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FULL-SIZE EXPERIMENTS OF AIR CURTAINS FOR SMOKE CONTROL IN CASE OF FIRE: FINAL RESULTS

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ABSTRACT

This paper analyses the air curtains capability to be used to prevent the smoke flow from the fire compartments. Full size experiments have been developed and several relevant conditions to assess smoke-tightness have been tested. During the tests the air curtain's diffuser was positioned horizontally in the top of a permanent opening (doors). With this configuration we have an approximately vertical descend jet through the used opening. This paper includes the final results of these tests. It was concluded that it is possible to obtain smoke-tightness, provided that the adequate parameters of the plane jet are adjusted in association with compartment's smoke exhaust.

KEYWORDS: Smoke control; plane jets; full size experiments; vertical air curtains.

1. INTRODUCTION

The smoke flow inside buildings is the major cause of death in a fire event. The technology currently used to prevent the smoke flow relies on the enclosure of building spaces by fire resistant walls, with fire resistant doors and a smoke control system. In many cases closing passageways with fire doors and gates makes difficulties to the building occupants in the identification process of the escape route and also delay the fire brigade in the start of an efficient firefighting. Has air curtains do not impair the visibility during evacuation and

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firefighting, could be acceptable use them to efficiently avoid the smoke flow, when the fire spread through the void is unlikely.

There are several applications of this concept in tunnels [1] and in building corridors [2], but these are based on the pull-push principle applied to horizontal air curtains. Several authors have studied the application of single vertical air curtains (upward or downward) [3, 4, 5, 6, 7, 8] and a research work has been done about double vertical air curtains [9, 12]. Some studies used CFD simulations to assess the performance of air curtains as regards curtain tightness in corridors [8], fire/explosion accidents in a clean room [10], contaminant dispersion from clean rooms [11] and as regards curtain tightness in staircases [12]. The mentioned research work is not presenting clearly the need for smoke exhaustion in the fire compartment, which the authors of this paper considers to be a key issue for achieving smoke tightness by air curtains for high temperature smoke. Therefore, further research had to be done on this topic in order to obtain a more general theory to support the application of air curtains to the open boundaries of fire compartments.

This project (Grant QREN no. 23226) aims to develop and apply air curtain technology to limit smoke flow through the building openings. The methodology followed in this research includes: (i) the development of an analytical model that relates the relevant characteristic quantities of a plane jet with the characteristics of the environment in which the fire occurs, (ii) 1/20 scale experiments with saltwater modelling to assess the convective parameters that control smoke tightness of the curtain [13], (iii) CFD simulations to assess the performance of a full scale air curtain near a fire source [14] and (iv) fire experiments with a full-scale test specimen [15]. In this paper the final results of the full-size experiments are presented.

2. METHODS

2.1 Analytical model

The analytical model was previously developed and presented elsewhere [13, 15]. Hereafter just the main steps will be presented.

The smoke tightness due to an air curtain (plane jet) is based on the balance of the air curtain momentum and the momentum of the smoke flow. The nozzle of the plane jet is put at the door soffit level and is flowing downward, being $\propto_0$ the angle measured between the curtain axis and the vertical plane. This work considers that the jet momentum is conserved. Since the smoke flow (in this case is horizontal) is normal to the plane of the opening (vertical), only the momentum due to the horizontal component of jet velocity is concerned. Thus, the smoke tightness is reached if the value of the pressure difference $\Delta \mathrm{P_s}$ due to the difference in fluid density between indoor and outdoor (assuming uniform density in each environment) is balanced by the pressure difference $\Delta \mathrm{P_a}$ developed by momentum ($\Delta \mathrm{P_a}/\Delta \mathrm{P_s} \geq 1$). The ratio $\Delta \mathrm{P_a}/\Delta \mathrm{P_s}$ is given by equation (1).

$$\frac{\Delta \mathrm{P_a}}{\Delta \mathrm{P_s}} = \mathrm{D_m} \mathrm{sen} \propto_0 \qquad (1)$$

where $\mathrm{D_m}$ is the deflection modulus, which is defined by the equation (2).

