# Effect of human walking on air curtain sealing in the doorway of an airtight building

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## ABSTRACT

Heat and mass flow between cold and warm environments due to the pressure difference between both sides. This exchange causes a loss of energy and human comfort in the buildings. The indoor air quality (IAQ) also reduces because of the passage of dust, odour, insects and bacteria along with the fluid across a doorway. To minimise this heat and mass flux and to maintain IAQ, an air curtain is often used as an artificial separation barrier in public and industrial buildings. Its performance is determined by the sealing effectiveness, defined as the fraction of the exchange flow prevented by the air curtain compared to the open doorway. The controlling parameter for the air curtain is the deflection modulus ($D_m$), which is the ratio of the momentum flux of the air curtain and the transverse forces acting on it due to the stack effect. Although air curtains are used to facilitate the human and the vehicle passage through doorways, the effect of the traffic on the stability and the effectiveness of an air curtain has not yet been studied. In the present study, we conduct laboratory experiments to examine the effect of a person passing through the curtain. The experiments were conducted using fresh water and salt solutions, with dimensions such that they were dynamically similar to the real-scale air curtains installations in the doorways of a building. We find that the effectiveness is decreased by the passage of a person and that the effect increases with the increasing walking speed. We visualised the jet and the wake using dyes of different colours to determine how the air curtain is deflected by the passage of a person.

## KEYWORDS

Air curtain, human passage, effectiveness

## 1 INTRODUCTION

Fluid exchange occurs through open doorways connecting warm and cold environments. It is driven by the stack effect caused by a temperature difference, a wind force or a pressure difference. The fluid transfer also involves the heat and moisture transport, which increases the energy consumption, and also carries substances such as insects, dust, fumes, bacteria, pollutants, which all negatively affect the indoor air quality.

Traditionally, the fluid exchange is reduced using mechanical installations like hinged or sliding doors, vestibules or plastic strip curtains. However, mechanical installations impede the human or vehicle traffic and restrict an easy passage, which can cause problems in the case of an emergency evacuation. Another way to separate the cold and warm environment without affecting the traffic flow is to install an air curtain across the doorway. An air curtain is basically a turbulent jet, which is produced by a fan and is discharged through a nozzle either horizontally or vertically. It can have different design configurations like drawing its primary air supply from either the cold or the warm environment, further being heated or cooled, being discharged at an angle towards the warm or the cold side, or using a recirculation mechanism.

The study of air curtains was started by a patent by *Van Kennel* in 1904 (cf. *Foster 2007*). *Hayes and Stoecker (1969a, b)* first carried out a systematic investigation of air curtains. They developed theoretical models, compared them with the experimental measurements and found the agreement satisfactory. The stability of an air curtain depends on the deflection modulus, which is defined as the ratio of the initial momentum flux and the transverse forces due to the stack effect as shown in equation 1. Here, $\rho_0$, $T_0$, $b_0$ and $u_0$ is the density, temperature, width and the velocity of the curtain at nozzle exit, respectively. The height of the doorway is denoted by $h_b$ and $g$ is the acceleration due to gravity. The subscripts $d$ and $l$ correspond to the properties of dense and light fluid, respectively.

$$D_m = \frac{\rho_0 b_0 u_0^2}{\mathrm{gh_b^2}(\rho_d - \rho_l)} = \frac{b_0 u_0^2}{\mathrm{gh_b^2}\left({}^{T_0}/_{T_d} - {}^{T_0}/_{T_l}\right)} \tag{1}$$

$$E = \frac{Q_{0pen} - Q_a}{Q_{0pen}} \tag{2}$$

Another important parameter is the effectiveness ($E$), which describes the sealing ability of an air curtain and is defined as the ratio of the volume flow rate stopped by the air curtain and the volume flow rate through an unprotected doorway. This can be expressed as the difference between the volume flow rate through the doorway in the presence of an air curtain ($Q_a$) and the reference value for the open-door situation ($Q_{open}$) when the air curtain is absent, divided by the reference value ($Q_{open}$) as defined in equation 2.

