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CIVIL ENGINEERING

Air curtain as a barrier for smoke in case of fire: Numerical modelling

G. KRAJEWSKI* and W. WĘGRZYŃSKI

Fire Research Department, Building Research Institute (ITB), 21 Ksawerów St., 02-611 Warszawa, Poland

Abstract. This paper presents the basic information about the use of air curtains in fire safety, as a barrier for heat and smoke. The mathematical model of an air curtain presented allows to estimate the velocity of air in various points of space, including the velocity of air from an angled air curtain. Presented equations show how various parameters influence the performance of an air curtain, thus allowing for better understanding of its principle of operation. Further, authors present results of their previous studies on air curtain performance and validation studies on various turbulence models used in CFD analysis. Results of new studies are presented with regards to the performance of an air curtain in case of fire, and final remarks on its design are given.

Key words: fire, air curtain, tunnel ventilation, smoke and heat exhaust system, CFD analysis.

1. Introduction

Rapid growth of the transit network is followed by growing number of underground structures such as urban transport railways, stations, road tunnels or underground road connections and junctions. These new projects often require development of new ways for providing safety to their users in case of fire. In the opinion of the authors, one of such tools can be an air curtain, used as a part of smoke and heat exhaust systems fit in the building. Engineers who would like to design such devices lack data regarding their performance in fire conditions. Available analytical models, described in details in Sec. 3, are difficult to use and provide only information about the velocity of the jet flow, while the end user has to evaluate the performance criteria. Feasibility of air curtains and the these performance criteria were the scope of both past and recent work of the authors. Results of the comprehensive study presented in Sec. 5 gave conclusions valid for wide scope of application of the air curtains in fire safety. The approach presented by the authors allows to combine known analytical models of air curtains used in the design of the device itself, with modern requirements and assessment methods of fire safety engineering.

2. Description of an air curtain

Air curtains are devices used in buildings as barriers replacing doors or means of separation of areas with different environmental conditions. The main reason behind their application is the elimination of mass and heat transfer through the opening without being a physical barrier for human movement or transport. Air curtains grown in popularity in 60's of 20th century, although the principles of their operation date back to 1904. The concept of air barrier was founded by van Kennel [1–3]. An air curtain device placed between two zones differing in temperature, density of air or pressure can efficiently stop the natural air flow between them [4].

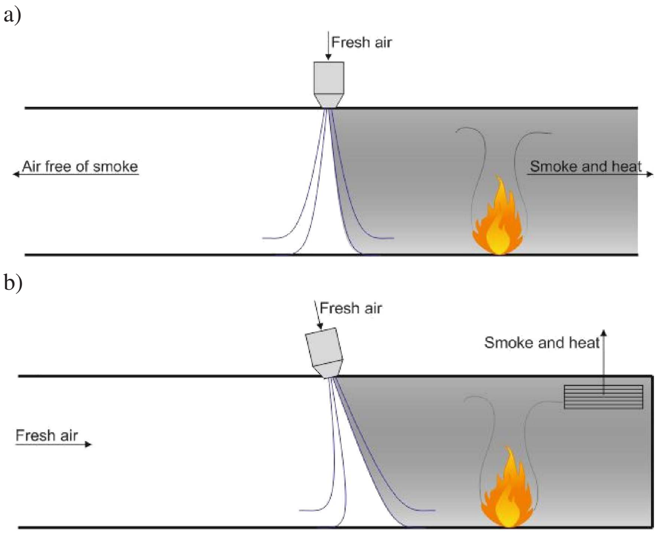

Fig. 1. Regions of air curtain, left side of figure presents possible shape of the air curtain, right side shows change of U_c/U_o along symmetry plane of curtain in x dimension (own work)

Air curtain can be also used as a tool of fire safety, in order to separate the zone with elevated temperature, lowered air density and high concentration of smoke from zone in which the human evacuation can take place [5]. The use of air curtains in this application has to be preceded by a risk analysis, as the device will break the natural stratification of smoke in area endangered by fire. Because of that, the protecting area of evacuation from smoke is at the cost of deterioration of environmental conditions for human evacuation on the fire side of air curtain. The main areas of application for air curtains are various tunnels and underground buildings, in which the risk of fire is high and there are difficulties in ensuring acceptable level of fire protection with other means. Application of air curtains for fire safety can be considered as a stand-alone

*e-mail: gkrajewski@itb.pl

device (Fig. 1a) or as a part of Smoke and Heat Exhaust Ventilation system (Fig. 1b). Stand-alone devices can be used in long corridors and tunnels open on both sides. This type of application allows pushing the smoke and heat away from the protected area. Air curtains can also be used as an integral part of smoke and heat exhaust system in the building. In this case, smoke and heat exhaust system causes under pressure in the area close to fire, and the air curtain acts as both barrier between the zones and as a mechanical supply of air for the system.

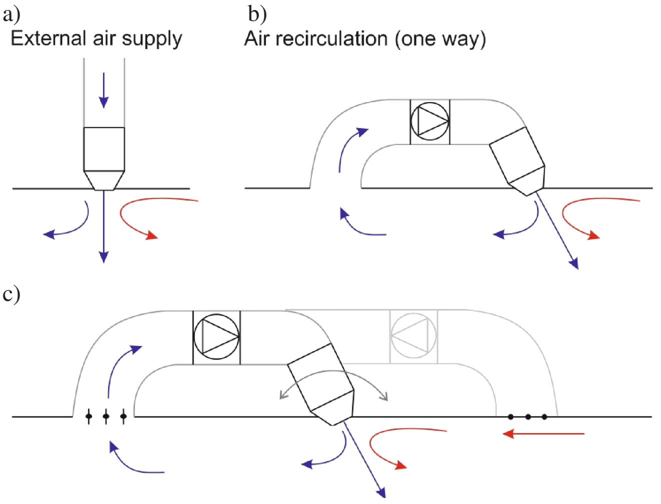

Fig. 2. Regions of air curtain, left side of figure presents possible shape of the air curtain, right side shows change of U_c/U_o along symmetry plane of curtain in x dimension (own work)

3. Analytical modelling of the jet flow from air curtain

The main parameters used in the analytical model of an air curtain are:

- air velocity at the outlet of the nozzle – U_o;
- width of the nozzle opening – o;
- angle at which the air is induced at the nozzle – α_o.

