TRANSIENT FLOW THROUGH DOORWAYS PRODUCED BY TEMPERATURE DIFFERENCES

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ABSTRACT

Flows through open doors can account for a significant part of total heat losses in housing. They can also influence the distribution of indoor air temperatures and contaminants within a building. Even at quite small temperature differences (less than 1°C) between the interior and exterior air, buoyancy forces are significant and a gravity current flow is established through an open doorway. This flow may cause a loss of heat due to the intrusion of cold air along the floor, or a heat gain in a refrigerated room, when the incoming air flows along the ceiling.

After an initial acceleration phase once the door is opened, the flow takes on a steady lock-exchange character which persists until the advancing cold air in the gravity current front reflects from the end walls and returns to the door. After this stage buoyancy driven flows still predominate and continue until passageways are filled with incoming air. If the air entering the room is warm it rises as a turbulent plume and the resulting stratification is determined by a "filling-box" process.

Experimental data are obtained from small-scale laboratory experiments using salt and fresh water to model the buoyancy differences between the cold and warm air. In the first series, the flow is nearly two-dimensional, corresponding to inflow or outflow through an open door at the end of a passage. In the second series, a door is opened in the centre of a vertical plane separating two fluids of different density and the consequent three-dimensional spreading is examined. The resulting flows model the air exchange in a large building, such as a warehouse.

Theoretical and experimental results from gravity current and lock-exchange flows in the laboratory are reviewed, and the results used to show that simple models provide both physical insight and accurate estimates to the air flows and the associated heat losses (or gains) through open doors.

1. INTRODUCTION

Flows through open doors account for a significant part of total heat losses in housing. Even at quite small temperature differences (a few degrees) between the interior and exterior air, buoyancy forces are significant and can establish an exchange flow through an open doorway. This flow may cause a loss of heat due to the intrusion of cold air along the floor, or a heat gain in a cold room, when the incoming air flows along the ceiling. Density driven flows can also determine the distribution of indoor air contaminants within a building. In modern domestic buildings, with design heat losses of around 1kW, the temperature differences between rooms can cause comparable heat transfers within the building. An understanding of these flows is fundamental to efficient building design and for the comfort and health of the occupants.

Heat and mass transfer by natural convection through rectangular openings in partitions have been studied by several authors. Brown and Solvason

(1962) carried out experiments with openings in a vertical partition from 7.5cm to 30cm high with air as the convective fluid. Fritzche and Lilienblum (1968) measured heat losses at the doors of a cold room by laboratory measurements with a full-size door. Shaw (1971), (1974) gave a theory for both natural convection and forced airflow across an opening in a vertical partition, supported by experiments in air through "door size" openings.

This earlier work has concentrated on the steady exchange flow driven by a fixed temperature difference across the opening. In practical circumstances the flows are time-dependent. As a door is opened the transient response takes the form of a gravity current of cold air travelling along the floor into the warmer room. The gravity current is characterised by a leading front or "head" which is deeper than the following flow. It is this transient flow which we concentrate on in this paper. On a longer timescale the temperature on the two sides of the doorway changes as a result of the flow. This aspect, although important, is not addressed here.

In this paper we describe two series of small-scale laboratory experiments using salt and fresh water to model the buoyancy differences between the cold and warm air. A good understanding of natural ventilation air-flows through open doors and windows can be obtained by using laboratory experiments in water tanks. It is possible to obtain the necessary dynamic similarity by maintaining the correct range of the relevant dimensionless numbers concerned with viscosity and diffusion. These are

		domestic		industrial
Reynolds number	$Re = \frac{(g'H)^{1/2}H}{\nu}$	10^3	-	10^6
Peclet number	$Pe = \frac{(g'H)^{1/2}H}{\kappa}$	10^3	-	10^6

where $g' = g\frac{\Delta\rho}{\rho}$, where g is the acceleration due to gravity and $\Delta\rho/\rho$ is the fractional density difference, ν is the viscosity and κ the diffusivity. The height of the door is H and $(g'H)^{1/2}$ is a measure of the flow speed U through the doorway. Using air as the working fluid in the laboratory these parameters are smaller by a factor of $((H(model)/H(fullsize))^{3/2}$, for the same temperature difference.

In experiments it is better to use water rather than air as the working fluid, with density differences produced by dissolving salt, instead of using temperature differences. It is worth noting that a temperature difference of 3K in air corresponds to a density difference of about 1%. By using water, a higher Reynolds number and a higher Peclet number can be obtained than by using air, and using salt avoids any problem of heat losses. The form of the flows can be visualised simply and effectively by dyes or using the shadowgraph technique. The latter technique is a very powerful visualisation method, and uses the presence of density gradients to outline the boundaries of fluids of different density. In the present experiments a projector was used at a distance of roughly 5 metres to form a shadow of the flow on a translucent screen, and the display was recorded by still photography (at regular preset time intervals) and by video.

