The consequence evaluation of an accident requires considering all accidental scenarios that can originate from a tank truck, concerning each reference substance. Generally speaking, the loss of containment scenarios can be classified into two categories, namely connected to atmospheric tank trucks (e.g. transporting gasoline or methanol), or pressurized ones (e.g. transporting LPG). As an example, we considered the pool fire scenario, deriving from an atmospheric tank truck accident occurring in a mono-direction tunnel. The expected consequences include stop of traffic upstream the accident location and possible exposure to radiating heat and smoke of passengers inside the tunnel. In this case, self-rescue stands for the ability of the people inside the tunnel to save themselves, depends on the information available immediately after the accident and is connected with the lay-out of the tunnel area. In order to evaluate the self-rescue possibilities, we focused on assessing the conditions for self-rescue on the basis of infrastructural and managerial conditions.
The infrastructural conditions must consider not only the number and quality of escape ways in the tunnel, but also the area lay-out and the protection that the tunnel can offer against certain scenarios (e.g. fire escalation or explosion). The presence of smoke/fire detection system, connected to automatic traffic shutdown systems, can reduce the vehicle number exposed to the hazard after the accident detection.
Clearly, all safety devices, if properly designed and managed, can reduce remarkably the number of people exposed to risk: in the worst situation of total absence of safety devices the number of injured people is directly connected to the length L of the stretch from the tunnel entrance to the accident point. The comparison between the two worst accident situations involved can be based on the following index:

$$\frac{\text{number of people involved in equipped tunnel}}{\text{number of people involved in non-equipped tunnel}} = \frac{L^*}{L}$$

where L^* is the vehicle column length with stop traffic system, depending on the intervention time of the accident detection and alarm device. Analysis of past accidents evidenced that a key safety factor is the reliability of fire detection and fire safety equipments, as well as their robustness against common mode failures due to fire.
The drainage and evacuation system for liquid releases represents a compulsory safety constraint in case of positive slope tunnels, to avoid the spreading of the fire upstream the accident. However, it must be noticed that this system represents a risk mitigating technique also in case of plane and downhill tunnels (reducing the extension and the lasting of the fire). In this case, the comparison between equipped and non-equipped tunnels must be based on physical proper effect modelling, in connection with fire of different dimensions and duration.
The criterion of controllability is focused on the ability of the emergency response services to minimize the damage and to prevent escalation of the accident. This criterion checks whether the emergency response services are capable of doing their job, considering the location of a possible accident, the available facilities and the precautionary measures taken. In particular, the following items are determining in tunnel accident:

- Accessibility: how much time does it take between the alarm and the actual start of the emergency activities?
- Working space: can all necessary prompt action vehicles, ambulances and other response equipment reach the accident spot inside the tunnel?
- Do the emergency response services have enough resources to fight the accidents and can all necessary equipment be used, given the circumstances in the tunnel area?

Examples of relevant measures in order to increase the self-rescue and controllability are: parallel access safety lanes, sprinklers, fire hydrants, water supplies and extra training. Dealing with safety evacuation ways and/or safety refuges, equipped with radio communication devices, the comparison between equipped or non-equipped tunnels is still possible and is based on different parameters, e.g., evacuation time, distance from the safe way, etc. At last, we must mention that, according to the already mentioned European Community Directive 2004/54/CE, a mechanical ventilation system is required when the tunnel length exceeds 1000 m and the traffic exceeds 2000 vehicles per hour. Longitudinal ventilation systems generally represent the best way to protect humans from fire and smoke exposure, following an accident inside a road tunnel of small/medium length. However, its application in the Trans-European road network is allowed in long tunnel (> 1000 m) only if a complete risk assessment study is performed. Therefore, in the following paragraph, we focus our attention on the evaluation of the effectiveness of a longitudinal ventilation system, in both plane and sloping tunnels, so to allow a quantitative comparison between equipped or non-equipped alternative tunnels.

2. 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". The critical velocity, that is the minimum value capable of avoiding backlayering and thus force smoke to move only downstream, is, obviously, a key parameter in designing a ventilation system. This approach 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.
Several 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.