Important parameters of the air curtain, despite of the flow being three dimensional, can be shown in 2D plane, whereas direction downwards from the air curtain is described as axis x, and the direction perpendicular to flow, on horizontal plane, described as axis y. The ratio of horizontal distance from the nozzle to the width of the nozzle will be referred as y/o and ratio of vertical distance from the nozzle to the width of the nozzle will be referred as x/o. Mathematical model of air curtain was described previously in [6–8].

In a vertical section of an air curtain up to four regions can be distinguished, also presented in Fig. 3:

1. potential core zone,
2. transition zone,
3. developed zone,
4. impinging zone.

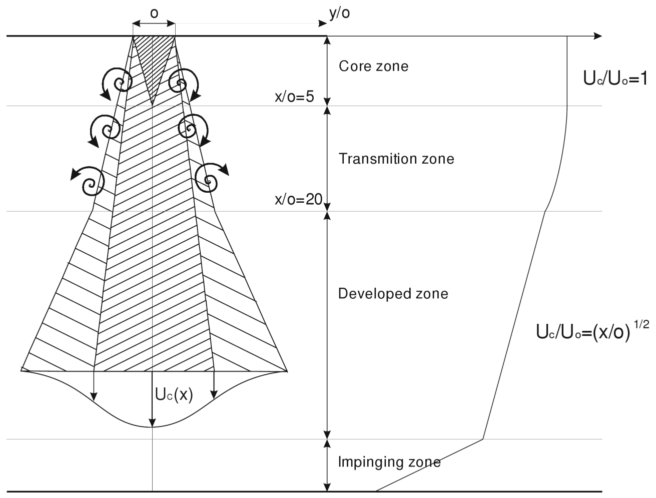

Fig. 3. Regions of air curtain, left side of figure presents possible shape of the air curtain, right side shows change of U_c/U_o along symmetry plane of curtain in x dimension (own work, based on Ref. 6

Potential core zone is a region, where the air velocity is constant, and close to initial speed in the nozzle. Region where the velocity starts to decay and the jet amplifies is described as the transition zone. It can be assumed that this region starts in the distance $x/o = 5$ from the nozzle. Velocity in this region can be described as shown in Eq. (1) [9], but due to the flow being very turbulent only mean values can be assessed accurately.

$$\frac{U(x,y)}{U_0} = \frac{1}{2}\left[1 + erf\left(\sigma_1 \frac{y + \frac{o}{2}}{x}\right)\right], \tag{1}$$

where o – characteristic dimmension of nozzle [m]; U_o – outlet velocity on the nozzle; x, y – distance from the nozzle in x and y axis [m] [9].

At the distance approximately $x/o = 20$ from the nozzle the velocity decay can be considered constant, and expressed with non-dimensional quantities [9]. Analytical solution of the velocity is given in Eqs. (2) and (3)

$$\frac{U(x,y)}{U_0} = \frac{\sqrt{3}}{2}\sqrt{\frac{7.67e}{x}}\left[1 + \tanh^2\left(7.67\frac{y}{x}\right)\right], \tag{2}$$

$$\frac{U_C(x)}{U_0} = C_1\left(\frac{x}{o} - C_2\right)^{-1/2}, \tag{3}$$

where C_1 and C_2 are constants which values depend on the shape of the nozzle and the parameters of the air flow. Constant C_1 values from 1.9 to 3.0 and constant C_2 values from -8 to 10, based on the work of Schlichting [9].

Close to the ground level the fourth region can be distinguished, the impinging zone. This is the zone in which the flow deflects from the ground, and thus is difficult to assess with simple means. The thickness of this zone is found to be approx. 15% of the height of the room. Despite being least known, this area is crucial for sustaining smoke tightness of the barrier.

In many applications the air curtain will work as a subject to a lateral side pressure, either overpressure caused by fire or underpressure caused as an effect of smoke and heat exhaust system or environmental conditions. According to Hayes and Stoecker [6, 10, 11] such jet represents a circular curvature. Variables used in mathematical description of this phenomena are shown in Fig. 4. The air curtain itself can be described with set of 5 non-dimensional numbers representative to the phenomena: Euler number, geometric aspect ratio, Reynolds number, turbulence intensity at the nozzle and the jet angle. The variables of the environment are kinematic viscosity, density, temperature and the pressure gradient. The relation between pressure, outlet velocity on the nozzle and other important factors, is shown in Eq. (4).

$$\frac{\Delta P}{\frac{1}{2}\rho U_o^2} = f\left[\frac{H}{o}, \frac{U_o o}{\nu}, I, \alpha\right]. \tag{4}$$

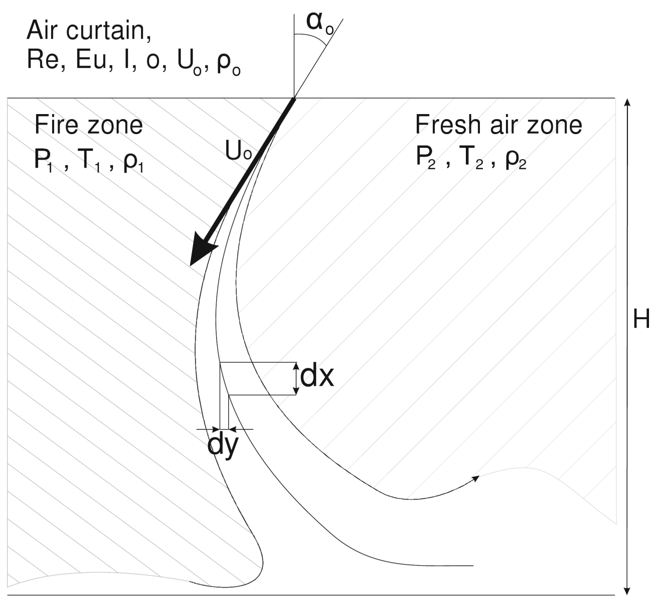

Fig. 4. Air curtain with air induced at angle α, with visual presentation of variables that influence the flow (own work, based on Ref. 11)