In this paper theoretical and experimental results from gravity current and lock-exchange flows in the laboratory are briefly reviewed, and the results used to show that simple theoretical models provide both physical insight and accurate estimates of the air flows and the associated heat losses (or gains) through open doors.

2 THEORY

2.1 Flow Through A Doorway Along A Passage

After an initial acceleration phase the flow along the passage takes the form of a gravity current (see Simpson (1982) for a review). The doorway is a choked orifice and acts as a hydraulic control with an exchange flow in which $F_1^2 + F_2^2 = 1$, where $F_i = U/(g'H_i)^{1/2}$ is the internal Froude number and $i = 1, 2$ corresponds to the upper and lower layers, respectively. In the experiments, and by symmetry, $H_1 = H_2$ (see fig. 1) and this gives

$$U = 0.5(g'H)^{1/2} \qquad (1)$$

The speed U of the leading edge of the current is constant and is given by (1) - see Benjamin (1968).

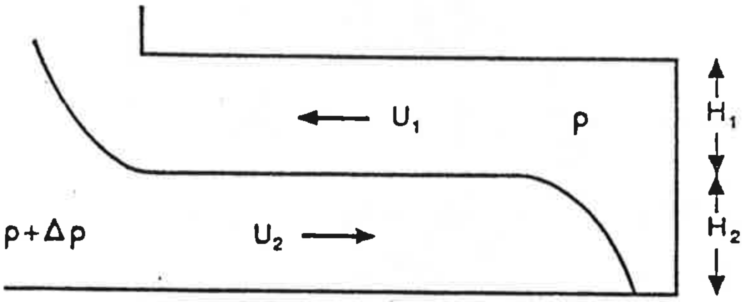


Fig. 1 Flow along a passageway.

The flow then remains steady until the advancing gravity current front reflects from the end wall and returns to the door. After this stage buoyancy driven flows still predominate and continue until the passageway is filled with incoming fluid.

2.2 Flow through a doorway into a room.

Now we will consider the flow through a doorway of width L into a wide room. First consider the flux through the doorway itself (see fig. 2).

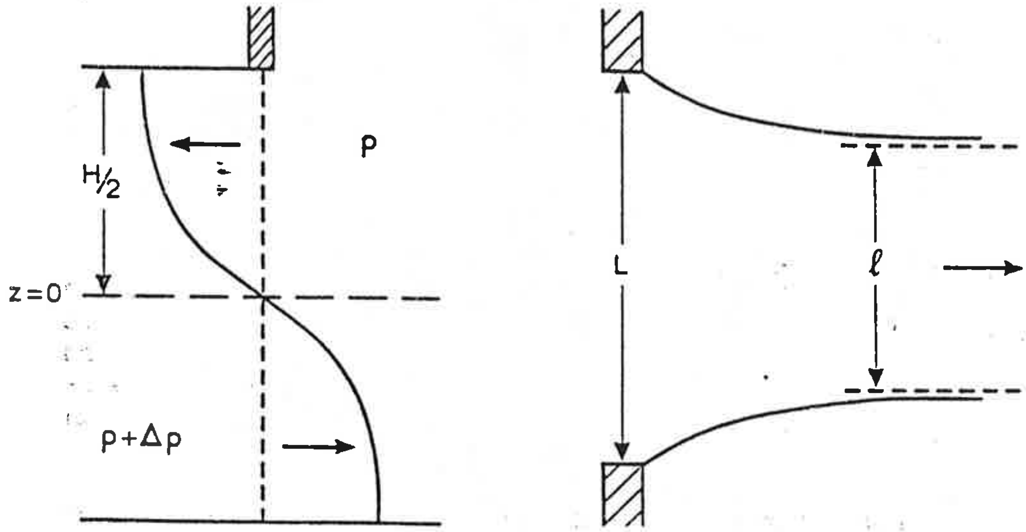


Fig. 2 Vertical section and plan of flow through a doorway.

