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Experimental study of the effectiveness of air curtains of variable width and injection angle to block fire-induced smoke in a tunnel configuration

Long-Xing Yu[a,b], Fang Liu[a,*], Tarek Beji[b], Miao-Cheng Weng[a,**], Bart Merci[b]

[a] *Chongqing University, Faculty of Urban Construction and Environmental Engineering, Chongqing, China*
[b] *Ghent University – UGent, Dept. of Flow, Heat and Combustion Mechanics, Ghent, Belgium*

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ABSTRACT

Small-scale experiments have been conducted to study the sealing effect of an air curtain for fire-induced smoke confinement in a tunnel configuration. The processed data confirmed the results obtained earlier from blind Computational Fluid Dynamics (CFD) simulations [1] using the Fire Dynamics Simulator (FDS) 6.5.3 [2,3]. Furthermore, the CFD simulations provided complementary information on the detailed flow and temperature fields which are difficult to obtain in experiments with the available techniques. A parametric study is performed, covering a range of air curtain velocities, slot widths, injection angles and total fire heat release rates (HRRs). The momentum ratio R, defined as the ratio of the vertically downward air curtain momentum to the horizontal smoke layer momentum at the position of the air curtain, is confirmed to be a key parameter for the air curtain performance. A ratio $R \approx 10$ is recommended for the optimum sealing effect in terms of smoke confinement. In addition, two other important parameters that determine the performance of air curtains for smoke confinement are presented. The first parameter is the dimensionless shape factor AR (AR = Width/Length) that characterizes the dilution effect of the air curtain jet. The second parameter is the injection angle θ that characterizes the horizontal force of the air curtain. The air curtain sealing effectiveness increases with both the increase of slot width (shape factor AR) and injection angle (θ). The air curtain width has a limited influence on the performance of the air curtain whilst the injection angle has a more significant influence on the sealing effectiveness of the air curtain for the scenarios considered in this study. An optimal injection angle of 30° inclined to the fire source is recommended in the engineering design of the air curtain for smoke confinement for situations where the fire location can be pre-determined to be only at one side of an air curtain.

1. Introduction

It is well-known that smoke is the most fatal factor in fires, and about 85% of people killed in building fires were killed by toxic smoke [4,5]. Smoke and heat control systems are an essential part of fire protection in the fire safety design of buildings. In the event of a fire, the air curtains (in various building configurations) have been proven to be effective in smoke confinement. The main advantage of such virtual screens, compared to the traditional fire doors, is the easy evacuation of people while still limiting smoke and heat transfer through the opening [6].

Air curtains based on the push-pull system have been shown to be effective in preventing suffocation caused by smoke during evacuation in a corridor [7]. Hu et al. [8] also reported, by means of small-scale experiments and numerical simulations obtained with the code Fire Dynamics Simulator [2,3] (FDS, Version 4.0.7), that the single-jet air curtain can be an effective way for smoke and CO confinement in channel fires. Also the Computational Fluid Dynamics (CFD) code FLUENT has been used for investigating air curtain flows numerically. Ji et al. [9] carried out a theoretical analysis and FLUENT simulations of smoke control by means of an air curtain in long channels and developed formulas providing the critical conditions to prevent smoke from intruding the protected side. Krajewski and Węgrzyński [10] studied the use of air curtains in fire safety as a barrier for heat and smoke by means of bench experiments and FLUENT (version 13.0). Again, they confirmed the potential use of air curtains as a tool for fire safety in buildings. Their work also shows the possibilities of CFD (Ansys Fluent) in designing air curtains used in fire safety engineering. The capabilities of FDS was also studied in Refs. [11,12]. In addition, the influence of various parameters on the performance of an air curtain

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[*] Corresponding author. Chongqing University, Shapingba District, 400045, PR China.
[**] Corresponding author. Chongqing University, Shapingba District, 400045, PR China.
E-mail addresses: drliufang@126.com (F. Liu), mcweng@outlook.com (M.-C. Weng).

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is reported in Ref. [10]. However, the result is based on the assumption that the only important destabilizing factor for the air curtain is the uniform pressure difference. Besides tunnel and corridor-like configurations, air curtains were installed and tested at the entrance of a stairwell [13] and an evacuation passageway [14].

In a nutshell, all the studies mentioned above indicate that air curtains can be useful for confinement of smoke during a fire. Nevertheless, to the best of our knowledge, the only real case where an air curtain has been actually installed is in a road tunnel called the A86 West Underground Link-up of Paris, in France [15]. However, there is no data indicating how such systems should be designed [16] to optimize their efficiency. For example, there is a lack of information on the appropriate jet properties in terms of discharge velocity, injection angle and slot width. Therefore, it is of great important to study the sealing effectiveness and the main parameters that affect the performance of air curtains for smoke blocking.

It is interesting though to note that there have been studies on the design of air curtains in various applications such as energy savings [17], comfort ventilation [18] and air pollution control [19], but none of them is intended to stop smoke spread in the event of a fire. The air curtain design method discussed in Refs. [20,21] and based on the free jet theory under the assumption of uniform transversal pressure difference is not suitable for a fire.

In the specific context of a fire, the transverse force of the ceiling jet destabilizing the air curtain is much stronger than the natural convection flow in the other applications. In fact, in the numerical study carried out in Ref. [1] by means of CFD, the sealing effect (i.e., propensity to block smoke spread) of an air curtain in a tunnel configuration is found to be dependent on the ratio, R, of the vertically downward air curtain momentum to the horizontal smoke layer momentum at the position of the air curtain. More specifically, the maximum sealing effectiveness is obtained for values of R between 8 and 10 [1].