$$\mathrm{D_m} = \frac{\rho_0 b_0 u_0^2}{g h^2 (\rho_0 - \rho_1)} \tag{2}$$

Where ρ_0 is the outdoor density, ρ_1 is the indoor density, b_0 is the thickness of the jet nozzle, u_0 is the initial jet velocity, g is the gravity acceleration and h the height above the neutral plane (when the difference in densities is uniform, the pressure difference varies linearly with the height). The smoke exhaust from the compartment generates an inlet velocity at the door u_a , which momentum shall be also considered. Therefore, the equation (1) takes the following form, equation (3).

$$\frac{\Delta P_a}{\Delta P_s} = \frac{\rho_0 b_0 u_0^2 \operatorname{sen} \propto_0 + \rho_0 h u_a^2}{g h^2 (\rho_0 - \rho_1)} \tag{3}$$

This analytical model undertakes that the minimum smoke exhaust flow rate from the compartment will be the sum of the plume thermal expansion with the entrained flow of the jet from outside, at least. The jet is entraining fluid from both sides, but just the flow rate coming from outside (of the compartment) and the flow rate at the nozzle corresponds to the mass intake into the compartment. Thus, the minimum exhaust flow rate $\dot{V}_{\mathrm{exaust}}$ includes the thermal expansion and a portion proportional to the jet flow rate, according to the equation (4):

$$\dot{V}_{\mathrm{exaust}} = \frac{\dot{Q}_c}{\rho_0 \overline{C_p} T_0} + C\left[0.22\left(\frac{2x}{b_0}\right)^{0.5} + 0.5\right] u_0 w b_0 \tag{4}$$

being C a constant of proportionality (that considers the geometry of the opening) to be assessed by experiments, x is the length of the jet, w is the door width, $\dot{Q}_c$ is the convective part of the heat release rate, $\overline{C_p}$ is the average specific heat at constant pressure (considering here the average is an approach, which does not have significant consequences since the final equations will be adjusted by empirical coefficients) and T_0 is the initial temperature.

The minimum initial jet velocity, u_0 , which complies with the smoke tightness requirement, is given by the equation (5).

$$u_0 = \sqrt{\frac{B g h^2 \left(1 - \frac{T_0}{T_1}\right) - h u_a^2}{b_0 \operatorname{sen} \propto_0}} \tag{5}$$

where B is a non-dimensional constant of proportionality assessed by experiments, g is the gravity acceleration, h is the height of the opening soffit above neutral plane, T_1 is the smoke temperature, u_a is the inflow velocity through the opening and $\propto_0$ is the angle between the curtain axis and the vertical plane. The absolute temperature of the hot fluid (T_1) is then calculated according to the equation (6). The final temperature dependence on C_{p1} requires an iterative solution.

$$T_1 = \frac{C_{p0}T_0}{C_{p1} - \frac{\dot{Q}_c}{\rho_0 T_0 \dot{V}_{exaust}}} \tag{6}$$

There are a number of methods that allow estimating the position of the neutral plane (eg, see [14]). The results of the experiments show that the flow near the jet is quite complex and that the neutral plane may be strongly disturbed.

The flow rate $\dot{V}_{jet}$ of the plane jet is given by equation (7):

$$\dot{V}_{jet} = 0.44(0.5\ b_0 x)^{0,5} u_0\ w \tag{7}$$

where x is the distance from the nozzle, b_0 is the thickness of the nozzle and w is the width of the nozzle (and of the door). The corresponding average velocity at the door u_{a_min} is given by equation (8), considering that the full length of the jet is limited by the floor, where H is the full height of the door.

$$u_{a\_min} = \frac{0.44}{(H \cos\propto)^{0.5}} (0.5\ b_0)^{0.5} u_0 \tag{8}$$

The thermal expansion $\dot{V}_{exaust} - \dot{V}_{door} = \dot{Q}_c / \rho_0 \overline{C_p} T_0$ was also calculated. Using this value, the ratio between total heat release rate and convective heat release rate may be assessed, according to equation (9).

$$\dot{Q}_c / \dot{Q} \quad = \frac{(\dot{V}_{exaust} - \dot{V}_{door}) \rho_0 \overline{C_p} T_0}{\dot{Q}} \tag{9}$$

2.2 Full-size experiments

In order to assess the smoke tightness of a full size air curtain, the compartment presented in figure 1 was built. The walls are done by gypsum board 10 mm thick. It is enclosed inside a hangar in order to avoid wind disturbances. Smoke is exhausted by a smoke fan from a 625 mm x 535 mm opening, located near the ceiling in the wall opposed to the door. The smoke fan is controlled by frequency and the exhaust volume flow rate at compartment exhaust opening was correlated by calibration with the displayed frequency. A thermocouple near the fan inlet and other thermocouple in the centre of the exhaust opening allow the correction of the exhaust volume flow rate due to heat losses that occur in the exhaust ducts between the compartment and the fan. The maximum capacity of the exhaust fan is 4.60 m^3/s.

