Air Distribution in Rooms, (ROOMVENT 2000)
Editor: H.B. Awbi

NATURAL VENTILATION OF AN ENCLOSED ROOM BY DOORWAY EXCHANGE FLOWS

Jeremy C. Phillips[1] and Andrew W. Woods[2]

[1]Centre for Environmental and Geophysical Flows, School of Mathematics,
University of Bristol, Bristol BS8 1TW, UK.
[2]BP Institute, University of Cambridge, Cambridge CB3 OEZ, U.K.

ABSTRACT

When a single doorway between a warm enclosed room and a large cooler exterior is opened, a two-layer exchange flow is set up in the doorway, with cool air filling the room along the floor, and warm air being displaced out through the doorway. The transient filling of the room continues until the cool lower layer reaches the doorway top. This process was studied experimentally using saline solutions to create density contrasts in a laboratory tank fitted with a doorway whose length and width could be varied. The height of the dyed dense layer filling the room was tracked using image processing techniques. A mathematical model based on maximal exchange flow through the doorway shows good agreement with the experimental data, and confirms that the fractional interface height in the room scales as $\frac{A_{room}}{A_{door}}\left(\frac{H}{g'}\right)^{\frac{1}{2}}$, where A_{door} and A_{room} are the areas of the doorway and room, H is the doorway height and g' is the buoyancy contrast between the layers. The use of the models to predict room cooling times by doorway exchange flows is illustrated.

KEYWORDS

Natural Ventilation, Exchange Flow, Transient, Experiment, Mathematical Model

INTRODUCTION

With increasing energy costs and the need to maintain comfortable building environments, there has been growing interest in the natural ventilation of buildings. A particularly important class of flows result when air masses of different temperature and hence density come into contact, for example through openings between rooms which are maintained at different temperatures. Even with small temperature differences, the heat fluxes transported by exchange flows are significant compared with the heat budget of modern buildings (Dalziel and Lane-Serff, 1991). Exchange flows also provide a transport mechanism for pollutants from hotter to colder rooms within buildings and for accidental releases of dense gas within buildings.

The exchange flows studied here are displacement ventilation flows (figure 1). For an enclosed room with one high-level and one low-level opening (figure 1a), displacement ventilation corresponds to the case in which an upper warm layer of air leaves the room through the higher opening and a lower cold layer of air enters the room through the lower opening (Linden *et al.*, 1990). When a heat source is supplied within the room, a steady regime can become established, with a sharp density contrast between the two layers of fluid if the source of buoyancy is localised (figure 1a). Linden *et al.* (1990) and more recently Linden and Cooper (1996) have examined these flows in some detail, successfully testing a quantitative model for the steady state flow with a series of analogue laboratory experiments using aqueous saline solutions. For a warm enclosed room with a single low-level opening to a colder exterior, the cold incoming air remains at the base of the room and there is little mixing in the room between the incoming cold and escaping warm air (figure 1b). This case has some features in common with the displacement ventilation problem associated with two openings (figure 1a), even though the flow is through a single doorway. In this paper, we investigate both experimentally and theoretically the transient exchange flow which develops on opening a single doorway at the base of a warm room connected to a larger, cooler exterior.

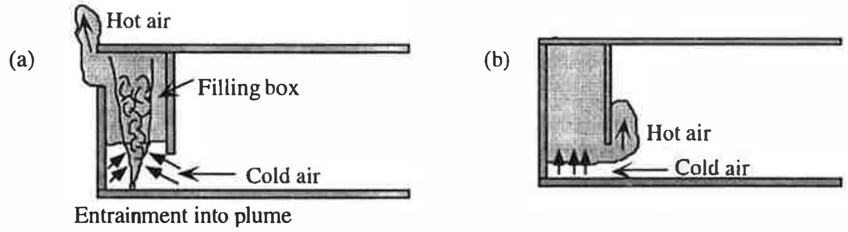


Figure 1. Displacement ventilation flows through (a) high-level and low-level openings and (b) a single opening

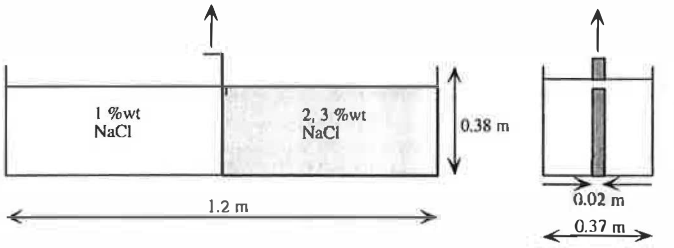
Our work builds on the earlier studies of Armi (1986) and Dalziel and Lane-Serff (1991), who analysed the steady-state exchange flows between effectively infinite environments on either side of a doorway. This study extends the experimental study of doorway exchange flows made by Gladstone *et al.* (1998) to include image processing methods to quantify the mixing between the counter-flowing layers, and presents a simple mathematical model of the process.