*Guyonnaud et al. (2000)* demonstrated differences between the *Hayes and Stoecker (1969a)* and *Lajos and Preszler (1975)* model. They showed, that knowing the height of the air curtain, jet thickness and jet velocity was not sufficient to completely describe the fluid mechanics of the air curtain. The convection of jet vortices and the height of the impinging zone also affect the effectiveness of the curtain. Later, *Sirén (2003a,b)* presented an overview of possible methods for the technical dimensioning of an upwards blowing air curtain, using momentum balance and moment-of-momentum balance principles.

Full-scale experiments have been carried out for a sealed room with a single opening by *Foster et al. (2006)*, and laboratory scale experiments with multiple openings and with a buoyant curtain have been performed by *Frank & Linden (2014)* and *Frank & Linden (2015)*. There have also been various numerical studies on the performance of air curtains (*Costa, Oliveira & Silva 2006; Foster et al. 2006*) which have shown a good agreement with the experimental data. There have also been some recent studies on the behaviour of air curtains subjected to transversal pressure variations (*Rouaud 2002, Rouaud & Havet 2006*), or when a person is standing in the doorway (*Lu & Fernandez 2008*). However, there remain issues and open questions about the behaviour of an air curtain when a person walks through it, and how this process can affect the air curtain effectiveness. The aim of the present study is to determine how the passage of a person through an air curtain affects its stability and effectiveness.

## 2 EXPERIMENTAL METHODS

Experiments were conducted with water and salt solutions and parameters were chosen such that they were dynamically similar to the real-scale air curtain installations. The kinematic viscosity of water is fifteen times lower as compared to air and thus the length scale can be lowered by a factor of 15 while maintaining the same Reynolds number. Such a substantial reduction in the length scale allowed us to conduct table-top experiments as presented in figure 1.

Experiments were carried out in a Perspex water tank of dimension of 2m X 0.2m X 0.25m. The tank was divided in two equal compartments by a removable vertical gate: one side was filled with fresh water of density $\rho_l$ and the other side with a salt solution of density $\rho_d$. An air curtain device was placed in the fresh waterside of the tank. The water of density $\rho_0$ was supplied to the curtain from a constant gravity head tank and a valve & a flow meter, which are connected in the supply line, controlled the flow. We used a cylinder pulled at a constant speed by a motor through the air curtain to represent the human walking. The dimensions of the cylinder were chosen such that the process was similar to the real-scale human passage. The speed of the cylinder was varied by a motor controller. For flow visualisations, blue dye was injected in the middle of the air curtain device just below the source. The trajectory of the axis of the cylinder was below this dye injection point. Another red colour dye port was connected at the front stagnation point of the cylinder to visualise the cylinder wake and entrainment. The experimental setup is shown schematically in figure1.

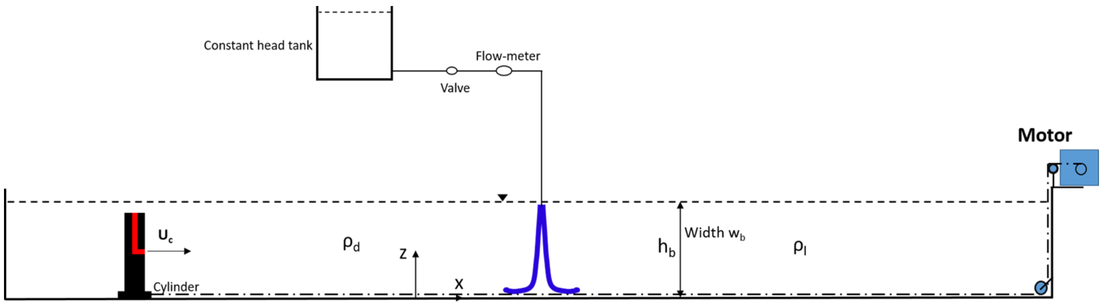


Figure 1: Schematic is showing the gravity current tank with the supply system for the curtain. The cylinder is connected to the motor by a system of pulleys and a flexible thread. The curtain and the cylinder wake are tracked by the blue and red coloured dye, respectively. Supply to the curtain is connected by a valve and a flow meter. Blue coloured jet is separating dense and light environments of density $\rho_d$ and $\rho_l$ .