The air curtain was suspended on outer side of the soffit of the door. The curtain fan is frequency controlled and flow velocity is continuously measured by a hot wire anemometer located at jet origin. The measurements of this anemometer were correlated with the average jet velocity by calibration. The curtain nozzle velocity is ranging from 12.6 m/s to 20.8 m/s.

Temperature inside the compartment is measured by 2 columns of 20 type J thermocouples and by 12 type K thermocouples glued to the wall surface. Three type K thermocouples are located at the lower face of the soffit. The smoke tightness at the door was assessed visually and by a rack of thermocouples in the symmetry plane of the door. The coordinates are presented at table 1. In this case the origin of x is placed in the outer surface of the wall that contains the door.

Table 1: Coordinates of thermocouples placed at the door

Thermocouple	8	9	10	11	12	13	14	15	16	17
x	149	203	215	230	242	251	257	261	292	289
y	1501	1700	1797	1848	1896	1950	1996	2050	2101	2137

A gasoline pool fire with a diameter of 720 mm was used as fire source. The area was varied in order to get lower heat release rate in some tests. The gasoline consumption was evaluated by weight variation and this method was calibrated by oxygen depletion. The centre of the pool fire is located at the point (2115; 3250) in the plane X0Z (see figure 1).

During tests the velocity of the curtain and the smoke exhaust velocity were reduced as much as possible with the objective of optimization of this technique. Figures 2 and 3 present the test compartment.

2. FULL-SIZE EXPERIMENTS RESULTS

3.1 Smoke tightness

To assess smoke tightness several combination of relevant parameters were made, and sixteen tests have been carried out. The studied parameters to achieve the smoke tightness were: heat release rate (in the range from 576 kW to 1206 kW), jet thickness (from 0.017 m to 0.045 m), jet velocity (from 8.3 m/s to 19.9 m/s), jet angle (from 18º to 26º) and exhaust flow rate (from 1.73 m^3/s to 4.60 m^3/s).

The smoke tightness was assessed by the analysis of the temperature measurements made at the door and also by visual analysis of the test. It was considered that thermocouples 8 to 17 were the most suitable for this analysis because the lower thermocouples (1 to 7) are placed in a zone where the eddies of smoke that get out of the plane of the door are driven again to the test compartment due to air admission at the door. Figure 4 presents the temperature measured by the thermocouple rack at the door in test 8 and similar results for a test (test 28) carried out in the same conditions but with the air curtain inactive (during the first 4 min) and also with the exhaust fan inactive (from minute 4:00 up to the end of the test). In the test 8 the measured heat release rate was 597 kW while in the test 28 was 632 kW. It is clear that the temperature at the door in test 8 is much lower than in test 28. The peak of temperature that can be seen at about 3:10 min is an eddy that drove the smoke through the door; thus it correspond to a loss of tightness. This occurred during the period where the velocity of the air curtain and exhaust fan were being optimized. Just in the period after this eddy the ventilation parameters (presented in table 2) were stabilized.

