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THE EFFECTS OF HEADWIND ON BUOYANCY-DRIVEN FLOW THROUGH A DOORWAY

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SUMMARY

Wind speeds are often comparable to air speeds through doorways produced by temperature differences. It might be expected that the wind has significant effects on the buoyancy-driven flow, thus affecting the ventilation within the interior. This paper investigates single-sided ventilation produced by buoyancy-driven flow through a doorway under the influence of headwinds of different magnitude.

Small-scale laboratory experiments are conducted using brine and fresh water to produce density differences between different regions of fluid. A tank with rectangular cross-section is suspended in a much larger flume tank. This rectangular geometry, which represents a corridor, was chosen as it is the simplest possible, with flows being close to two-dimensional. The flume produces a time-independent, uniform flow along its length, which can be used to model a steady headwind on the doorway. The experiments showed that the flow within the corridor varied markedly with the relative sizes of wind-drven and buoyancy-driven velocities.

Three basic flow régimes are described. Models are described which correspond well with experimental data. The implications for the control of air-quality and ventilation in the corridor are discussed.

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INTRODUCTION

The nature and strength of airflow through doorways due to temperature differences between inside and outside has received a good deal of attention due to the new-found popularity of natural ventilation as an alternative to air conditioning. Buoyancy-driven flow through a doorway and down a long corridor has been extensively studied by Lane-Serff, Linden and Simpson [1]. Earlier experimental work on buoyancy-driven flow through openings was carried out by Brown and Solvason [2], amongst others. The incoming air flows through the doorway and then takes the form of a gravity current flowing either along the floor or the ceiling depending on whether the external air is colder or warmer than that in the corridor. The dynamics of gravity currents are well-known and are described by Benjamin [3] and Simpson [4], for example.

This paper describes the transient flow of this gravity current, with an additional forcing provided by a headwind on the open end of the corridor. The end of the corridor is sealed and the ventilation is single-sided. Thermal exchanges with the walls of the corridor are ignored. Air speeds through a typical doorway due to a temperature difference of 5°C are of the order of 0.5ms^{-1}. Wind speeds are often of this magnitude or greater and therefore it might be expected that the effects of wind on the buoyancy-driven flow may be considerable. Indeed, it is not obvious that a gravity current model will be appropriate when wind effects are significant. The relative sizes of the wind and buoyancy produced velocities are measured by an external Froude number defined by

$$Fr = \frac{U}{(g'H)^{1/2}}, \qquad (1)$$

where U is the uniform wind velocity incident normal to the doorway. The height of the doorway is H and g' is the reduced gravitional acceleration given by $g' = g\Delta\rho/\rho$, where g is gravitational acceleration and $\Delta\rho/\rho$ is the initial fractional density difference between inside and out. The gravity current velocity scales with $(g'H)^{1/2}$ and so the Froude number defined by (1) gives the ratio of the wind speed to that of the buoyancy-driven flow. In the Froude number zero case, there is a two-layer hydraulic exchange flow through the doorway, as illustrated in Figure 1, and theoretical predictions, as in Benjamin [3], give that the velocity u_{gc} of the gravity current is constant and given by

$$u_{gc} = 0.5\,(g'H)^{1/2}. \qquad (2)$$

Furthermore, the gravity current height of the gravity current is $0.5H$. In this case, the flux Q_{gc} of dense air entering the corridor is just $0.5Au_{gc}$, where A is the area of the doorway. It should be noted that these theoretical predictions assume that there is no energy loss in the flow. In practice, Lane-Serff, Linden and Simpson [1], found u_{gc} to be around $0.47(g'H)^{1/2}$.

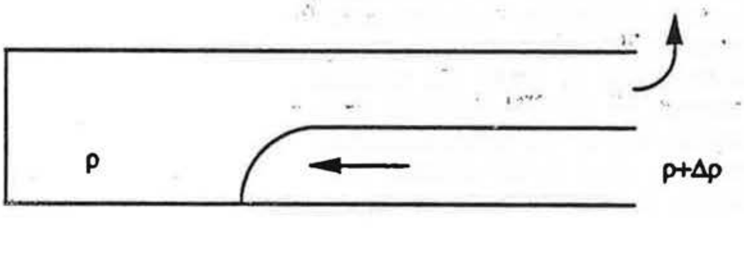

Figure 1. Classical gravity current flowing into a corridor at $Fr = 0$.