APPARATUS AND METHODOLOGY

Experiments investigating the transient filling of a room through a single doorway were conducted in a rectangular glass tank 1.2 m long x 0.37 m wide x 0.38 m deep. A 2 mm thick aluminium partition was situated on the mid-point of the tank, 0.60 m from either end, with a 20 mm wide doorway extending from the floor of the tank up to 350 mm (see figure 2). The doorway opening was controlled by a removable lock gate, which could be raised to simulate the opening of a doorway (heights 100-200 mm in 20 mm steps). Dyed saline solution (2, 3 wt%) was used in one side of the tank to simulate a reservoir of cold exterior air and clear weak saline solution (0.5 wt%) was used on the other side to simulate heated air within a finite volume room. Preliminary experiments (Gladstone *et al.*, 1998) had used the partition situated only 0.18 m from one end, to simulate a small heated room connected to a larger, cooler exterior, as illustrated in figure 1(b). However, this equipment configuration allowed only a small number of measurements to be made at the start of the experiment. For this reason, these transient experiments were conducted with the partition in located centrally in the tank.

The tank was initially filled with fresh water to a depth of 0.37 m and then the lock gate was closed and salt was added to each side of the lock to make up saline solutions. The reduced gravity (g') of the 'room' had values of 0.105 m s^{-2} and 0.174 m s^{-2} in experiments using 2 and 3 wt% saline solutions.

One side of the tank was dyed using food colouring, and the position of the height of the interface between the two saline solutions was recorded using a video camera. The video sequences were analysed using the computer image analysis package *DigImage* (Dalziell, 1993) to locate and measure the time evolution of the height of the top of the unmixed dense (dyed) saline solution in the room. Vertical transmitted light intensity profiles were measured 10 cm from the doorway on each side; the light intensity on the exterior (dyed) side of the doorway was matched with that in the room, thus locating the top of the unmixed (dyed) layer. The analysis confirmed that the mixed layer depth is small, approximately 2 cm in all experiments.



Side View Along Tank Centreline

End View

Figure 2. Diagram of the Experimental Apparatus

The experiments were designed to be analogous to real ventilation flows. For a typical doorway height (H) of 2-3 m and a temperature difference (ΔT) of 10 °C, the buoyancy contrast $g' = g(\Delta T/T_u) = g(\Delta\rho/\rho_u)$ is about 0.4 m s^{-2} (the subscript u refers to the upper layer or light fluid) The typical flow speed through a doorway scales as $(g'H)^{1/2} \sim 1$ m s^{-1}, where H is the door height and g' the reduced gravity, and so the Reynolds number of the flow $(g'H^3)^{1/2}/\nu \sim 10^5$, while the interfacial Richardson number ~ 1. The flows are therefore fully turbulent, but there is little mixing across the fluid interface (Turner, 1979, p. 92). In the experiments, we sought to reproduce this physical regime. Typical flow velocities were of order 0.1 m s^{-1}, producing Reynolds numbers of order 10^4 and Richardson numbers of order 1.

EXPERIMENTAL OBSERVATIONS

On opening the lock gate, a current of dense saline solution propagated into the room along the tank floor. At the same time, a reverse flow of the lighter weak saline solution issued from the room through the upper section of the doorway, creating the exchange flow. The temporal evolution of the interface height in both the room, h_i, and the doorway, h_d, for this experiment is shown in figure 3. No data could be obtained for the initial 15 s, during which pulses of fluid periodically passed through the doorway, rather than the continuous flow which characterised the subsequent exchange. The data suggest that after this initial transient, for $t \geq 15$ s, the interface height, h_i, increases linearly with time until $h_i \approx 0.55H$ where H is the door height. Subsequently, for $h_i > 0.55H$, the rate of ascent of the interface gradually decreased with time. After an initial phase of flow establishment, $t \leq 15$ s, the interface height at the doorway, h_d, became approximately equal to $0.55H$ (figure 3). This is in close agreement with the value $0.54H$ reported by Dalziel and Lane-Serff (1991). The interface height in the doorway remained at the constant value $0.55H$ until eventually the interface in the room rose above this point $h_i > 0.55H$. Subsequently, the height of the interface in the doorway increased with that in the interior of the room, so that for the remainder of the exchange flow, $h_i \approx h_d$ (figure 3).