Assuming that the only important outside factor is the pressure difference (which will be true in fire scenario and for mechanically influenced flow) and that the moment of inertia is in the direction of the air flow, moment of inertia in x and y coordinates can be described with Eqs. (5) and (6):

$$\Delta p dy = -\left(\rho_o/g\right) o U_o^2 \sin\left(\alpha\right) d\alpha, \tag{5}$$

$$\Delta p dx = \left(\rho_o/g\right) o U_o^2 \cos\left(\alpha\right) d\alpha, \tag{6}$$

where g is gravitational pull [m/s^2], Δp – pressure difference between the sides of the air curtain [Pa], ρ_o – induced air density [kg/m^2], o – width of the nozzle [m], α_o – angle of the jet at the nozzle [°].

Assuming that for $x = 0$, $y = 0$ and $\alpha = \alpha_o$

$$y_c = \frac{\rho_o o U_o^2}{g \Delta p}\left(\cos\alpha_o - \cos\alpha\right), \tag{7}$$

$$c_c = \frac{\rho_o o U_o^2}{g \Delta p}\left(\sin\alpha - \sin\alpha_o\right), \tag{8}$$

where y_c and x_c are the coordinates of the air curtain centerline. If α is removed from the equation, the equation will take form of Eq. (9):

$$\left(\frac{g\Delta p}{\rho_o o U_o^2} x_c + \sin\alpha_o\right)^2 + \left(\frac{g\Delta p}{\rho_o o U_o^2} x_c + \cos\alpha_o\right)^2 = 1. \tag{9}$$

4. Conditions during fire and assessment criteria

Application of an air curtain as a mean of fire safety requires its reliable operation in an eventual case of fire. Potential area of application for air curtain is the separation of the area in which the fire occurred from the area where evacuation takes place, or from area which has to be protected due to other important factors. As a mean of fire safety in the building, air curtain performance has to affect human safety in limiting influence the fire can have, in the form of:

- high temperature of the smoke,
- lowered visibility in the smoke,
- toxicity of the smoke,
- radiation from both smoke and the fire.

As the air flow is transparent for the radiation, the latter effect cannot be directly restricted, although inducing large amounts of cold air can successfully lower average temperature of gasses on the fire side of air curtain, thus lowering the total amount of heat radiated from them. The other effects of the fire can be either completely mitigated by the air flow from the curtain, or limited to a level where they do not pose a danger to evacuees. The total performance of the air curtain will be a sum of the performance of the device itself, and the smoke and heat exhaust system which it can work together with.

The worst case for assessing the performance of an air curtain is when there is no exhaust from area where fire occurred, and this area is in overpressure versus protected evacuation zone. General criteria for assessment of fire ventilation systems in fire situation can be found in [12–14].

The temperature of the air in the area of evacuation shall not be higher than 60°C [15, 16]. More to that, it is expected that radiation from a smoke layer will not exceed 2.50 kW/m^2 which relates to smoke layer temperature of 200°C. As the air curtain is a physical barrier for the smoke flow, it is expected that its performance prohibit buoyant layer of smoke from crossing it.

Soot concentration in the smoke and air mixture is usually presented as a value of visibility of evacuation signs. This follows the assumption that the signs are no longer visible if the smoke concentration on their path causes the light absorption or diffusion. For light emitting evacuation signs this can be expressed as shown in Eqs. (10)–(12) [15].

$$I = I_o e^{-KL}, \tag{10}$$

$$S = \frac{8}{K}, \tag{11}$$

$$K = K_m \rho C_{\text{smoke}}, \tag{12}$$

where I – intensity of light at a distance from source, I_0 – intensity of light at the source, K – extinction coefficient, L – distance from the source, S – distance at which a sign cannot be longer visible, K_m – extinction coefficient per unit of mass density, ρ is the smoke density and C_{smoke} is the mass fraction of smoke in the mixture.

As it may be difficult for an air curtain to remain complete smoke tightness due to the leakage in the impinging zone, the visibility or smoke density of air passing through the air curtain may be chosen to not be the determining criteria for its performance. Also, the toxicity of smoke can be evaluated as the concentration of toxic fractions in the smoke, although that requires in depth knowledge of the combustion process. Once mass fraction of chosen toxic product is assessed, it is possible to evaluate its effect on a person that can be exposed to it in a given time, by i.e. Fractional Effective Dose method [17, 18]. It is often assumed that if visibility criteria are met, it is highly unlikely that dangerous levels of toxic gases will occur.

5. Evaluation of generic air curtains used as a barrier for smoke and heat

The air curtain has to be designed for its particular application, due to architectural and environmental parameters being an important factor affecting its performance (height, temperature, pressure difference etc.). Nonetheless, generic applications were analysed in order of evaluating both the performance of a generic air curtain in fire conditions and the chosen Computational Fluid Dynamics (CFD) models used for the analysis. Following studies were performed by authors in Building Research Institute (ITB), Poland:

- evaluation of the possible use of an air curtain in separating zones in case of fire, with use of numerical calculations, 2011 [5],
- sensitivity study of the turbulence model used in CFD simulations of air curtains, including a full-scale physical model study, 2013 [19],
- assessment of air curtain performance for various design criteria (angle, nozzle outlet air velocity, design fire), 2014.