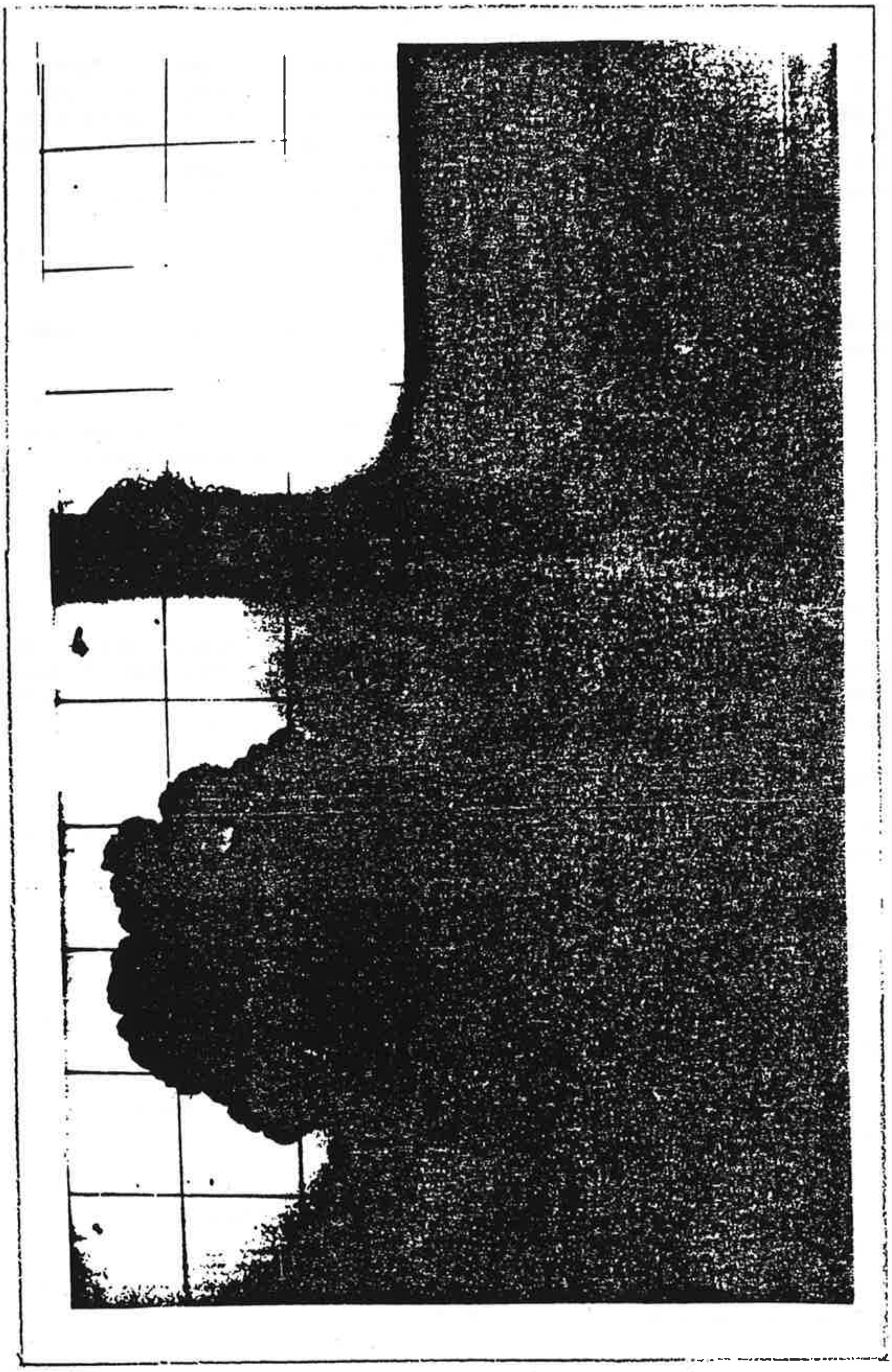


Fig. 3 Photograph of simultaneous plan and elevation of flow of dense fluid (dark) through a doorway. The grid is at 10cm intervals in both views.

If the flow is irrotational then it contracts after passing through the doorway. with the width of the contraction ℓ given by

$$\ell/L = \pi/(\pi + 2) \qquad (\sim 0.61), \tag{2}$$

(if L is small compared with the width of the room: Lamb (1932)). If there is no net flow through the doorway then the pressure at the mid-level z=0 is everywhere equal, p_0 say. Then the hydrostatic pressure far to the right of the doorway is

$$p_1 = p_0 + \rho g z,$$

and that on the left is

$$p_2 = p_0 + (\rho + \Delta\rho) g z,$$

giving a pressure difference Δp of

$$\Delta p = \Delta\rho g z.$$

If we assume ideal flow with velocity V the Bernoulli equation gives

$$\frac{V^2}{2} = \frac{\Delta p}{\rho} = \frac{\Delta\rho}{\rho} g z.$$

If F is the flux to the left (or right) then

$$F = \ell \int_0^{H/2} V dz,$$

where ℓ is given by (2).