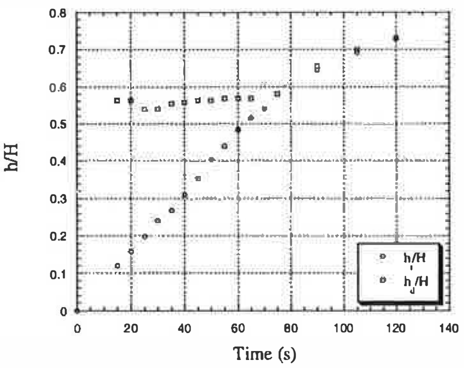


Figure 3. The evolution of interface height with time for a typical experiment

THEORETICAL ANALYSIS

In many ventilation problems, the density differences are small, so that we can use the Boussinesq approximation (Turner, 1979, p.9) in deriving the model of flow through the doorway and that in the room. If the lower layer of dense fluid has density ρ_l and flows with velocity u_l into theroom, and the lighter fluid of density ρ_u and velocity u_u flows from the room, then conservation of volume requires that

$$u_l h_d = u_u (H - h_d) \quad . \tag{1}$$

We expect the flow to be controlled at the doorway so that the composite Froude number of the flow equals unity (Armi, 1986, Dalziel and Lane-Serff, 1991)

$$\frac{u_l^2}{h_d} + \frac{u_u^2}{H - h_d} = g' \tag{2}$$

where the reduced gravity $g' = \dfrac{(\rho_l - \rho_u)g}{\rho_u}$. Thus the lower layer velocity is related to the interface depth according to

$$u_l = \left[g' \frac{h_d (H - h_d)^3}{h_d^3 + (H - h_d)^3} \right]^{\frac{1}{2}} \quad . \tag{3}$$

The rate of ascent of the density interface within the room is given by conservation of the lower layer fluid. Assuming there is no mixing of the inflowing fluid with the upper layer, conservation of mass requires that

$$A \frac{dh_i}{dt} = w h_d u_l \tag{4}$$

where A is the cross-sectional area of the room and w the width of the door. Therefore,

$$\frac{dh_i}{dt} = \frac{w}{A} \left[g' \frac{h_d^3 (H - h_d)^3}{h_d^3 + (H - h_d)^3} \right]^{\frac{1}{2}} \quad . \tag{5}$$

In order to solve the system and thereby predict the time evolution of the interface height, $h_i(t)$, we must complete the model (1-5) by specifying the relationship between the depth of the interface in the room, $\hat{h}_i = h_i / H$ and that in the doorway, $\hat{h}_d = h_d / H$. During the first stage of the exchange flow ($\hat{h}_i < 0.55$), the interface height in the doorway was independent of that in the room (figure 4)

$$\hat{h}_d = 0.55 \text{ for } \hat{h}_i < 0.55 \ . \tag{6a}$$

Once the interface in the room had ascended above the point $\hat{h}_i = 0.55$, we observed that the doorway interface height followed that in the room (figure 4),

$$\hat{h}_d \approx \hat{h}_i \text{ for } \hat{h}_i > 0.55 \ . \tag{6b}$$

Equations (5) and (6) therefore suggest that

$$\hat{h}_i \approx 0.24\hat{t} \text{ for } \hat{\mathrm{h}}_i < 0.55 \tag{7}$$

and

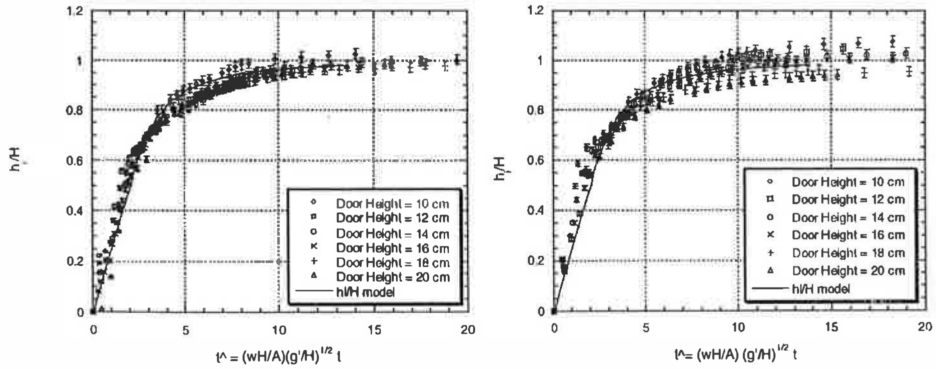
$$\frac{d\hat{h}_i}{d\hat{t}} \approx \left(\frac{\hat{h}_i^3 (1-\hat{h}_i)^3}{\hat{h}_i^3 + (1-\hat{h}_i)^3} \right)^{\frac{1}{2}} \text{ for } \hat{h}_i > 0.55 \tag{8}$$