This study involved an experimental investigation of the qualitative and quantitative nature of the observed flows over a wide range of Froude numbers between 0 and 11.4. A theoretical model is described in the high Froude number case as well as the low Froude number case.

The corridor used for the experiments had a rectangular cross-section, with a doorway at one end occupying the full cross-section of the corridor. This geometry was chosen as it is the simplest possible with flows being close to two-dimensional. The open end of the corridor was directed upwind and hence the flow modelled was that of a single-sided ventilation of the corridor under the influence of a headwind.

EXPERIMENTS AND DYNAMICAL SIMILARITY

Dynamical similarity

The important dimensionless parameters associated with the buoyancy-driven airflow through an opening are the Reynolds and Péclet numbers defined by

$$Re = \frac{UH}{\nu},$$

and

$$P\acute{e} = \frac{UH}{\kappa},$$

where ν is the kinematic viscosity of air and κ is the diffusivity of heat in air. The flows described here have Reynolds and Péclet numbers typically in the region of several thousand. At such large values the nature of the flow is expected to be independent of Re and $P\acute{e}$. This means that provided we maintain Re and $P\acute{e}$ at sufficiently high values, we can use scale models to represent these flows. The experiments used water as the working fluid and density differences were produced by adding salt.

Experiments

The corridor was modelled by a clear perspex tank with rectangular cross-section. One end of the corridor had a removable cover to represent a door at the upwind end of the corridor. The flow into the interior was initiated by the removal of this cover. The corridor was suspended in a much larger flume tank, as in Figure 2. The flume produces a time-independent, uniform flow along its length, which can be used to model a steady headwind on the doorway. The corridor was suspended at an intermediate depth so that the oncoming flow was uniform over the doorway. Care was taken to ensure that the doorway was normal to the oncoming flow.

The flow was visualized by dyeing the initial interior fluid with red food colouring and lighting the apparatus from behind. The experiments were recorded on video camera. Measurements of the position of the front of the gravity current were made from the video using a built-in stopwatch. The video gave good qualitative and quantitative results. The experiments were carried out for values of Froude number between 0 and 11.4. In addition, the case of no density difference , *i.e.* $Fr = \infty$, was examined.

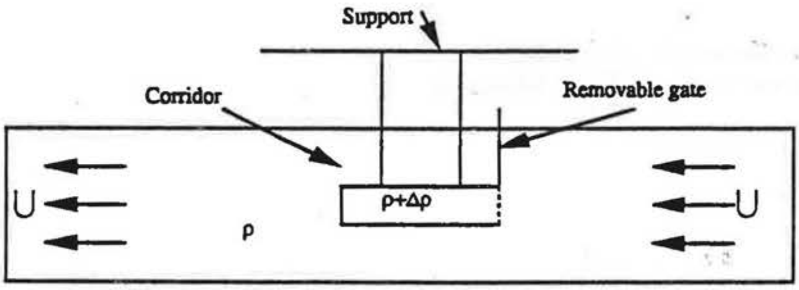

Figure 2. Experimental set-up.

Parameter ranges

The ranges of the important parameters for the experiments were as follows:

Parameter	Experimental range
Fr	$0 \rightarrow 11.4$
Re	$10^3 \rightarrow 10^4$
$P\acute{e}$	$10^6 \rightarrow 10^7$
g'	$0.1 \rightarrow 10cms^{-2}$
U	$0 \rightarrow 11.4cms^{-1}$

EXPERIMENTAL RESULTS

Qualitative results

At Froude number zero, the observed flow was a half-height gravity current, with the interface between incoming and outgoing fluid half-way up. When the reflected gravity current has returned to the doorway, the interface at the doorway ceases to be at half-height and the flow is no longer quasi-steady. As the Froude number is increased, the interface between incoming and outgoing fluid at the doorway rises. Nevertheless, within the corridor, the interface adjusts and a gravity current is still observed to flow into the interior. This current does not occupy half the height of the corridor as there is a loss of energy in the flow due to the mixing between the layers. This situation is illustrated in Figure 3.