Experiments were started by measuring the densities $\rho_l$, $\rho_d$ and $\rho_0$ using the Anton-Paar density meter (DMA 5000) with an accuracy of $10^{-5}$ g/cm$^3$. In the present study, the fluid supplied to the curtain was fresh water, so that $\rho_0 = \rho_l$. The flow rate through the curtain was measured using the Omega flow meter (FLR1013) and maintained constant to be about 5 litres per minute (LPM) with an accuracy of ±3% of full scale. Before the start of the experiment, the water level in the fresh water side with the air curtain device was slightly lower than in the saltwater side. We started the experimented by switching on the flow through the curtain device. Once the flow in the curtain was stabilised and the water level in both sides were equal, we removed the separating gate between the fresh and salt water compartments. Blue and red dye port were opened and the cylinder was dragged at a constant velocity ($U_c$). The separation gate was closed once the cylinder reached the opposite side and the curtain was immediately switched off. Subsequently, we thoroughly mixed the fluid in both sides and measured the new densities in both sides as $\rho_{l,new}$ and $\rho_{d,new}$.

Experiments were carried out for different density differences by changing the density of salt water to vary the deflection modulus ($D_m$). We calculated the entrained volume and the effectiveness from the measured densities. Nikon D3300 was used to capture the colour top and the side-view videos of the experiment at 24 fps. It was used to qualitatively comment on the infiltration, which will help in explaining the observed trend of the effectiveness-deflection modulus curve for different cases.

## 3 RESULTS

In this section, we discuss the effect of the human passage on the effectiveness of an air curtain as shown in figure 2. For the base case without a cylinder, the effectiveness first increases with the deflection modulus ($D_m$) until it reaches a maximum value and then starts to decrease again. The maximum effectiveness is about 0.8, which is similar to the previously observed value by *Frank & Linden (2015)*. At this point, the curtain is stable and reaches the bottom of the tank. With further increase in $D_m$, the effectiveness reduces because of the increased mixing in the curtain by the jet entrainment and the impingement.

The cylinder was pulled from the dense fluid to the light fluid side in the present study. As seen in figure 2, the effectiveness of the curtain reduces with the passage of the cylinder and the air curtain becomes progressively less effective for higher cylinder speeds. This reduction in the effectiveness is more prominent at higher deflection modulus values. In the present study, the deflection modulus is varied by changing the density difference while maintaining the same curtain momentum flux. The fluid exchange for the case of a switched-off air curtain device ($Q_{open}$) at higher deflection modulus values is relatively small because of a small density difference. However, the entrained volume by the cylinder ($Q_{cyl}$) is almost constant in all cases as the cylinder velocity is an order of magnitude higher than the gravity current speed. Thus, the influence of the cylinder passage on the effectiveness ($E_{new} = E_{base} - Q_{cyl}/Q_{open}$) increases with the increasing deflection modulus.