Notable comprehensive study on CFD approach review for air curtain performance analysis was presented by Amitesh and Tiwari [20].

5.1. Evaluation of the possible use of an air curtain in separating smoke free zones in case of fire. The purpose of the first studies was to evaluate the potential use of air curtains as a tool for fire safety in the buildings. For this first study authors compared their own results with results of full scale experiment carried by the *Ecole des Mines de Nantes* [3]. Results of this comparison, shown as plot of centerline velocity decay in experiment [3] and CFD study [5] are shown in Fig. 5. Following simple validation case, final CFD analysis were performed, that shown the potential use of air curtain as a device separating zones in case of fire. Chosen results from the CFD study [5] are presented in Figs. 6 and 7.

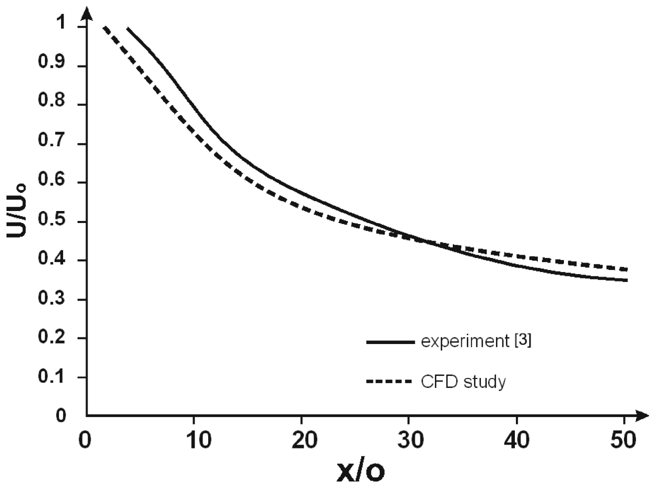

Fig. 5. Results of centreline velocity decay, for $U_o = 27$ m/s, $I = 0.5\%$, $\alpha = 0^\circ$ [5]

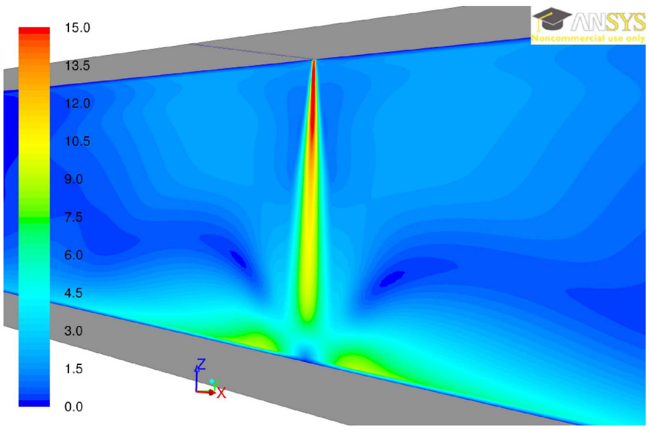

Fig. 6. Contours of velocity (0–15 m/s), for $U_o = 27$ m/s, $I = 0.5\%$, $\alpha = 0^\circ$, realizable k-ε turbulence model [5]

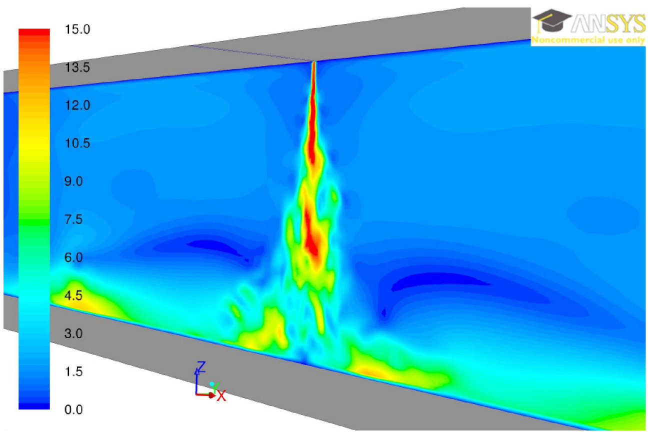

Fig. 7. Contours of velocity (0–15 m/s), for $U_o = 27$ m/s, $I = 0.5\%$, $\alpha = 0^\circ$, LES turbulence model (Ref. 5)

Results of analysis confirmed the possibility of this application of an air curtain. Obtained separation of zones where fire occurred and evacuation zone was acceptable, the amount of smoke that went through the air barrier did not cause significant rise of temperature or limiting visibility below acceptable level. The study also shown that CFD simulations may be a viable tool in assessment of the air curtain performance, although there is a need for further validation of the model in broader range of cases.

5.2. Verification of the turbulence model used in CFD studies on the air curtains. In 2012 and 2013 authors performed full scale experiment in Building Research Institute (ITB), Poland for the purpose of CFD model validation [19]. A full scale model of a tunnel was built, with the dimensions of 8.0×1.0×2.0 m. The test equipment enabled tests for angle of 0–45° and nozzle outlet velocities up to 30 m/s. The nozzle width was 20 mm, and the pressure difference between sides of the air curtain could be set from 0 to 200 Pa. Only cold flow of air can be analysed in the tunnel. Scheme of the tunnel is shown in Fig. 8 and photography of the measuring hardware in Fig. 9. Sample results of velocity measurements are presented in Table 1 and in Fig. 10.

To confirm the boundary conditions used in further simulations, numerical calculations of stand-alone air curtain were performed. The initial conditions were the same as in the experiment. Blowing angle of the jet was 0°, the outlet velocity from the nozzle was 10 m/s, 20 m/s and 30 m/s, Fig. 10. Turbulence intensity was the same as in experiment ($I_o = 5\%$). The three-dimensional model of the analyzed domain was build according to the experimental setup. In the middle of the ceiling an air curtain outlet was created. The domain has been divided into a finite number of control volumes using an unstructured hexahedral grid. The total quantity of control volumes was approximately 2 500 000 with dimensions ranging from 2 mm in the area of the air curtain outlet to 20 mm on the peripheries of the domain.