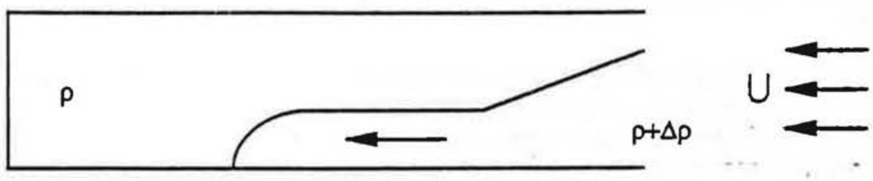

Figure 3. Raising of the doorway interface as Fr increases.

At low Froude number, there is little mixing across the interface. The amount of mixing increases with the Froude number, and this increase appears to be due to the increase in mixing across the interface increases due to the shear between the counterflowing layers. The increase in pressure associated with the headwind implies that the height of the interface is raised at the doorway as the Froude number increases. An example is shown in Figure 4, where the interface can be seen sloping sharply downwards from the doorway. As a consequence of the fact that the incoming and outgoing flows carry the same volume flux, the shear across the interface is increased as the interface rises. Since the density difference across the interface is unchanged, the Richardson number at the doorway is reduced and shear mixing is enhanced.

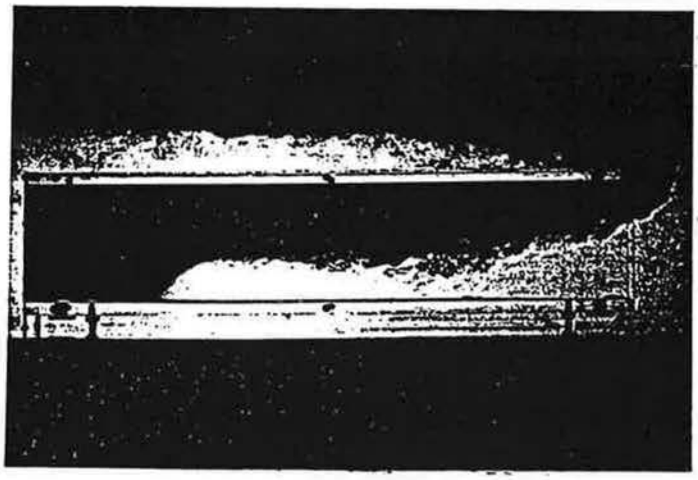

Figure 4. Photograph of experiment at $Fr = 0.7$.

At Froude number $O(10)$, the doorway region becomes well-mixed. In spite of this, a gravity current is still seen to flow from the mixed doorway region into the interior of the corridor. However, as a result of mixing in the doorway, this gravity current is observed to contain both interior and exterior fluid, unlike the cases for $Fr \leq O(1)$. Therefore, the density difference driving this mixed gravity current will be less than that in the low Froude number cases and so we expect its velocity to be smaller, as indicated by equation (2).

It is worth noting that even in the high Froude number cases, the flow is buoyancy-driven well within the corridor; the wind does not penetrate far within the room. This is borne out by the fact that in the $Fr = \infty$ case, exterior fluid only enters the interior by a turbulent mixing process, which decreases with distance down the corridor.

Quantitative results

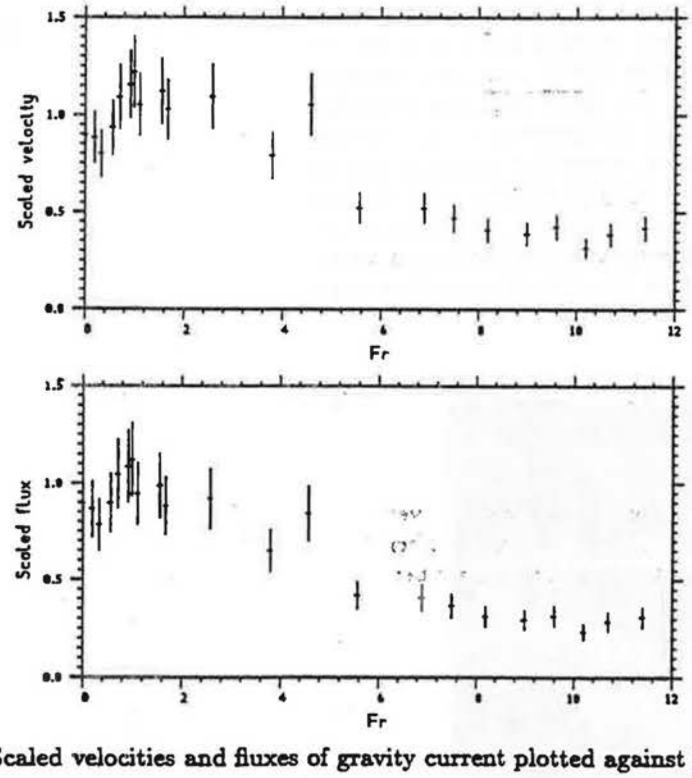

Figure 5. Scaled velocities and fluxes of gravity current plotted against Froude number.