The simulations carried out in Ref. [1] were blind in that no experimental data were available to confirm the validity of the results. In the present work, we present data from 90 small-scale experimental tests with complementary information obtained from CFD (more specifically, FDS [22]) on the detailed flow field in order to characterize the ceiling jet. Moreover, we focus on the specific effects of the air curtain width and injection angle, which has not been discussed before.

2. Experimental set-up

Reduced-scale experiments have been carried out to examine the influence of the jet properties on the sealing effect of the air curtain. Details of the experiments are described hereafter, including the experimental apparatus, fire source and air curtain set-up, instrumentation, experimental schemes and procedure and data processing.

2.1. The experimental apparatus

Fig. 1 shows the reduced-scale model (3.00 m long, 0.32 m wide and 0.48 m high) used in this work. The model simulated a fire within a ‘corridor-like’ (or ‘tunnel-like’) compartment and the smoke propagating along the evacuation passageway. The entry and exit of the ‘tunnel-like’ enclosure are open to the outside. An air curtain was installed at the ceiling (see Fig. 1) to block smoke spread to the downstream region. The tunnel (floor, ceiling and the frame) was constructed from 1.25 mm thick stainless steel. For visualization, the front and back faces of the tunnel were constructed from 5 mm thick anti-fire glass.

2.2. The fire source

A Liquefied Petroleum Gas (LPG) gas burner with active flow control was employed to model a burning object. The diameter of the fire source is 16 cm with small nozzles scattered on the fire surface. The fire source is located on the floor at 0.5 m away from the left opening of the fire compartment. Details of the positions are shown in section 2.4. The main advantage of using a gas burner is the easily controllable heat release rate, via a fuel flow controller. The total heat release rate ($\dot{Q}$) of the fire was determined from the heat of combustion (per unit volume) of the fuel (ΔH_c) and the volume flow rate of the fuel ($\dot{V}$), assuming a combustion efficiency (χ) of 100% [23–25]:

$$\dot{Q} = \chi \cdot \Delta H_c \cdot \dot{V} \tag{1}$$

The heat of combustion of LPG (57.55 MJ/m^3) was measured by the water flow calorimeter. Two fires with HRRs of 3.62 kW and 2.92 kW were considered. Based on Froude scaling ($\dot{Q}_m/\dot{Q}_f = (L_m/L_f)^{5/2} = \lambda_L{}^{5/2}$, where the subscripts m and f respresent respectively the reduced-scale model and the full scale and L is a representative dimension of the set-up) the corresponding full-scale HRRs are 3.2 MW and 2.5 MW, considering a geometrical scale-up factor of 15. Fig. 2 shows the porous gas burner (household type) and LPG flames used in this work.

2.3. The air curtain

As shown in Fig. 1, an axial fan was used to supply the air. The fan speed was controlled by the velocity controller (variable frequency drive, VFD). A plenum chamber was used to equalise the pressure for a more even distribution of velocity at the air curtain outlet.

Different air curtain slots were constructed beforehand in order to be tested in the experiments. Three air curtain widths (W = 1 cm, 2 cm and 3 cm) were considered. A zoom-in photo of air curtain slot used in the experiment is shown in Fig. 1.

The air curtain velocities at different setting numbers of velocity controller (variable frequency drive, VFD), e.g., at 10, 20, 30, 40, 50 Hz, were measured by anemometer sensors (SWA 03 +, omnidirectional probes) before the experiment. Four positions (at 1/5, 2/5, 3/5 and 4/5) across the length of the air curtain (in the centreline of the outlet) were measured. The measurement was repeated twice for each test. An average value was used as the maximal mean velocity of the air curtain along the centreline of the outlet. The velocity data is presented in Table 1.

Fig. 3 displays the variation of the air curtain momentum ($\rho_j A_j V_j{}^2$) and mass flow rate ($\rho_j A_j V_j$) with different slot widths as a function of the fan frequency for several fire HRRs and slot widths. The air density (ρ_j) is calculated based on the measured ambient temperature of each test shown in Table 1. The average velocity of the air curtain slot (V_j) is calculated based on the measured maximum velocity at the center and the power-law velocity profile [26] for fully turbulent flow from a slot.

The results displayed in Fig. 3, on the left, show that the air curtain momentum varies only with the fan frequency (and thus the fan power). For a fixed frequency, there is no variation in momentum with the HRR or the slot width, which confirms the accuracy and repeatability of the measured velocity data.

The results displayed in Fig. 4, on the right, show that, for a fixed fan frequency (and thus fixed momentum), the mass flow rate decreases as the slot width decreases. This effect will be discussed in more detail in section 4.

2.4. Instrumentation

The main quantity recorded for the present experiment is the gas temperature. The temperature measuring system consists of 87 thermocouples and a data logging system. The thermocouples were arranged to measure both the longitudinal smoke temperature distribution along the test section and the vertical temperature distribution of the smoke layer. In order to better capture the temperature gradients close to the boundaries, more thermocouples were positioned near the ceiling and floor (with a narrow spacing) along the height of the tunnel.

K-type bare-bead thermocouples (Nickel-Chromium/Nickel-silicon) with a diameter of 0.5 mm, a response time of less than 1 s and a