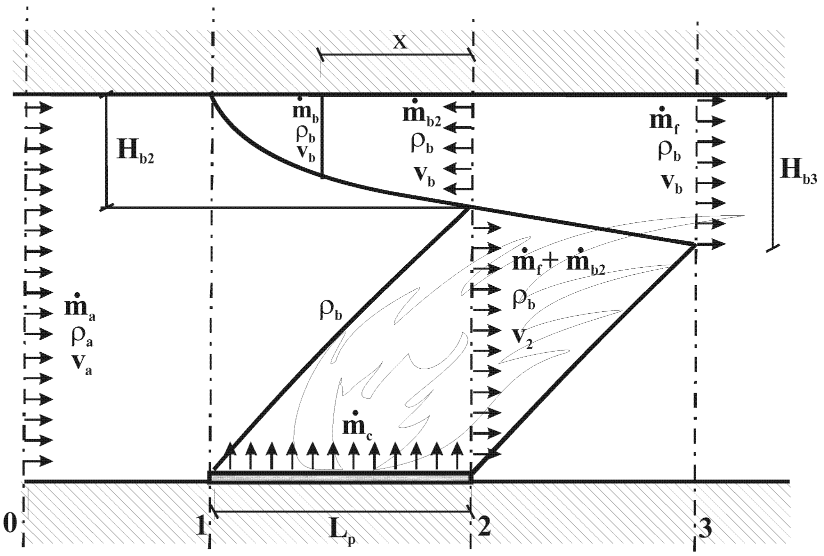

Figure 1. Physical model of pool fire and smoke in plane tunnel.

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 . The reference physical model is depicted in Figure 1.
According to the model, the fresh air velocity depends on the parameters α, r and b, respectively connected to the stoichiometric, thermal and fluid-dynamic characteristics of the combustion process, as follows:

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

where:

$$r = \frac{\rho_a}{\rho_f} \quad (2)$$

$$\alpha = \frac{\dot{m}_a}{\dot{m}_f} \quad (3)$$

$$b = \frac{\dot{m}_{b2}}{\dot{m}_f} \quad (4)$$

$$b = \frac{f}{1-f} \quad (5)$$

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.
We must remark that, 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, and under the conditions: backlayering absence ($b = 0$) and $r = 2$, the maximum value of the critical velocity results:

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

As shown in Palazzi et al. (2005), 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 the physical model depicted in Fig. 3, taking into account the tunnel slope, the mathematical model was developed, under the 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. $v_{b2} = v_z$.

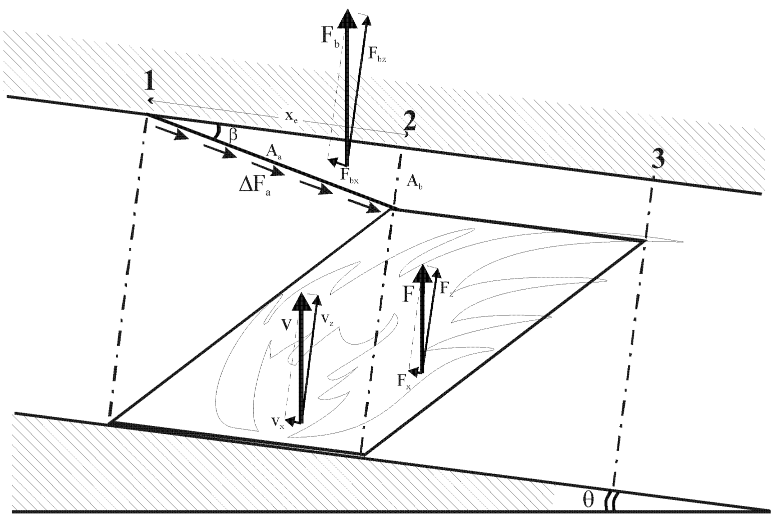

Figure 2. Physical model of pool fire and smoke in sloped tunnel.

$$\frac{1}{2}\rho_b v^2 = (\rho_a - \rho_f) g \frac{H - H_{b2}}{2} \frac{1}{\cos\theta} \tag{7}$$

$$v_{b2} = v_z = v \cdot \cos\theta \tag{8}$$

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

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

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

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

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

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

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

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

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

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

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

$$v_{b2} = \left[(r-1) g H \left(1 - \frac{A_{b2}}{A} \right) \cos\theta \right]^{1/2} \tag{17}$$

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

$$v_2^2 - v_2 v_{b2} - (r-1)gH\frac{v_2}{v_{b2}}\sin\theta = 0 \qquad (18)$$

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

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

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:

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

Under the most stringent safety constraint of backlayering absence (b=0), the function $\varphi(\theta)$ can be analytically obtained, according to the calculations outlined in Appendix A and yielding following final expression:

$$v_a = \alpha\frac{(r-1)^{1/2}}{r}(gH)^{1/2}\frac{1+\tan\theta}{\sqrt{\cos\theta}}\,. \qquad (21)$$