Fig. 8. Scheme (up) and a photography (down) of the test tunnel facility (Ref. 19)

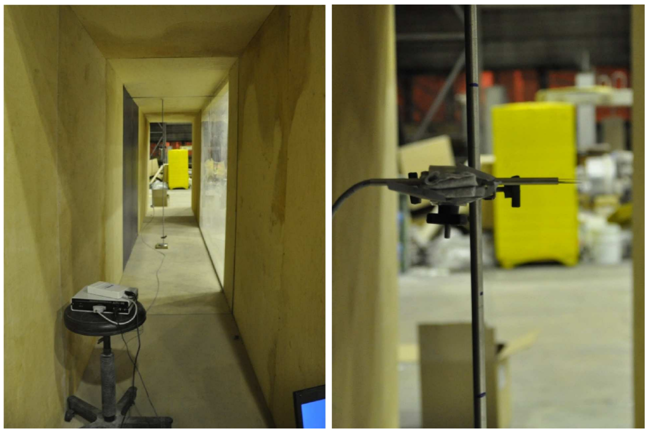

Fig. 9. Interior (left) and measuring equipment of the test tunnel (Ref. 19)

Table 1
Avarage air velocity in chosen measurement points (Ref. 19)

U_o [m/s]	Avarage air velocity [m/s] in given distance from the nozzle (x) [m]						
	0.0	0.4	0.8	1.2	1.4	1.6	1.8
10	9.9	5.7	3.9	2.8	2.7	2.4	1.8
20	19.8	11.4	7.6	6.1	5.7	4.8	3.7
30	29.7	16.9	11.6	9.5	8.2	6.7	5.1

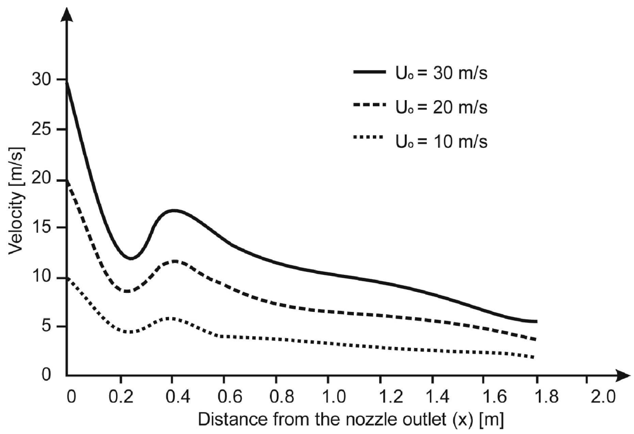

Fig. 10. Velocity of the air in the distance from the nozzle outlet in x axis for different U_o values (Ref. 19)

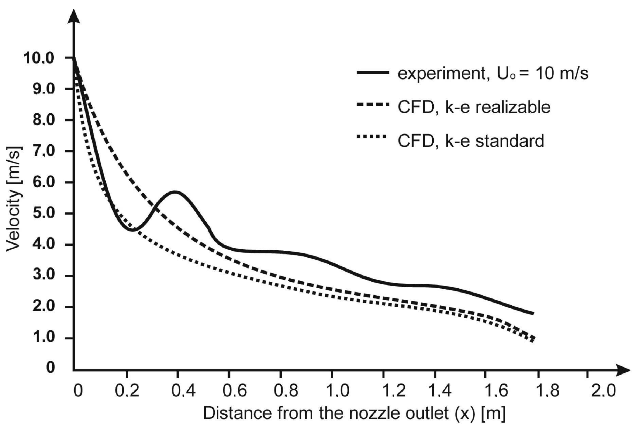

Fig. 11. Velocity of the air in the distance from the nozzle outlet in x axis from experiment and CFD studies (Ref. 19)

Chosen results of the numerical calculations of the free jet are shown in Fig. 11. The agreement between numerical calculations and the full scale experiment, with exception of the zone from $x/o = 5$ to $x/0 = 20$ (transition zone). As the transition zone of the air curtain is reported as very turbulent region of the flow, the method of approximation of the results may have high influence on the result comparison. Comparison of the results over whole height of the tunnel was the best turbulence model RANS Realizable k-ε, Table 2.

Table 2
Differences [%] between measured values and the result of CFD analysis (k-ε realizable turbulence model)

U_o [m/s]	Difference between measured values and CFD re-sults [%] in given distance from the nozzle (x) [m]						
	0.0	0.4	0.8	1.2	1.4	1.6	1.8
10	3.6	13.5	1.5	15.5	8.2	2.6	9.5
20	1.0	21.4	11.3	4.7	6.6	6.9	25.4
30	3.7	11.2	0.1	3.4	10.4	15.5	2.0

5.3. Assessment of air curtain performance for various design criteria. Studies carried in 2014 were focused on the design criteria for air curtains. Parameters chosen as the most influential, and thus being the most important in the design process are:

- the width of the nozzle;
- the velocity at the nozzle outlet;
- the angle of the jet;

and as an additional criterion, various sizes of test fire were analysed.

The chosen turbulence model, in accordance with earlier research, was RANS Realizable k-ε, which proven to be the most accurate for both cold flow of air in air curtain [6, 21] and hot flows in case of fire [22]. The finite volume method was used for model discretisation, and hexahedral mesh of 5 500 000 elements was prepared. Mesh sensitivity studies were performed, showing no influence of mesh size on the results. In first series of tests one side of the tunnel had an overpressure of 5 Pa, the opposite side was a flow of hot air with temperature 400°C. In second series of tests, a model fire was simulated in a tunnel with sizes of 6 MW, 10 MW, 13 MW and 30 MW.