Thus

$$F = \pi/(3(\pi + 2))(g'H)^{1/2} HL$$

writing the reduced gravity g' for $\frac{\Delta\rho}{\rho} g$

As can be seen from the photograph (fig. 3) the flow is, however, dissipative and spreads out after passing through the door. On dimensional grounds we expect $V \sim (g'H)^{1/2}$ and thus, since the area of the door is HL

$$F \sim (g'H)^{1/2} HL,$$

and in fact

$$F = (Cd/3)(g'H)^{1/2}(HL) \tag{3}$$

with Cd=0.61 gives good agreement with experiments (Steckler, Baum and Quintiere 1984).

The flow emerging through a doorway into a wide room can be considered as part of an axisymmetric gravity current, that is: the spreading out of a dense fluid in all directions from a point source. We will, therefore, now consider this type of flow. See fig. 4.

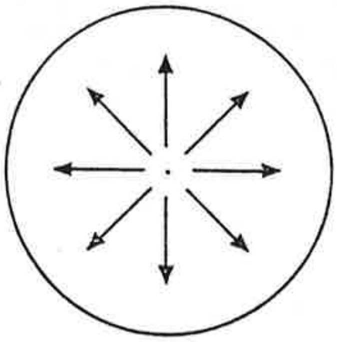
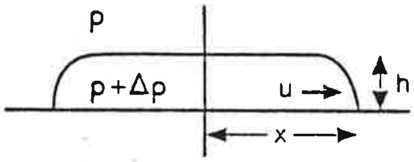


Fig. 4 Plan and cross-section of idealised gravity current.



- If, as is usually the case in practice, the viscous forces are negligible then there must be a balance between the inertial and buoyancy forces. This is expressed by the relation

Inertial ~ Buoyancy

$$\rho u^2 \approx \Delta\rho g h$$

where U is the speed of the advancing front. Further we expect $u \approx x/t$, where x is the foremost point of the advancing cold air (see fig. 4), and t is the time elapsed since opening the door. and also the total volume of the density current

$$Vol = \pi x^2 h = Qt$$

(where Q is the rate of input of fluid). Substitution into the force balance gives

$$\rho x^2/t^2 \approx \Delta\rho\, gQt/x.$$

Again writing g' for $\frac{\Delta\rho}{\rho}$g, the advance of the front of the cold air is then given by

$$x \approx (Qg')^{\frac{1}{4}} t^{\frac{3}{4}}.$$

So, on these simple physical grounds, we expect

$$x = c(Qg')^{\frac{1}{4}} t^{\frac{3}{4}} \qquad (4)$$

where c is a (universal) dimensionless constant.

We will use results (3) & (4) in a semi-empirical analysis in conjunction with the results of the experiments below.