Dealing with a more general condition of backlayering presence in a limited extension of the tunnel, we must notice that, in the explored range $0 \le \theta \le 6°$, $0.01 \le b \le 0.04$, it results $\varphi(b,\theta) \cong 1$.
Furthermore, it must be remarked that to fully benefit the advantages of the analytical expression further experimental effort is needed, investigating in depth the influence of θ on v_a.
Therefore, in the following, the modified behaviour of backlayering mainly accounts for the dependence of the critical ventilation velocity in a sloped tunnel.
A theoretical insight into the details of the backlayering is developed in the next 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):

$$F_{bx} = \Delta F_{ax} \qquad (22)$$

where:

$$F_{bx} = (\rho_a - \rho_b)g\sin\theta \cdot V_b \qquad (23)$$

$$V_b = \frac{1}{2}A_b x_e \qquad (24)$$

Generally speaking, in a macroscopic balance, the drag force acting on a draught can be expressed in the form: $F_a = f_a SK$, 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:

$$\Delta F_{ax} = f_a A_a \Delta K_a \cos\beta \qquad (25)$$

$$A_a = A_b / \sin\beta \qquad (26)$$

$$\Delta K_a = \frac{1}{2}\rho_a\left[(v_a + \Delta v_a)^2 - v_a^2\right] \tag{27}$$

By substituting eqs. (23)- (27), into eq. (22), one can write:

$$(\rho_a - \rho_b)g\sin\theta\frac{1}{2}A_{b2}x_e = f_a\frac{A_{b2}}{\sin\beta}\frac{1}{2}\rho_a\left(\Delta v_a^2 + 2v_a\Delta v_a\right)\cos\beta \tag{28}$$

$$\Delta v_a^2 + 2v_a\Delta v_a = \frac{1}{f_a}(r-1)gH_{b2}\sin\theta \quad \Rightarrow \quad \frac{\Delta v_a}{v_a} = (1+\gamma\sin\theta)^{1/2} - 1 \tag{29}$$

where:

$$\gamma = \frac{(r-1)gH_{b2}}{f_a v_a^2} \tag{30}$$

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

$$H_{b2} = H\frac{b(1-b)}{1+3b} \cong bH \tag{31}$$

$$v_a^2 \cong \frac{\alpha^2}{r^2}(r-1)gH \tag{32}$$

So that, from eq. (30), it follows:

$$\gamma \cong \frac{r^2}{\alpha^2}\frac{b}{f_a} \tag{33}$$

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:

$$\frac{\Delta v_a}{v_a} \cong \frac{1}{2}\gamma\sin\theta = k\sin\theta \propto \theta \tag{34}$$

By virtue of eq. (34), one can write:

$$v_{a\theta} = v_a + \Delta v_a = v_a(1 + k\sin\theta) \tag{35}$$

$$v_{a\theta} = \alpha\frac{(r-1)^{1/2}}{r}(gH)^{1/2}(1 + k\sin\theta) \tag{36}$$

3. EXPERIMENTAL

Materials and methods are described in detail in Palazzi et al., 2005, as concerns experimental runs carried out with the laboratory plane tunnel.

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. The model, reproduced in Figure 3, is made of fire-proof concrete, with a Pyrex-glass made testing chamber

Figure 3.Laboratory scaled plane tunnel.

It should be noticed that, as shown in Fig. 4, the laboratory-scaled tunnel was equipped with an adjustable slope device, controlled by a digital laser level, within a slope range 0°≤θ≤6°.
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 $0° \leq \theta \leq 6°$ (see Fig. 5).
Further experimental runs are needed to investigate a broader range of angles and to validate the presented modelling approach. In addition the general and more common situation of b ≠ 0 is to be solved by proper modelling effort.
In follow-up experimental and theoretical studies on medium slope effect, the involved phenomena will be addressed in more detail.

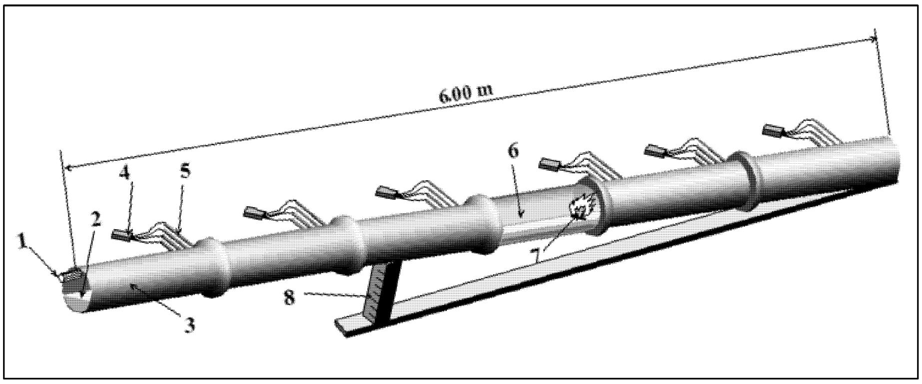

Figure 4. Experimental set-up in sloping tunnel tests.
(1=longitudinal ventilation fan; 2=fire-proof floor; 3=fire-proof concrete tunnel; 4=data acquisition module; 5=stainless steel thermocouples; 6=Pyrex glass testing chamber; 7=fire source; 8=adjustable slope device)