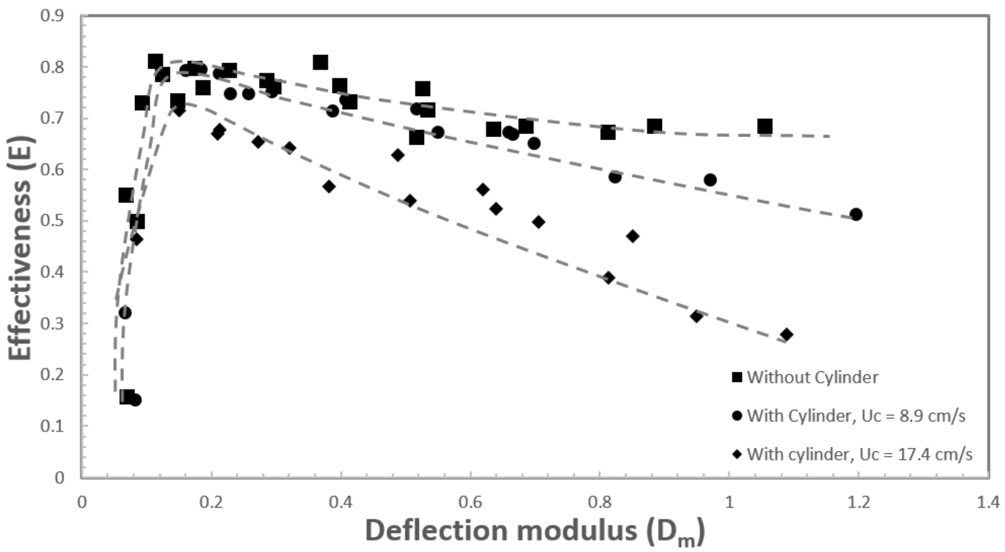


Figure 1: Figure shows the effect of human walking and their speed on the effectiveness of an air curtain. Effectiveness is shown for the cases with and without human/cylinder passage.

At smaller deflection modulus values, the curtain does not reach the bottom of the tank and thus, the cylinder does not have any noticeable effect on the effectiveness. For the deflection modulus values close to $D_{m,max}$, the impact of the cylinder passage on the effectiveness is noticeable: the effectiveness is reduced by 10% at the maximum cylinder velocity. As the deflection modulus increases, the effectiveness further decreases and at $D_m$ higher than 1, the effectiveness reduces by about 25% compared to the base case for Uc=8.9 cm/s, and by more than 100% for $U_c$ =17.4 cm/s.

Dye visualisations have also been performed to qualitatively study the infiltration by the passage of the cylinder. The blue colour dye was injected at the nozzle exit to track the curtain. In figure 3 (a), the curtain is shown for $D_m$ of 0.4 when it is undisturbed and the cylinder is far away from the curtain. The jet impinges at the tank bottom and is distributed between both sides of the tank. The cylinder wake and, hence, the entrained dense fluid are visualised using the red dye. The cylinder travels from the dense to the light fluid side as marked by a white arrow in figure 3(b). The interaction can be observed in the figure when the cylinder is just below the curtain. The curtain is blocked by the cylinder passage and the cylinder is followed by a trailing red wake. As the cylinder passes the curtain, the jet is still unestablished and an unhindered fluid exchange between both sides is possible. The fluid flows from the dense fluid to the light fluid side due to the combined effect of the gravity current and the cylinder wake. In figure 3(c), we can see this infiltration while the jet is gradually re-establishing: after the passage of the cylinder, the jet starts to re-establish by penetrating the wake. The jet in the established region starts acting as a separation barrier and thus the available exchange area reduces with time. The time for which the unhindered exchange after the cylinder passage can take place depends on the jet velocity and the opposing force by the cylinder wake and the gravity current. For lower cylinder speeds, the curtain re-establishes faster. The infiltration is lower at lower cylinder speeds because of a lower re-establishment time and a lower infiltration or wake velocity. This is in line with the integral measurement of the effectiveness (figure 2), where the reduction in the effectiveness is lower for a lower cylinder speed. The curtain reaches the bottom of the tank in figure 3d and, as a result, the exchange by the wake is almost stopped.