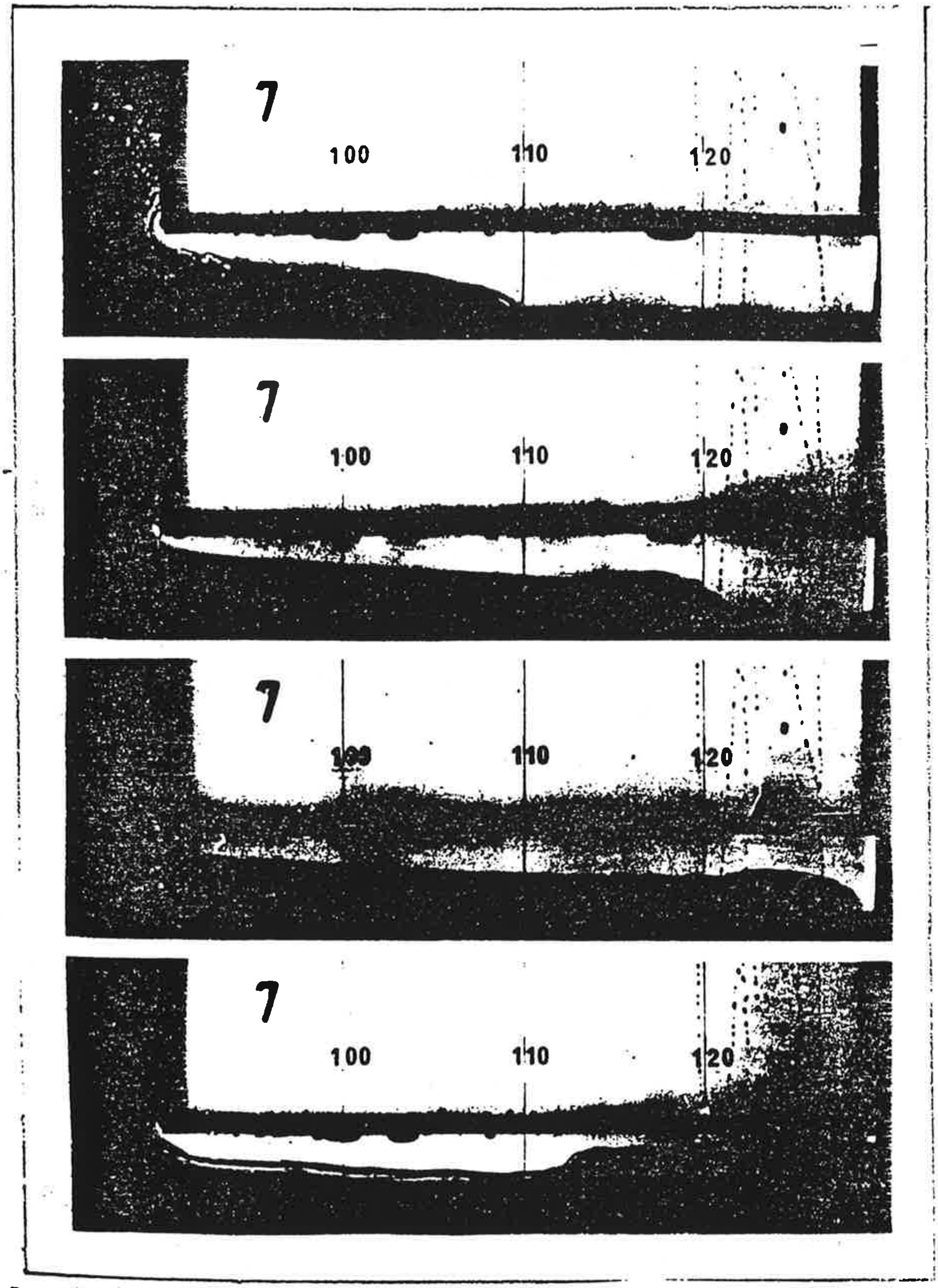


Fig. 5 Four views of the advance of a dense flow along a passageway in a laboratory experiment. The door height is 10cm and the spacing of the vertical lines is 10cm.

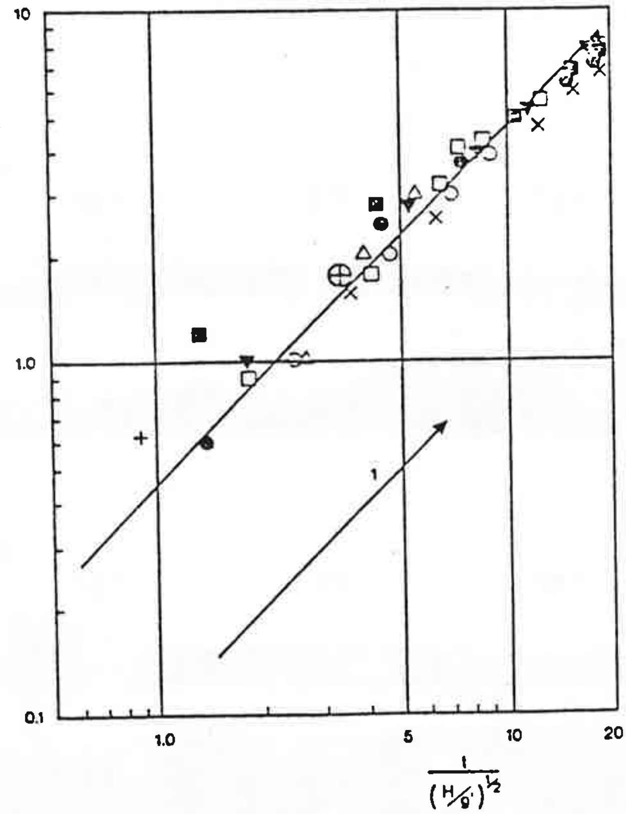


Fig. 6 Measurements from a series of experiments similar to that shown in fig. 5. The point ⊕ corresponds to observations made in the home of one of the authors.

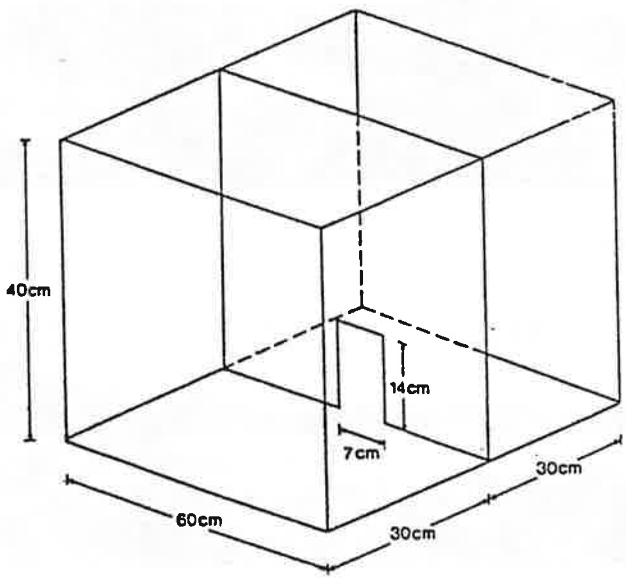


Fig. 7 The apparatus used to investigate flows through a doorway between two rooms.