The scaled velocities and scaled fluxes of the gravity currents seen are plotted against Froude number in Figure 5. The velocities and fluxes are scaled with their theoretical values in the Froude number zero case. Hence, the values are approximately 1 when Froude number is zero, in good agreement with the previous experimental work of Lane-Serff, Linden and Simpson [1]. For $Fr \leq O(1)$, there appears to be some initial increase in the velocities and fluxes, before they both decrease at higher Froude numbers. The fluxes fall off more rapidly with Froude number than do the velocities as the gravity currents flowing down the corridor are no longer half-height due to energy loss.

As mentioned previously, the height of the interface at the doorway is observed to rise with the Froude number, as shown in Figure 6. These data were obtained from visual observation of the experiments. For values of the Froude number up to $Fr = 5.8$ the interface height was obseved to remain relatively steady.

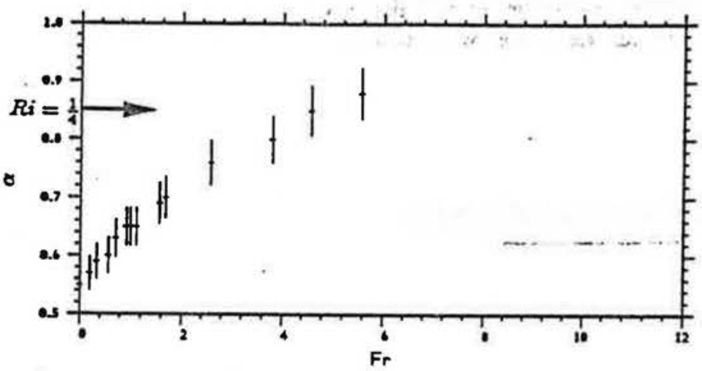

Figure 6. Fractional interface height, α , against Fr.

A measure of the stability of the interface between the counterflowing layers at the doorway is the Richardson number given by

$$Ri = \frac{g'H}{(u_1 - u_2)^2}, \tag{3}$$

where u_1 and u_2 are the velocities of the lower and upper layers respectively. For $Fr \leq O(1)$, when the amount of mixing across the interface is not sufficient to affect the density of the air flowing into the corridor, the Richardson number varies according to

$$Ri = (4\alpha(1-\alpha))^2, \tag{4}$$

where α is the fractional interface height of incoming fluid at the doorway. When the Froude number is zero, $\alpha = 0.5$, and the Richardson number is equal to one. As the Froude number increases, the interface rises and the Richardson number falls.

Note that for $Fr = 1$, the value of Ri is approximately 0.86; this is not a large decrease and supports the observation that the interface is still quite stable.

As the Froude number increases further, the interface rises, the Richardson number falls and the interface becomes unstable. When $Ri = \frac{1}{4}$, $\alpha \approx 0.85$, and this value, at which significant mixing is expected, is shown in Figure 6. Experimental measurements of α are inappropriate at larger Froude numbers because of the unsteady nature of the interface.

For Froude numbers of $O(10)$, the doorway region is well-mixed and the gravity currents observed to flow into the interior have velocities between 1/3 and 1/2 of there expected values in the Froude number zero case. A quasi-steady model for this high Froude number flow is now described.

QUASI-STEADY MODEL FOR HIGH FROUDE NUMBER

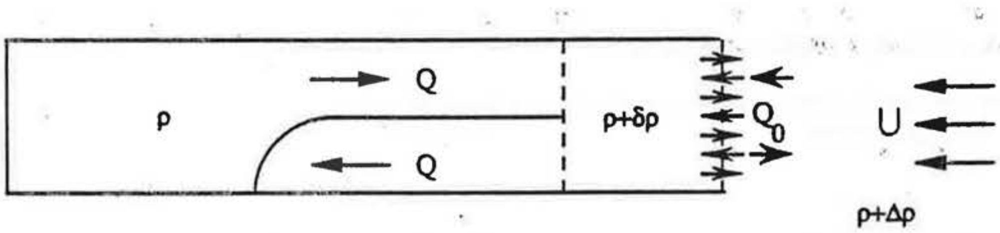

Figure 7. Steady model for high Froude number.

