EXPERIMENTAL STUDY OF MIXING IN A CLOSED ROOM BY DOORWAY EXCHANGE FLOWS

Charlotte Gladstone, Andrew Woods
Jeremy Phillips, Colm Caulfield

Centre for Environmental and Geophysical Flows, School of Mathematics,
University of Bristol,
Bristol, England, BS8 1TW

ABSTRACT

We present a series of analogue laboratory experiments of the transient exchange flow between a room filled with warm air and a cold exterior following the opening of a doorway. Our experiments suggest that the time-scale for mixing the fluid in the room below the top of the doorway is independent of the door height. We then describe the steady-state two-layer stratification that is established when, in addition to the exchange flow, a localised heat source provides heat at the base of the room. Our experiments suggest that the height of the steady interface depends primarily on the aspect ratio of the doorway and is independent of the strength of the source of heat.

KEYWORDS

Exchange flow, mixing, heat source

INTRODUCTION

The interaction of buoyancy driven flows produced by heat sources with the exchange flows which develop through doorways is one of the most important aspects of the ventilation of a room. Models and experiments have been developed to study the flows which arise when there are openings at the top and base of a heated room (Linden et al., 1990; Linden and Cooper, 1996); the presence of an opening at the base and top of the room leads to the establishement of unidirectional flows through each of the openings and a relatively simple theory of the two-layer stratification which develops in the room.

However, the very common process in which an exchange flow through a single doorway connecting a warm room to a cold exterior causes the interior of the room to cool, is considerably more compl[...] mixing associated with th[...] through the doorway. It is t[...] we study experimentally[...] contribution, providing new experimental results which could be used to constrain and test both numerical and theoretical models. We first investigate the transient exchange flow which develops following the opening of a closed doorway connecting two different regions of fluid. We then examine the steady state density structure which develops when there is also a source of buoyancy at the base of the room. We discuss the implications of our results for the natural ventilation of buildings.

METHODS

We conducted a series of analogue laboratory experiments using aqueous salt solutions in clear laboratory-scale glass tanks. By appropriate dimensional scalings, we are then able to use small, laboratory scale tanks, 37(width) x 37(height) x 120(length) cm, to reproduce the dynamical conditions associated with ventilation in a room. The perspex tank allows for easy flow visualisation and detailed anaysis of the flow using image processing techniques.

Our experimental tank included a partition at a distance of 18.5 cm from the end of the tank, and a doorway of variable aperture (2-10 cm in width and 5-20 cm in height) was placed in this partition. Before removing the doorway, the aqueous solution on each side of the doorway was set to a desired value and measured using refractometry. By removing the experimental doorway along a vertical groove, the transient exchange flow commenced. In the experiments in which we simulated a heat source at the base of the room, a plume of fresh fluid was also released into the room with a prescribed volume flux. In each experiment, we video-recorded the evolution of the flow, and subsequently measured the height of the interface between the external fluid and the original fluid in the model room. The exterior region was sufficiently deep that only the upper part of this region, above the doorway, was affected by the light outflow from the room, and hence the environment below the door-top was constant throughout the experiment.

The experiments were designed to be dynamically similar to the flows which develop in real rooms. In particular, the

Reynolds number, which determines the scale of the turbulence, and the Richardson number, which determines the ability of the flow to mix, were similar. Indeed, in the laboratory typical flow speeds are 0.01-0.1 m/s, length scales are 0.01-0.1 m and the buoyancy of the flow g' = 0.02-0.1 m/s^2, giving a Reynolds number of order 100-1000 and Richardson numbers of order 0.1-10. In contrast, in a ventilated room, the air speed is of order 0.1 m/s, the length scale of the flow is 1m and the buoyancy is order order 0.01-0.1 m^2/s for a temperature difference of order 1-10 K, leading to Reynolds and Richardson numbers of comparable magnitude to the experiments, 100 and 0.1-100. In both cases, owing to the small value of the Richardson number, we might expect considerable mixing of the exchange flow near the doorway (Turner, 1979), where the flow is most intense, before it spreads out into the room.