3. EXPERIMENTS:

3.1 Two-dimensional flows

The experiments described here were carried out in a water tank 3m long, 0.5m deep and 0.2m wide. The whole tank is first filled with tap water and, after the door has been closed, salt is dissolved in the water "outside the door" to attain the required density difference. In our experiments this was usually between 1 and 5%. When the door had been removed the flow through the doorway was observed, the flow being made visible by dye and by shadowgraph. Fig. 5 shows an example of the flow through an open doorway at the end of a passage.

The classical gravity with a raised head can be seen. There is very little mixing between the incoming dense fluid and the fluid within the passage. Outside the house at the same time the less dense fluid can be seen rising up the outer wall and mixing with the surroundings.

Fig. 6 shows some of the experimental results, plotted on a log/log scale in non-dimensional form. The distance x is non-dimensionised by the depth H of the channel, and the time t by the expression $(H/g')^{1/2}$. It can be seen that the results lie close to a straight line with gradient 1, showing that the velocity U is constant. The experimental result for the uniform speed is $U = (0.47 \pm 0.06)(g'H)^{1/2}$, close to the theoretical value given in (1) above. Experiments were also carried out with an open staircase at the end of the passage. At the end of the passage, the gravity current eventually filled up all the space in the ground floor until the dense fluid reached the level of the upper floor but no higher. (See the last view in fig. 5).

3.2 Three-dimensional Flows

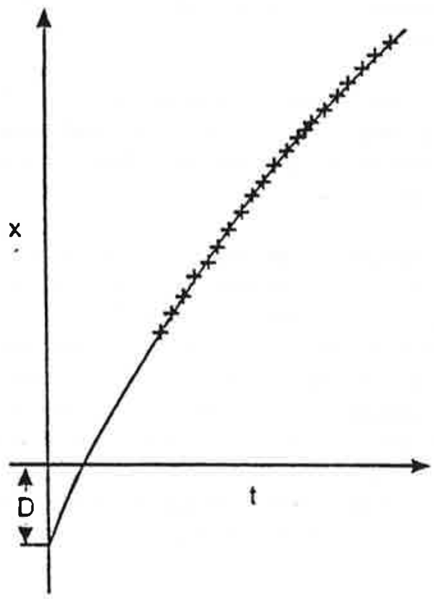
In order to study flows into wide rooms experiments were carried out in an apparatus consisting of a perspex box with a vertical partition across it (see fig. 7). The vertical partition contained a doorway with a (vertically) sliding door. Flows through various doorway sizes are investigated.

The box was filled with water and, with the door shut, salt and dye dissolved on one side of the partition. When the door was opened the denser fluid flowed through the door and spread out along the floor of the box as a gravity current as can be seen in fig. 3 and a buoyant plume of the lighter fluid rises on the other side of the partition.

The motion of the warm plume in the cooler room depends on the distance from the top of the doorway to the ceiling. When this distance is small the flow again takes the form of a gravity current travelling across the ceiling. On the other hand, if the distance is large a buoyant plume is formed which produces significant mixing within the room. An analysis of buoyant plumes filling spaces is given by, for example, Huppert & Worster 1983, Huppert et al 1986. This aspect of the flow is beyond the scope of the present paper and we will confine ourselves to considering the flow of the dense fluid along the ground.

We now discuss the quantitative results of these experiments. Fig. 8 shows the results of a typical experiment in which the distance x of the front of the dense fluid plotted against time t measured from when the door is opened. The solid curve is a $x \sim t^{3/4}$ curve but in order to fit the experimental points it is necessary to shift the x-origin down by a distance D i.e. behind the door. Therefore the flow appears to behave as an axisymmetric gravity current (see equation (4)) originating from a vertical origin at a distance D behind the door (see fig 9). Thus we shall interpret the results as suggesting that the flow can be considered as a sector of an axisymmetric gravity current. The observed flow near the door appears to be in agreement with this hypothesis. The fluid outside the sector comes from the spilling of the dense fluid from the edge of the sector together with mixing at the edge of the sector in part caused by eddies shed by the doorway as well as the general turbulent nature of the flow.

Fig. 8 Measurements from a typical experiments of front position (x) against elapsed time (t).