Given the supposed steady state as shown in Figure 7, which assumes incompressibility of the fluid, it is possible to deduce from the equation for steady flow, *viz.*

$$\frac{d}{dt}(\delta\rho) = 0, \tag{5}$$

that Q, Q_0, $\delta\rho$, ρ and $\Delta\rho$ as defined in Figure 7, must be related by the equation

$$(\rho + \Delta\rho) Q_0 - (\rho + \delta\rho) Q_0 + \rho Q - (\rho + \delta\rho) Q = 0. \qquad (6)$$

Here, Q is the flux of the gravity current from the mixed region down the corridor, Q_0 is the flux into the corridor of external fluid and $\rho + \delta\rho$ is the uniform density of the mixed doorway region.

Equation (6) can be rearranged to yield an equation for the density, $\rho + \delta\rho$ of the mixed region

$$\phi \equiv \frac{\delta\rho}{\Delta\rho} = \frac{Q_0}{Q + Q_0}, \qquad (7)$$

or an equation for the interior gravity current flux, Q

$$Q = \left(\frac{1 - \phi}{\phi}\right) Q_0. \qquad (8)$$

Furthermore, the value of Q, the flux of the half-height gravity current into the interior can also be expressed in terms of $\delta\rho$ by the formula

$$Q = Q_{gc} \phi^{\frac{1}{2}}, \qquad (9)$$

where

$$Q_{gc} = \frac{H^{\frac{3}{2}} W g^{\frac{1}{2}}}{4} \left(\frac{\Delta\rho}{\rho}\right)^{\frac{1}{2}}, \qquad (10)$$

where Q_{gc} is the flux associated with a half-height gravity current driven by density difference $\Delta\rho$ with initial interior density ρ and W is the width of the corridor. It should be noted that this model is an idealization in the sense that it assumes that half-height gravity currents flow down the corridor. In reality, the gravity currents are less than half-height due to energy losses. The mixed density, $\rho + \delta\rho$, can be eliminated from equations (7) and (9) to give a cubic equation constraining Q in terms of Q_0 as follows

$$\lambda^2 (\lambda + \mathrm{K}) - \mathrm{K} = 0, \qquad (11)$$

where λ is the ratio Q/Q_{gc} and K is the ratio Q_0/Q_{gc}. Alternatively, $K(\lambda)$ is given by

$$K(\lambda) = \frac{\lambda^3}{1-\lambda^2}. \qquad (12)$$

Figure 8 shows a graph of λ as a function of K.

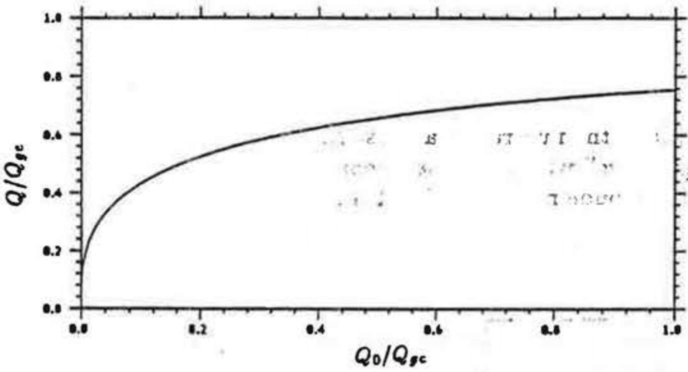

Figure 8. Flux along the corridor plotted against flux through the doorway.

Note that for each K in the range $0 \leq K \leq 1$ there is a unique real solution for λ. The ratio of the velocity of the gravity current from the mixed region into the interior to the velocity of the gravity current driven by density difference $\Delta\rho$ in the no wind (*i.e.* Froude number zero) case is equal to λ, since

$$\frac{Q}{Q_{gc}} = \frac{\frac{A}{2}u}{\frac{A}{2}u_{gc}}, \qquad (13)$$

where A is the cross-sectional area of the corridor.