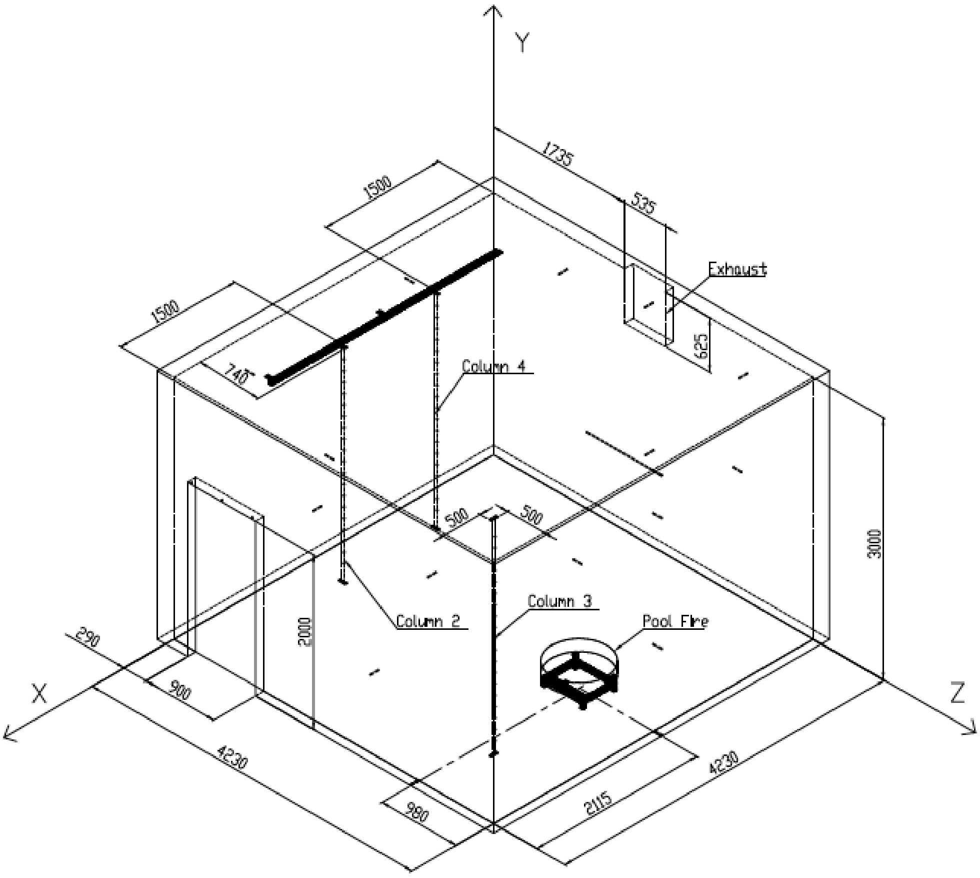

Figure 1: Full-size test compartment

The characteristic of the tests are presented in table 2. In some tests the air curtain was activated and stopped without change of any other parameter, in order to demonstrate that the air curtain is effective in the retention of the smoke. The results, shown in figure 5, demonstrate that is possible to use a plane jet to avoid smoke flow through a permanent opening.

The smoke temperature inside the compartment and the smoke depth were determined after the analysis of the temperature measurements inside the compartment. The considered smoke depth is the difference between the interface (cold/smoke layers) and the door soffit. It was considered the average temperature of the smoke. Further details about the criteria followed may be found at [15].

Figure 2: Perspective of the test compartment and view of the gasoline pool fire

Figure 3: View of the thermocouple columns inside the compartment

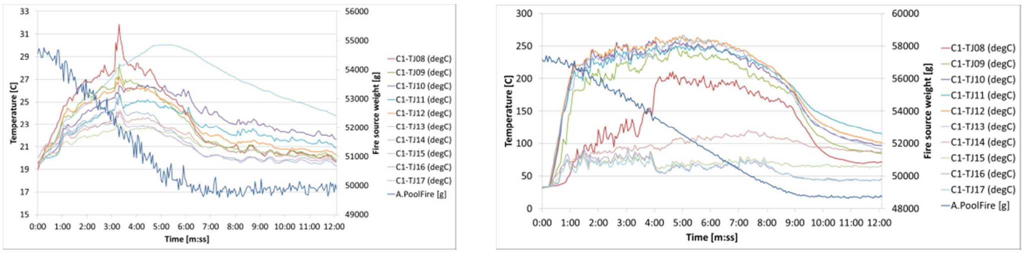

Figure 4: Smoke tightness at the door: comparison of test 8 with another test in the same conditions but with air curtain inactive

3.3 Pressure forces and exhaust flow rate

Table 3 shows the assessment of $\Delta P_a/\Delta P_s$, according to equation (3), using the test results. In the test 7 it is clear that the ratio $\Delta P_a/\Delta P_s$ is higher than for the other tests. This represents that the air curtain velocity and the exhaust flow rate were not optimized; therefore just the fifteen other tests are relevant to show the optimal adjustment of air curtain velocity and exhaust flow rate. For the relevant tests is obtained $0.37 \leq \Delta P_a/\Delta P_s \leq 2.50$. This value allows the calculation of u_0 , according to equation (3).