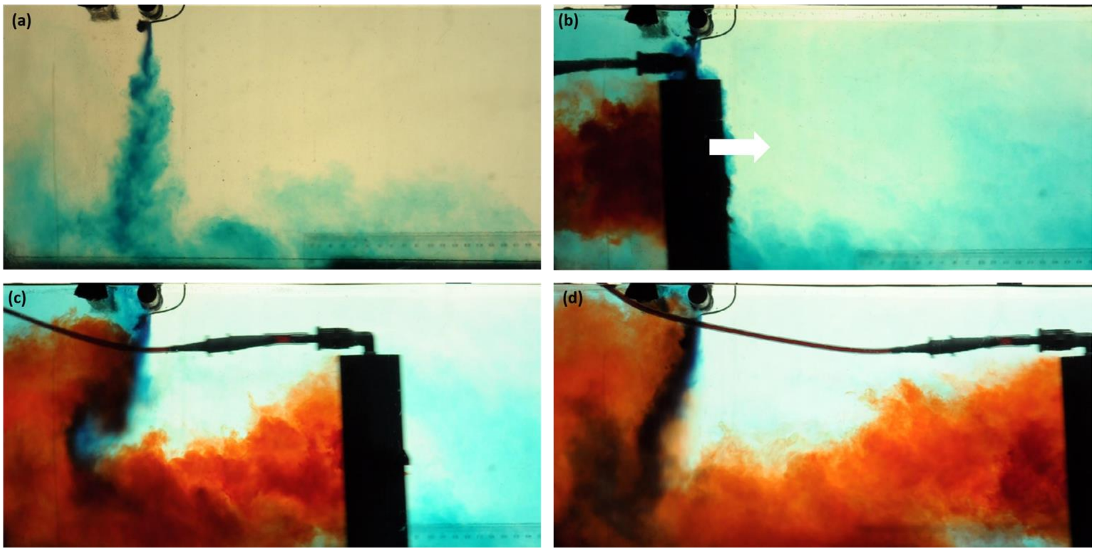


Figure 3: Dye visualisation of the temporal evolution of air curtain and entrainment in human wake is shown from side view. Cylinder is moving from the dense fluid to the light fluid side of the doorways and from left to right in the image as marked in (b). Infiltration across the curtain can be seen in (c).

To gain the three-dimensional perspective of the interaction, we also recorded the top view of the process. In the top view, we see the averaged effect in the vertical direction. In the present study, a classical cylinder wake cannot be expected as the cylinder is not dragged in a quiescent environment. As seen in figure 4, the wake expands radially outwards as it moves further away from the cylinder. Thus, the exchange width will also increase with time, which will cause increased infiltration along the nozzle length.

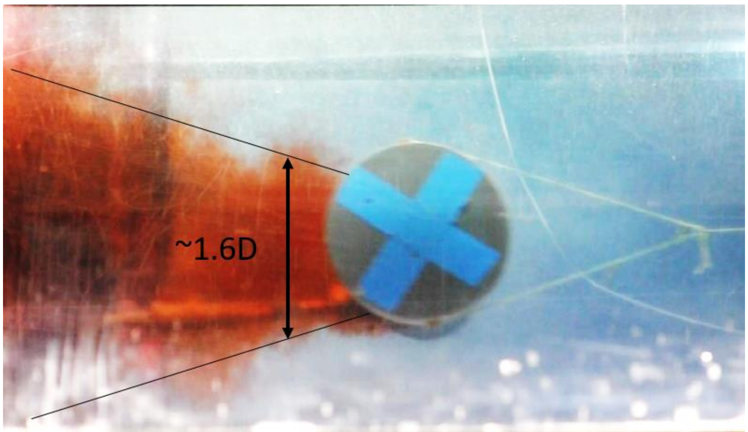


Figure 2: Dye visualisation of the top view of curtain and cylinder wake interaction. Wake expands in radially outward direction away from the cylinder. Image is captured from the bottom and cylinder base is cross marked with blue tape which has 60% larger diameter than cylinder and is 8 mm thick.

## 4 CONCLUSIONS

We conducted an experimental study to examine the effect of an object passing through an air curtain on its sealing effectiveness. We measured the flow rate through and the density across the doorway with and without the air curtain to calculate the deflection modulus and the effectiveness of the air curtain. We found that the effectiveness is decreased by the passage of a person and that the reduction in effectiveness increases with an increasing walking speed. We visualised the jet and wake using dye to determine how the air curtain is deflected by the passage of a person. Top and side view of dye visualization of jet and wake show that the infiltration of fluid carried in the wake of the person is the reason for the reduction in the curtain effectiveness and that the air curtain takes longer to re-establish at higher walking speeds. The wake width and thus the infiltration in span-wise direction increases with increasing time after the cylinder passage. In the present study, we also observed that the effect is independent of the direction of travel, a result of the relatively fast walking speed compared with the stack-driven exchange flow under normal circumstances. Our study shows that the human or vehicle traffic reduces the effectiveness. To minimize the exchange, we suggest a pause of traffic before the air curtain and then passage across the air curtain with greatly reduced velocity. One other way to reduce the entrainment is to take a 90 degree turn at the entrance. Higher jet velocity reduces the establishment time, which will also help in minimising the entrainment across the curtain.

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