Choice of Q_0

We now are in a position to choose a value of Q_0 and from this both find the density of the mixed doorway region and predict the properties of the gravity current which flows into the interior. The assumption made is that fluid is entrained into the mixed region from outside with entrainment velocity, u_e, given by

$$u_e = Eu_0, \tag{14}$$

where E is some entrainment constant and u_0 is the velocity of the gravity current driven by density difference $\Delta\rho - \delta\rho$. Accordingly, equation (8) becomes

$$\phi = \frac{1}{1 + E^{-2/3}}. \tag{15}$$

Figure 9 shows a graph of the velocity ratio (and equally the flux ratio) against E. For values of E around 0.1, this theoretical value agrees well with the experimental observations of the velocity of the gravity current for Froude numbers of $O(10)$ as shown in Figure 5.

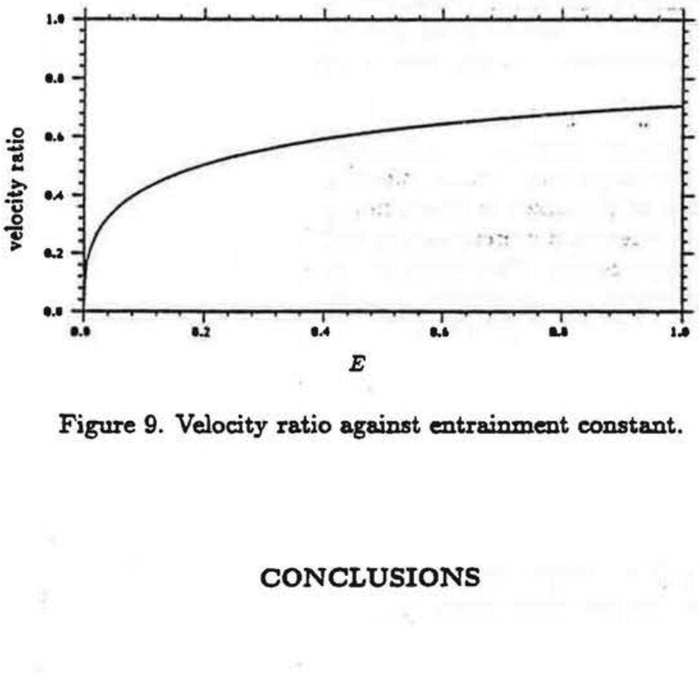

Figure 9. Velocity ratio against entrainment constant.

CONCLUSIONS

The experiments described in this paper have shown that wind effects are highly significant in single-sided airflow through a doorway. Although the experiments were conducted on a simple two-dimensional geometry, it would be expected that the qualitative nature of the flow will remain the same for more complicated three-dimensional arrangements.

For small Froude number, $Fr \leq O(1)$, the only effect of the headwind is to raise the interface between the counterflowing layers at the doorway. Once into the corridor, and away from this adjustment region, a classical gravity current, consisting of dense external fluid, with height close to half that of the corridor, is seen.

The flow then undergoes a transitional phase up to $Fr = O(10)$ where the fluid is well-mixed in some region near the doorway. A weak gravity current is observed to travel into the interior from the mixed region. The height of this current is approximately 75% of that for low Froude number. The flux of external fluid through the doorway is greatly reduced, by a factor of $O(10)$. It is worth noting that the velocity ratio as shown in Figure 9 is relatively insensitive to variations in E, except for $E \leq O(0.01)$. This demonstrates some robustness of the high Froude number model described.

The results are consistent with measurements reported recently by Wilson and Kiel [5], on buoyancy-driven flow through a doorway. Their data show that the flux through the doorway is reduced as the wind speed is increased. Although in their case, the flow geometry is different in that the doorway is shielded from the wind, turbulence is generated in the doorway by the wind, and the increased mixing that is produced reduces the flow through the doorway. A similar effect has also been observed in laboratory experiments of buoyancy-driven exchange flow in the presence of turbulence by Kiel [6].

The implications of this reduction of flux through the doorway for the control of air quality within the corridor are significant. At these large Froude number, the air change rate will also be reduced by a factor of $O(10)$. It is worth noting that $Fr = 10$ can be achieved with a 2m high door, temperature difference of 5°C and a wind speed of 20kmhr^{-1}, which is by no means unusual. This result will be of particular importance in the single-sided natural ventilation of factories or other industrial buildings where harmful gases or airborn particles are produced.

Acknowledgements

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