where

$$\hat{t} = \frac{wH}{A} \left(\frac{g'}{H} \right)^{\frac{1}{2}} t \ . \tag{9}$$

COMPARISON WITH EXPERIMENTS

In figures 4a and 4b, we show experimental measurements of the dimensionless interface height, $\hat{h}_i = h_i / H$, plotted as a function of the dimensionless time $\hat{t}$ for doorway heights from 100 mm to 200 mm and buoyancy contrasts of 0.105 m s^{-2} and 0.174 m s^{-2}. The error bars represent an error of ± 2 mm in determining the height of the unmixed layer top, h_i, introduced in the estimation of the mixed layer thickness using the image processing method described above. The solid line plotted on figures 4a and 4b shows the universal model formed by coupling the solutions for the two phases of the filling process (equations 7 and 8) developed above.



(a) (b)

Figure 4. Evolution of dimensionless interface height with dimensionless time during transient exchange flow experiments. (a) g' = 0.105 m s^{-2} (b) g' = 0.174 m s^{-2}

At the lower buoyancy contrast used, the data appear to collapse satisfactorily within experimental error over the range of door heights. The model provides an acceptable leading order description of the filling process, although shows slight underprediction of the interface height in the first phase and slight overprediction in the second phase. The increased flux at the start of the experiment may correspond to the propagation of dense fluid into the room as a spreading gravity current, with additional hydraulic controls on this release condition not accounted for in the model. At the higher buoyancy contrast used, there is greater scatter in the experimental data, particularly during the second phase of the filling process. However, the model still provides an acceptable leading order fit to the data, particularly for intermediate door heights.

APPLICATION

The analysis and experimental study reported in this paper provides estimates for the time scale for the exchange flow to set up a steady density distribution following the opening of a doorway. The time required for the filling front in the room to extend to 90% of the doorway height is given by the expression

$$\tau_{0.9} = 5\left(\frac{A_{\text{room}}}{A_{\text{door}}}\right)\left(\frac{H}{g'}\right)^{\frac{1}{2}} \quad . \tag{10}$$

We estimate filling times of order $\tau_{0.9}$ = 3-150 minutes. The larger estimate corresponds to large rooms, for example, classrooms, open offices or meeting halls, or doorways across which the temperature contrast is small. The smaller estimate corresponds to small domestic rooms or doorways across which there is a larger temperature and, for example when there is hot smoke produced by a fire within the room.

ACKNOWLEDGEMENTS

This work is sponsored by the EPSRC Built Environment Programme, UK.

REFERENCES

Armi, L. (1986). The hydraulics of two flowing layers with different densities. *J. Fluid Mech.* **163**, 27-58.

Dalziel, S. (1993). Rayleigh-Taylor instability: experiments with image processing. *Dyn. Atmos. Oceans* **20**, 127-153.

Dalziel, S. and Lane-Serff, G.F. (1991). The hydraulics of doorway exchange flows. *Building and Environment* **26**, 121-135.

Gladstone, C., Woods, A.W., Phillips, J.C. and Caulfield, C.P. (1998). Experimental study of mixing in a closed room by doorway exchange flows. *Proceedings 6th International Conference on Air Distribution in Rooms* **2,** 555-561.

Linden, P.F., Lane-Serff, G.F. and Smeed D.A. (1990). Emptying filling boxes: the fluid mechanics of natural ventilation. *J. Fluid Mech.* **212**, 309-335.

Linden, P.F. and Cooper, P. (1996). Multiple sources of buoyancy in a naturally ventilated enclosure. *J. Fluid Mech.* **311**, 177-192.

Turner, J.S. (1979). *Buoyancy effects in fluids* Cambridge University Press.