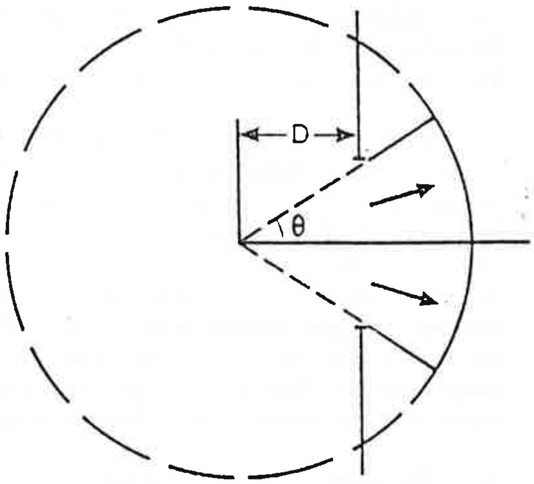


Fig. 9 Plan of flow through a doorway with (imaginary) total gravity current.

In order to compare the results with (4) we must note that Q is the flux of the total (imagined) gravity current i.e.:

$$Q = \pi F/\theta \quad (\tan\theta = L/2D) \tag{5}$$

and x should be replaced by x + D. See figure 9. If we choose scale length x_0. and scale time t_0 given by

$$x_0 = H^{\frac{3}{4}} L^{\frac{1}{4}}$$

$$t_0 = (H/g')^{1/2} (3\theta/Cd\pi)^{\frac{1}{3}}$$

equation (4) can be written as

$$(x+D)/x_0 = c(t/t_0)^{\frac{3}{4}} \tag{6}$$

The experimental results are plotted in fig. 10 on a log-log scale to compare with eqn (4). This gives an estimate for c of 0.92 ± 0.04 which is in agreement with previous experiments designed to study axisymmetric flow (0.84 ± 0.06, Britter 1979).