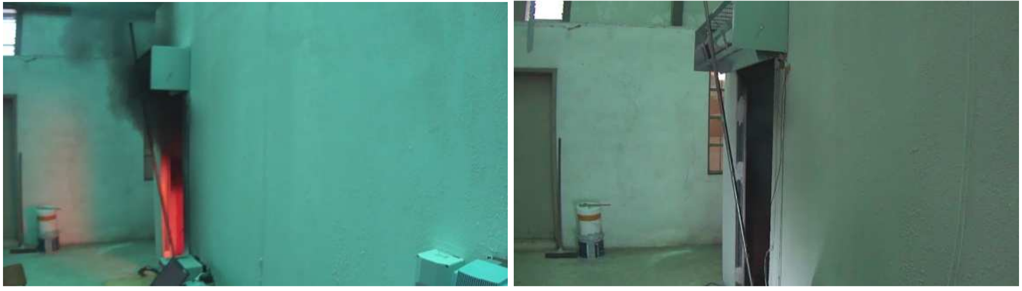

Figure 5: Full-size experiments. Non active air curtain (left) and active air curtain (right)

Table 2: Test results

Test number	Heat release rate [kW]	$\bar{T}_{smoke}$ [ºC]	$\bar{\rho}_{smoke}$ [kg/m³]	h [m]	$\dot{V}_{door}$ [m^3/s]	u_a [m/s]	$\dot{V}_{exaust}$ [m^3/s]	u_0 [m/s]	b_0 [m]	$\propto_0$ [º]
7	576	192	0.76	0.43	1.45	0.80	2.42	14.4	0.025	22
8	597	182	0.78	0.43	1.02	0.57	1.73	13.3	0.025	22
9	832	245	0.68	0.43	1.40	0.78	2.71	13.5	0.025	22
10	1116	260	0.66	0.43	1.62	0.90	3.14	12.8	0.025	22
11	1093	276	0.64	0.83	1.63	0.91	3.33	12.6	0.025	26
12	1188	250	0.68	0.83	1.64	0.91	3.22	13.0	0.025	18
13	656	208	0.74	0.83	1.33	0.74	2.33	15.2	0.025	18
14	1130	311	0.61	0.83	1.87	1.04	4.02	14.0	0.025	18
15	1193	270	0.65	0.83	1.75	0.97	3.52	8.3	0.025	18
16	1206	270	0.65	0.83	1.88	1.04	3.71	12.8	0.045	18
17	1143	338	0.58	0.83	1.71	0.95	3.66	19.9	0.017	18
18	1220	351	0.57	0.83	1.79	0.99	3.80	19.7	0.017	22
19	801	251	0.67	0.83	1.45	0.80	2.77	18.7	0.017	22
20	699	207	0.74	0.83	1.32	0.73	2.33	18.0	0.017	22
21	1116	293	0.62	0.83	1.85	1.03	3.85	13.2	0.045	22
22	1037	289	0.63	0.83	2.01	1.11	3.76	11.9	0.045	18

The flow rate $\dot{V}_{jet}$ of the plane jet is given by equation (7). The corresponding average velocity at the door u_{a_min} is given by equation (8). In Table 3 it is shown that $1.01 \leq u_a/u_{a_{min}} \leq 2.80$. The constant C of equation (4) may be assessed from these conditions. It is relevant to stress that a lower value of $\Delta P_a/\Delta P_s$ is associated with a higher value of u_a/u_{a_min} and *vice versa* (see figure 6). When the jet velocity u_0 is low it is necessary to increment the door velocity u_a to avoid the smoke flow to outside. When the jet velocity u_0 is higher it is possible to lower the door velocity u_a; but if the jet velocity u_0 is much higher, it is necessary to increment again the door velocity u_a in order to be compatible with the higher flow rate entrained by jet into the compartment. Figure 6 shows the linear fit for the four best results of these tests, which were considered to be optimized. It is clear that there are some results (yellow marks) that are considered to be in the limit of the tightness that are above the trend line. Moreover, there are some test results, where was not possible to reach the smoke tightness, which are very close to this line. This clearly shows that, for design purposes, a safety coefficient shall be used when this trend line is considered the limit of the smoke tightness. Further work shall be developed in order to find a more accurate definition of the thickness and average temperature of the smoke layer.