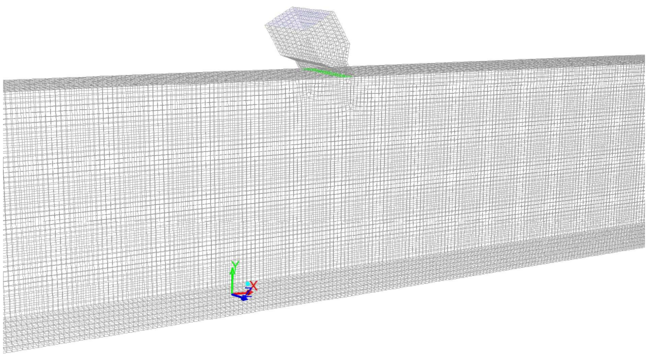

Fig. 12. 3-D model of room fit with air barrier at angle 30° used in numerical analysis

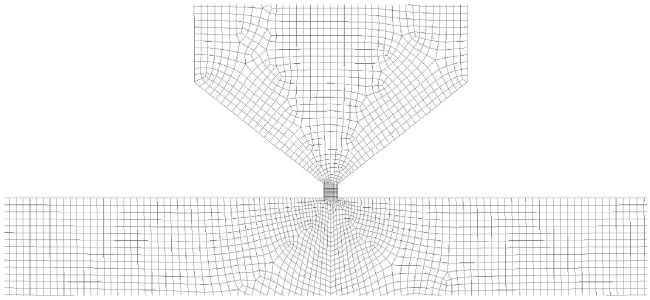

Fig. 13. View of the hexahedral mesh used in analysis, in a plane trough the centerline of the model

Performance of the air curtain in above described conditions was assessed for width of the nozzle 5.0 cm, 10.0 cm, 15.0 cm and 20.0 cm (depending on the test), velocity at the nozzle outlet 10 m/s, 20 m/s and 30 m-s, and the angle of the jet 0°, 10°, 20° and 30°.

The acceptance criteria of correct air curtain performance was the temperature on the opposite side of air curtain lower than 60°C. The visibility or toxicity of smoke on the opposite side of air curtain was not analysed as an acceptance criteria, although was evaluated in order of assessing potential performance of an air curtain.

First series of performed analysis showed, that despite the angle of the air curtain, a device with $o = 10$ cm and $U_o = 10$ m/s was unable to provide expected conditions on the other side of an air barrier (temperature exceeding 75°C) with a small overpressure. In a second series of the research, the impact of pressure was analysed, and showed that with overpressure 5 Pa the curtain loses its tightness, and with overpressure 10 Pa air curtain with $U_o = 10$ m/s is completely broken. The overpressure caused by the fire itself can reach values up to 20 Pa, and thus air curtains with higher velocities were tested against this value. In the third series air curtain with $U_o = 10$ m/s shown good performance against fires of 6 MW and 10 MW, while against fire 13 MW the design criteria were not met. This shows potential area of application for smallest air curtains in low fire risk areas. Air curtains applicable for tunnel ventilation should have width not smaller than 15 cm and velocity not smaller than 20 m/s.

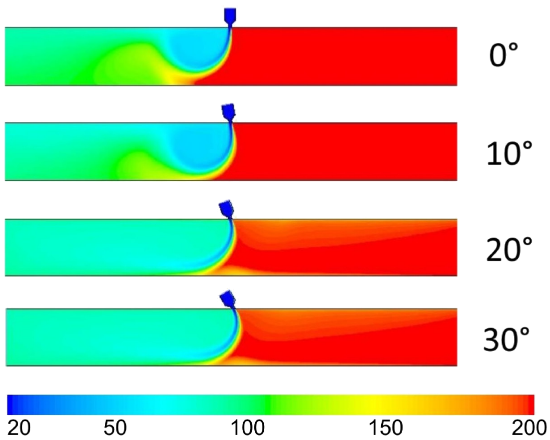

Fig. 14. Temperature plot, for $U_o = 10$ m/s, $I = 0.5\%$, $\Delta p = 6$ Pa, $\alpha = 0°$, 10°, 20° and 30°

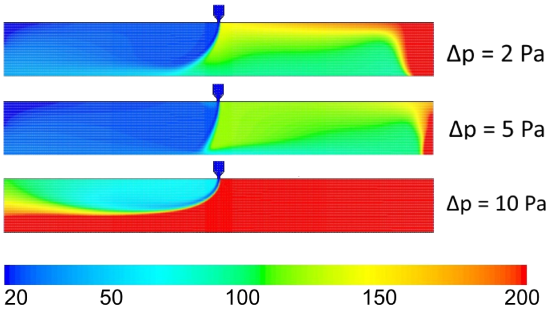

Fig. 15. Temperature plot, for $U_o = 10$ m/s, $I = 0.5\%$, $\Delta p = 3.5$ and 10 Pa, $\alpha = 0°$

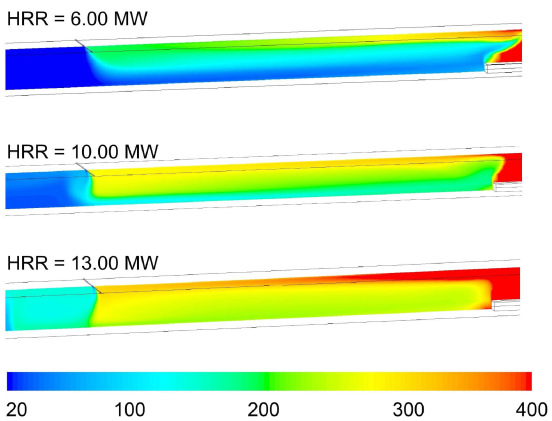

Fig. 16. Temperature plot (20–200°C) for proximity of air curtain and the source of fire, for $U_o = 10$ m/s, $I = 0.5\%$, $\alpha = 30°$, HRR = 6.0 MW, 10.0 MW, 13.0 MW