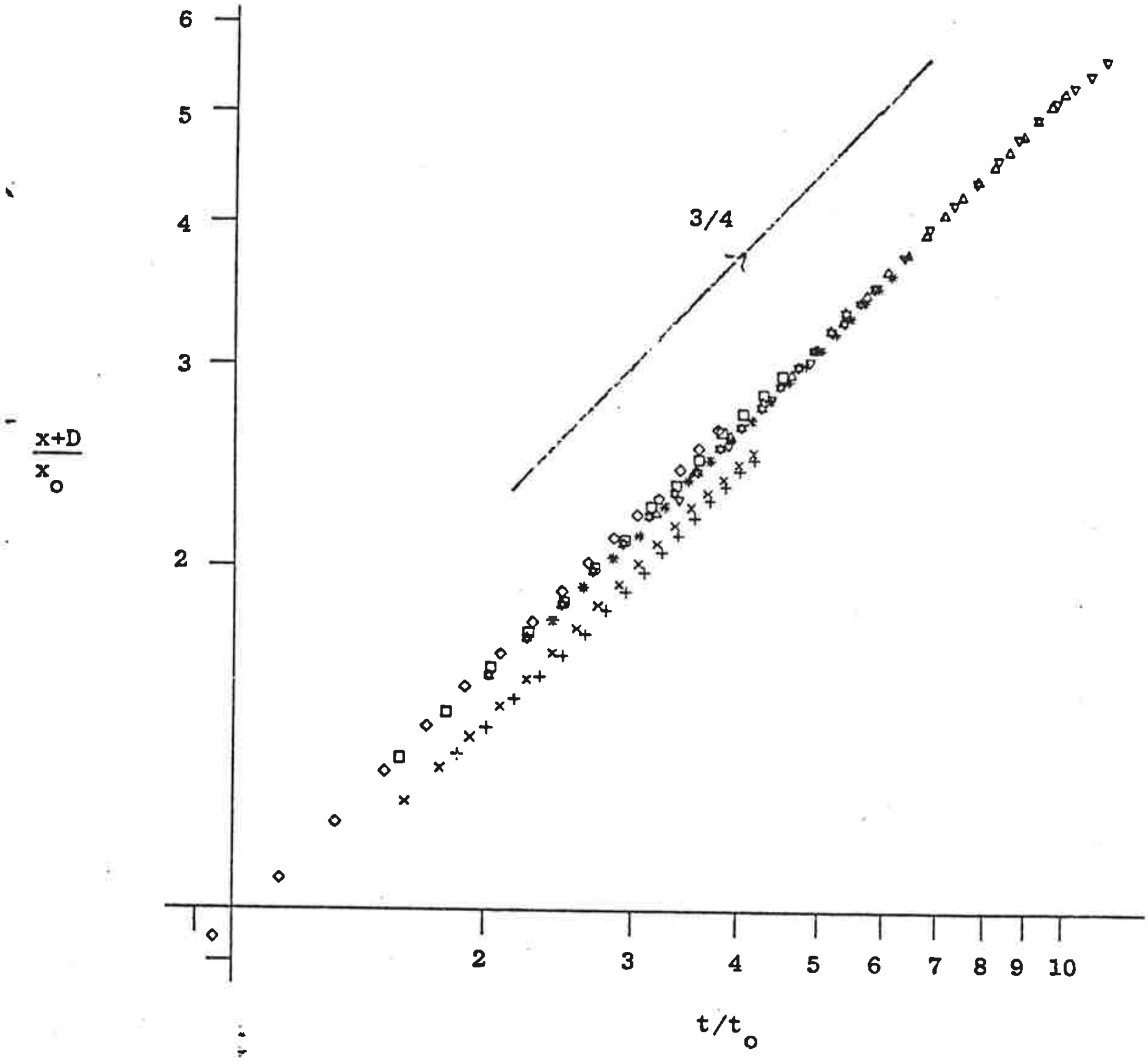


Fig. 10 Measurements of the spread of the gravity current through a doorway with time.

To determine what the angle of spread θ be we match an initial acceleration phase to the $t^{3/4}$ curve, see fig. 11. Unfortunately we cannot at present determine what happens in this initial phase. However, at these Reynold's numbers ($10^3 - 10^4$), we expect θ to depend primarily on the door aspect ratio $A = H/L$, i.e. $\theta = f(A)$. It was found that the expression

$$\theta = 0.75 - 0.14A \qquad (7)$$

gave an adequate value for θ with A between about 0.5 and 2, and there was no significant correlation between θ and Reynold's number $Re = L(g'H)^{1/2}/\nu$. This implies that θ is smaller for taller/thinner doors as expected. Also note that in eqn (4) θ appears (by way of Q from eqn (5)) raised to the (minus) quarter power so errors in θ of 20%, say, would give errors in x of less than 5%. We emphasise that eqn (7) is merely a linear representation of f(A) for the range of A between 0.5 and 2, with an accuracy no better than 10%.

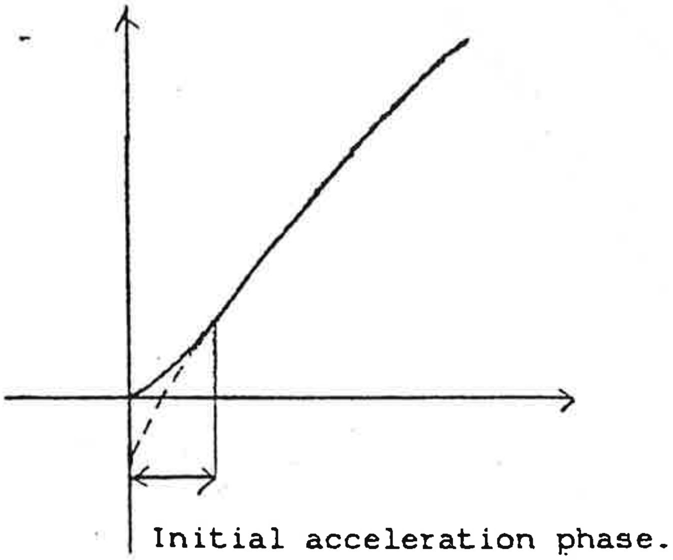


Fig. 11 Graph of front of gravity current against time showing initial acceleration phase before the flow adopts a $t^{3/4}$ behaviour.

It should be noted that the analysis above describes only the broad nature of the flow and not the full complexity of the flow that is evident from the photographs. It may not be possible to take this simple physical analysis much further than given above. In the future we intend to study the mixing properties of these flows to determine the resultant stratification.

4. Summary

These experiments described in this paper reveal some aspects of the flow through an open doorway between two regions of different temperatures. We have concentrated on the transient flow which is generated when the door is opened. Flow visualisation shows that the flow of cold air into the warm room takes the form of a gravity current. The speed of advance of the front of the gravity current was found to be in agreement with theoretical predictions and was related to the flux of heat through the doorway.

The flow into the cooler room takes the form of a plume of warm air which rised above the doorway. Although this aspect of the exchange flow has not been discussed in this paper it is an integral part of the heat flow from one room to another. A plume mixes very rapidly with its surroundings.

while a gravity current mixes relatively little. This asymmetry produces profound differences in the longer term on the thermal statification that develops either side of the doorway. This, in turn, will produce significant changes in the air flow through the doorway from those analysed in this paper. These effects are the subject of further study.

The model experiments described in this paper provide a convenient method of examining these flows. The results show that it is possible to reproduce full-scale Reynolds and Peclet numbers and to achieve dynamic similarity using small-scale laboratory apparatus. In addition, this technique allows the possibility of measuring mixing rates and "heat" fluxes using conductivity probes to measure salt concentration. These, more detailed questions, will form the basis of future work.

Acknowledgements

This work was supported by the Natural Environment Research Council and British Gas PLC.

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