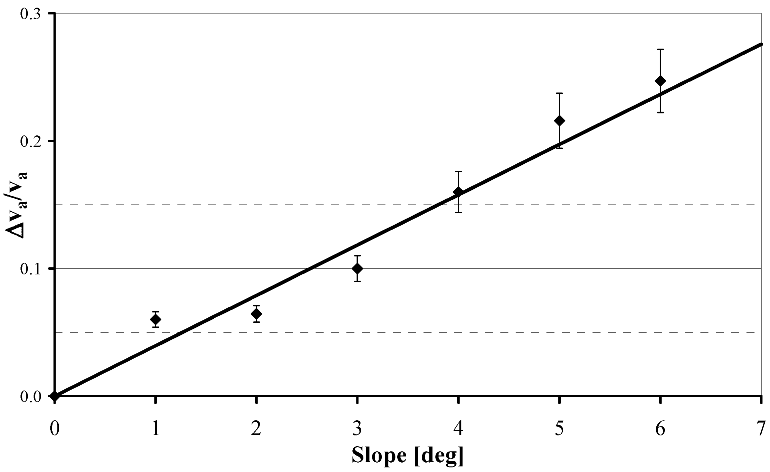

Figure 5. Measured and calculated increase of velocity as a function of the tunnel slope angle slope.

4. 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. In order 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".

In this work a mathematical analytical model is developed suitable to obtain the critical ventilation velocity in the case of a sloped tunnel and consequently to be adopted as a simple design tool. 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 presented 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.

Appendix

$$v_{b2} \cong \left[(r-1)gH\cos\theta\right] \tag{A1}$$

$$v_2^2 - v_2 v_b - (r-1)gH\frac{v_2}{v_{b2}}\sin\theta = 0 \tag{A2}$$

$$v_2 = v_{b2}\left[1 + \frac{(r-1)gH\sin\theta}{v_{b2}^2}\right] = v_{b2}(1+\tan\theta) \tag{A3}$$

$$v_a = \frac{\alpha\dot{m}_f}{\rho_a A} = \frac{\alpha}{r}v_2 \tag{A4}$$

$$v_a = \alpha \frac{(r-1)^{1/2}}{r}(gH)^{1/2}\frac{1+\tan\theta}{\sqrt{\cos\theta}} \tag{A5}$$

Notation

A	Area of section 2 ($A=A_2+A_{b2}$), m^2	$\dot{m}_{b2}$	Backlayering mass flow rate (section 2), kg·s^{-1}
A_a	Contact area backlayering/cold air draughts, m^2	$\dot{m}_f$	Smoke mass flow rate, kg·s^{-1}
A_b	Backlayering area, m^2	r	Ratio air to smoke densities, -
A_{b2}	Backlayering area (section 2), m^2	v	Vertical velocity in acceleration region, m·s^{-1}
b	Ratio backlayering to smoke flow rates, -	v_a	Air velocity, m·s^{-1}
f	Entrainment constant: smoke into fresh air flow, -	$v_{a\theta}$	Air velocity in sloped tunnel, m·s^{-1}
f_a	Drag coefficient, -	v_{b2}	Backlayering velocity in the section 2, m·s^{-1}
F	Generation term in acceleration region, kg·m·s^{-2}	v_{ca}	Maximum value of critical velocity, m·s^{-1}
ΔF_a	Cold air draughts, kg·m·s^{-2}	v_z	Orthogonal component of velocity, m·s^{-1}
F_{bx}	Longitudinal component of backlayer buoyancy, kg·m·s^{-2}	V_{23}	Volume between section 2 and 3, m^3
F_x	Longitudinal component of F, kg·m·s^{-2}	V_b	Backlayering volume, m^3
g	Acceleration of gravity, m·s^{-2}	V_{hot}	Hot gas volume, m^3
H	Tunnel height, m	x	Longitudinal coordinate, m
H_b	Backlayering height, m	x_e	Distance at which backlayering becomes 0, m
H_{b2}	Backlayering height (section 2), m	α	Ratio air to smoke flow rates, -
k	Parameter defined by eq. 34	γ	Parameter defined by eq. 33
K_a	Air kinetic energy, kg m^2·s^{-2}	ρ_b	Backlayering density, kg·m^{-3}
L_p	Pool length, m	ρ_f	Smoke density, kg·m^{-3}
$\dot{m}_a$	Air mass flow rate, kg·s^{-1}	θ	Slope of the tunnel, deg

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