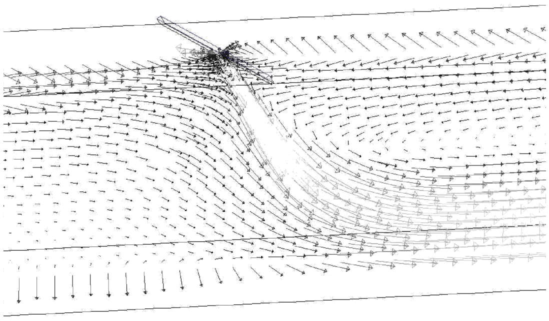

Fig. 17. Velocity vectors at the proximity of air curtain (0–5 m/s) for $U_o = 10$ m/s, $I = 0.5\%$, $\alpha = 30°$, HRR = 6.0 MW, fire on the right side of air curtain

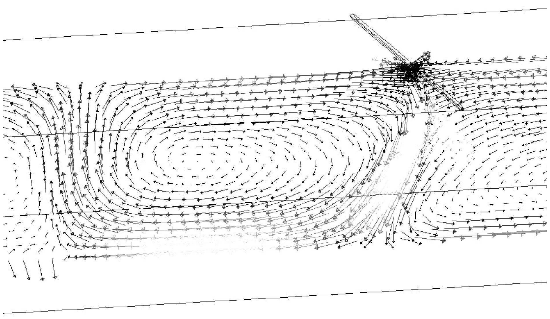

Fig. 18. Velocity vectors at the proximity of air curtain (0–5 m/s) for $U_o = 10$ m/s, $I = 0.5\%$, $\alpha = 30°$, HRR = 13.0 MW, fire on the right side of air curtain

For higher velocities of air and angles higher than 10° results of the analysis shown, that air curtain is capable of providing smoke-free zone in case of fire, when exposed to high temperature. The performance of the device was found best for angle of 30° and air velocity 30 m/s. Results of the research are shown in Figs. 19, 20.

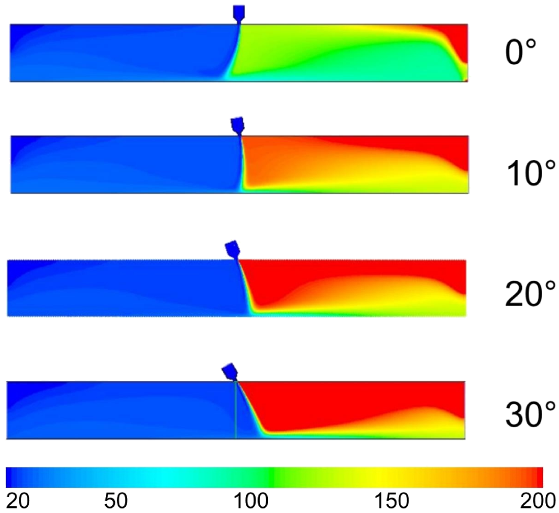

Fig. 19. Temperature plot (20–200°C), for $U_o = 20$ m/s, $I = 0.5\%$, $\Delta p = 10$ Pa, $\alpha = 0°$, 10°, 20° and 30°

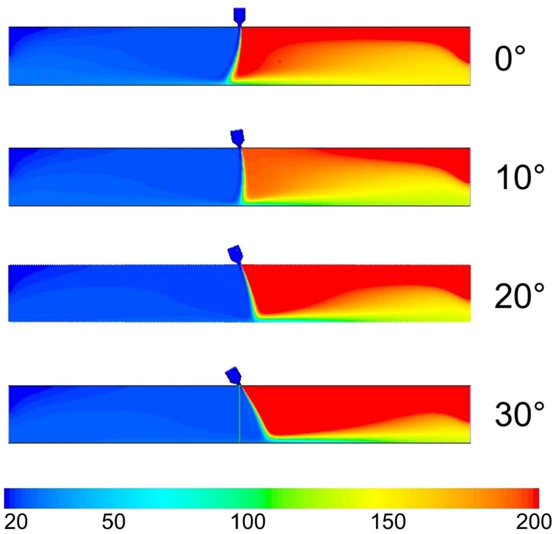

Fig. 20. Temperature plot (20–200°C), for $U_o = 30$ m/s, $I = 0.5\%$, $\Delta p = 10$ P, $\alpha = 0°$, 10°, 20° and 30°

Performed research also showed that for a tunnel with a height of 4.6 m and a design fire of 30 MW, air curtain characterized by $x/o = 50$ could not meet expected performance criteria, while these conditions were met for air curtain with $x/0 = 25$. These observations show, that the width of an air curtain is an important design criteria, for tunnel solutions.

6. Conclusions

The practical application of an air curtain as a tool for fire safety is possible, although engineers lack reliable assessment methods and performance criteria for such devices. After comprehensive study of the performance of an air curtain, in case of fire in a corridor with height of 2.00 m and tunnel with height of 4.60 m general requirements for stand-alone devices can be issued, formed in a form of the application matrix, Table 3.

Table 3
Matrix of application, standstill air curtain with no additional latteral pressure

Angle [°]	Velocity at the outlet of nozzle (U_o) [m/s]			
	10 m/s	15 m/s	20 m/s	30 m/s
0°	N/A	N/A	N/A	C/A
10°	N/A	N/A	C/A	A
15°	N/A	N/A	C/A	R
20°	N/A	C/A	A	R
25°	N/A	C/A	A	R
30°	C/A	A	A	R

N/A – not applicable, C/A – possibly applicable under special conditions (i.e. low fire risk), A – applicable in most cases, R – recommended for use

The width of an air curtain should be chosen in accordance with requirements of its application, although the ratio of x/o should not exceed 60. In cases of tunnel fires (HRR $>$ 30 MW) the width should be not less than 20 cm.