Table 3: Test analysis

Test number	$\Delta P_a/\Delta P_s$	u_{a_min} [m/s]	u_a/u_{a_min}	$\dot{Q}_c/\dot{Q}$	$\dot{V}_{exaust} - \dot{V}_{door}$ [m^3/s]	Smoke tighteness
7	3.05	0.61	1.32	0.61	0.97	yes
8	2.50	0.56	1.01	0.43	0.70	yes
9	2.28	0.57	1.36	0.57	1.30	yes
10	2.06	0.54	1.66	0.49	1.51	yes
11	0.69	0.54	1.68	0.56	1.69	no
12	0.60	0.54	1.67	0.48	1.58	yes
13	0.76	0.64	1.16	0.55	1.00	yes
14	0.65	0.59	1.77	0.69	2.15	limit
15	0.37	0.35	2.80	0.54	1.77	no
16	0.91	0.76	1.37	0.55	1.83	yes
17	0.73	0.67	1.43	0.62	1.95	no
18	0.85	0.67	1.49	0.60	2.01	limit
19	0.84	0.63	1.27	0.60	1.32	yes
20	0.86	0.61	1.20	0.52	1.01	yes
21	1.06	0.79	1.30	0.65	2.00	yes
22	0.89	0.71	1.58	0.61	1.75	yes

The thermal expansion $\dot{V}_{\mathrm{exaust}} - \dot{V}_{\mathrm{door}} = \dot{Q}_c/\rho_0\overline{C_p}T_0$ was calculated and is shown in Table 3. Using this value, the ratio between total heat release rate and convective heat release rate may be assessed, according to equation (9). It is shown that for these tests $0.43 \leq \dot{Q}_c/\dot{Q} \leq 0.69$, that agrees with common values accepted for convective fraction of heat release rate. These values allow the estimation of the range where the parameters relevant for the calculation of an air curtain for smoke retention (namely u_0 , u_a and $\dot{V}_{\mathrm{exaust}}$) shall lay.

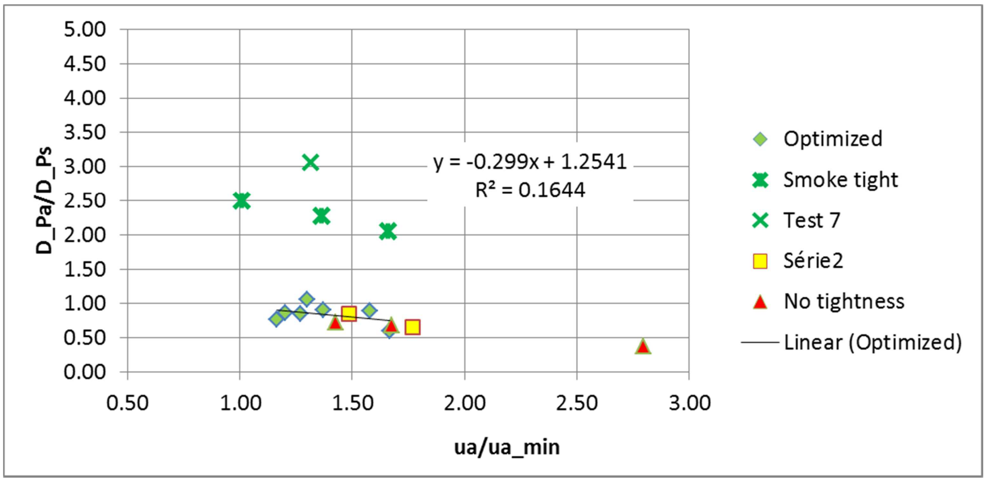

Figure 6: Association of variables $\Delta P_a/\Delta P_s$ and u_a/u_{a_min}

4. CONCLUSIONS

The results obtained show that it is feasible to restrict the flow of smoke to inside of the enclosure using a plane jet of cold air at the opening (air curtain). The experiments showed that the existence of the plane jet is critical to smoke-tightness of the opening because when it is too weak the smoke tightness fails. Thus, the results of the experiments demonstrate the feasibility of the use of air curtains for smoke control. According to this analysis, the limit of the smoke tightness correspond to the equation $\Delta P_a/\Delta P_s = -0.30\ u_a/u_{a_{min}} + 1.25$ (with $1.30 \leq u_a/u_{a_{min}} \leq 1.67$).

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