Any curtain that is a part of smoke and heat exhaust system has to be designed and analysed in combination with that system. In such case, even air curtains described as not applicable can be proven working sufficiently for the requirements.

As additional result of performed studies general requirements for assessment of performance can be issued, regarding CFD modelling of air curtains in fire conditions. Recommended turbulence model for such analysis is RANS Realizable k-ε model. For modelling the nozzle, the mesh shall consist of at least 10 elements in the width of it or mesh sensitivity study shall be performed to evaluate the impact of mesh size on the results of the analysis. The analysis shall be conducted with a source of fire appropriate for the type of building in which the device is used, located in proximity of the device – not further than 20 m from the device. Some recommendations on the fire size for such analysis can be found in [23–25]. Due to small amounts of smoke that can leak through the impinging zone of the air curtain despite its performance, and that can accumulate with time, analysis shall be performed as transient and not shorter than 30 minutes.

The air curtain should prevent the flow of heat and smoke into a protected area, and the critical values chosen for such analysis recommended for practical use can be chosen as:

- temperature on the smoke-free side of the air curtain not higher than 60°C, at the height of 2.0 m above the ground level,
- mass density of smoke not higher than 0.105 g/m^2 or the local visibility of evacuation signs with internal light source should not fall below 10 m, at height of 1.80 m above the ground level.

Future development of air curtains should be focused on their compliance with smoke and heat removal systems and their performance in non-standard applications such as protecting tunnel cross-roads. Authors of this paper have already planned further evaluation of air curtain performance and CFD validation studies with the use of Froude number scale modelling, that is planned for 2015.

REFERENCES

[1] L. Goyonnaud and C. Solliec, "Mass transfer analysis of an air curtain system", *Trans. on Engineering Science* 18, CD-ROM (1998).
[2] F. Gugliermetti, L. Santrapia, and G. Zori, "Air curtain applied to fire smoke pollution control", *Trans. on Ecology and the Environment* 66, CD-ROM (2003).
[3] L. Guyonnaund, C. Solliec, M. Dufresene de Virel, and C. Rey, "Design of air curtains used for area confinement in tunnels", *Experiments in Fluids* 28, 377–384 (2000).
[4] L.L. Wang andZhong, "An approach to determine infiltration characteristics of building entrance equipped with air curtains", *Energy and Buildings* 75, 312–320 (2014).
[5] G. Krajewski, G. Sztarbała, "Air curtains used for separating smoke free zones in case of fire", *Proc. 12th Conf. Internal Building Performance Simulation Association* 1, CD-ROM (2011).
[6] G. Krajewski, "Air barriers used for separating smoke free zones in case of fire in tunnel", *Proc. 7th Int. Conf. "Tunnel Safety and Ventilation"* 1, CD-ROM (2014).
[7] G.N. Abramovitch, *The Theory of Turbulent Jets*, Massachusetts Institute of Technology, Massachusetts, 1963.
[8] N. Rajaratnam, *Turbulent Jets*, Elsevier, Amsterdam, 1976.
[9] H. Schlichting, *Boundary LAYER THEORY*, Mc Graw-Hill Book, New York, 1968.
[10] F.C. Hayes and W.F. Stoecker, "Heat transfer characteristics of the air curtain", *ASHRAE Trans.* 2120, CD-ROM (1969).
[11] F.C. Hayes and W.F. Stoecker "Design data for air curtains", *ASHRAE Transactions* 2121, CD-ROM (1969).
[12] G. Sztarbała, "An estimation of conditions inside construction works during a fire with the use of computational fluid dynamics", *Bull. Pol. Ac.: Tech.* 61 (1), 155–160 (2013).
[13] K. McGrattan and S. Miles, "Modelling enclosure fires using computational fluid dynamics (CFD)", *SFPE Handbook of Fire Protection Engineering* 3, 3-229–3-246 (2008).
[14] W. Węgrzyński and G. Krajewski "Selection of models and boundary conditions as a result of numerical analysis of smoke and heat propagation", *Building Materials* 8, CD-ROM (2014), (in Polish).
[15] T. Jin, *Visibility Through Fire Smoke, Part 5. Allowable Smoke Density for Escape from Fire*, Fire Research Institute of Japan, Tokyo, 1975.
[16] P. Weng, "Tenability criteria for design of smoke hazard management systems", *Ecolibrium* 8, 3–37 (2011).
[17] D.A. Purser, "Toxicity assessment of combustion products", *SFPE Handbook of Fire Protection Engineering* 2, 2-83–2-171 (2008).

[18] P. Weng, "Tenability in building fires: limits and design", *Fire* 1, CD-ROM (2010).

[19] G. Krajewski, "Verification of CFD turbulence model used to simulations of air curtain", *Proc. Building Physics in Theory and Practice* 1, CD-ROM (2013).

[20] P. Amitesh and A.C. Tiwari, "Performance analysis of air curtain: a review of CFD approach", *Corona J. Science and Technology* 3 (I), 1-7 (2014).

[21] G. Krajewski, "Verification of numerical computation on the basis of physical tests of flat stream used for separating unsmoky areas", *Building Engineering and Architecture* 12 (2), CD-ROM (2013), (in Polish).

[22] W. Węgrzyński and G. Krajewski, "Application of investigation of a model scale to verify CFD computations of fire ventilation in communicating tunnels", *Mining and Tunnel Building* XX (4), CD-ROM (2014).

[23] *Fire and Smoke Control in Road Tunnels 05.05B-1999*, PIARC, 1999.

[24] M. Jannsens, *Development of a Database of Full-Scale Calorimeter Tests of Motor Vehicle Burns*, Southwest Research Institute, San Antonio, 2008.

[25] H. Ingason and A. Lonnermark, "Heat release rates from heavy goods vehicles trailers in tunnels", *Fire Safety J.* 40 (7), 646–668 (2005).