RESULTS

(i) TRANSIENT EXPERIMENTS

We conducted a series of transient experiments using a range of doorway heights and values of the density contrast between the room fluid and the exterior (Table 1).

Table 1 -- Range of Experiments

Salinity Contrast (wt% salt)	Door Height (cm)	Width (cm)
.25, .5, .75	20, 15, 10	2

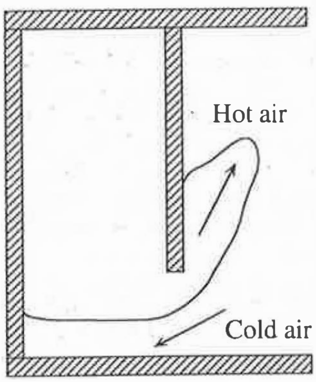


Figure 1: Transient Exchange Flow

Figure 2 shows a time sequence of images which illustrate how the concentration of dye, and hence the degree of mixing of the two

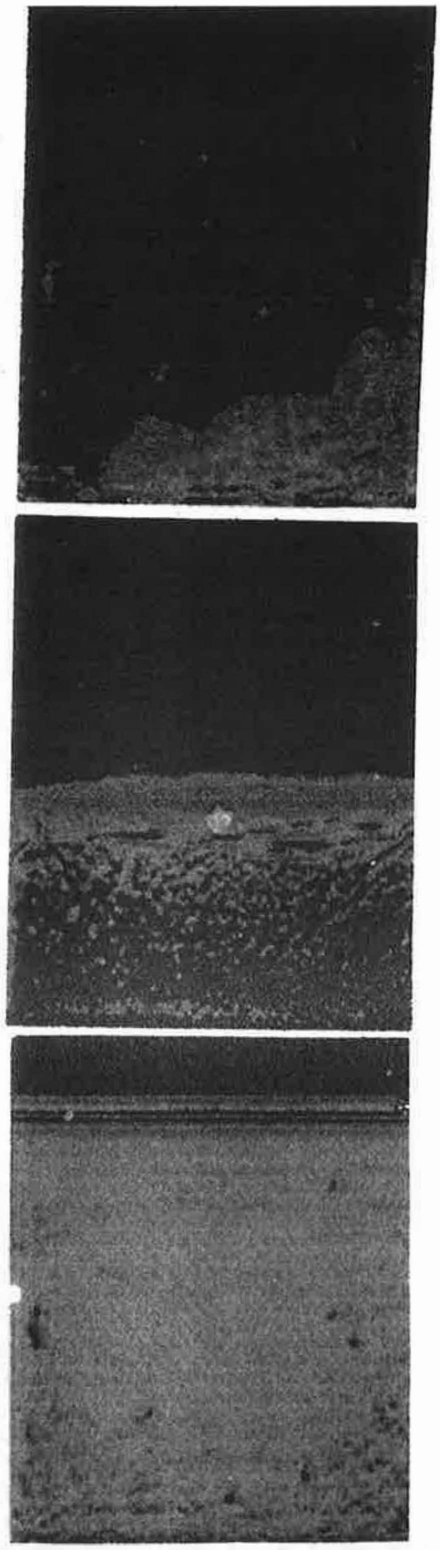


Figure 2: three images of the density profile in the room during the transient exchange flow. The horizontal tick mark on the right hand side corresponds to the top of the doorway

fluids varies with space and time in a typical experiment. Immediately after opening the doorway, the dense fluid rushes in along the base of the room, and mixes vigorously with the original room fluid. Once the gravity current of dense fluid reaches the end wall of the room, it is reflected and propagates back towards the doorway, further mixing the dense fluid inflowing fluid with the room fluid. When this stratified mixed layer has formed, the density contrast between the input fluid and that at the base of the room decreases, and a layer whose density is close to that of the external fluid gradually deepens at the base of the room below the mixed layer. The colour scale in the figure is directly related to the density of the fluid.

The details of this exchange process are complex owing to the vigourous mixing and formation of a density stratified layer in the room. In the experiments, the mixed layer occupied a depth of several cm, a significant fraction of the door height. Once the interface between the original room fluid and the mixed layer rose above about one half the door height, fluid in the mixed layer actually flowed out of the room as the exchange flow continued.

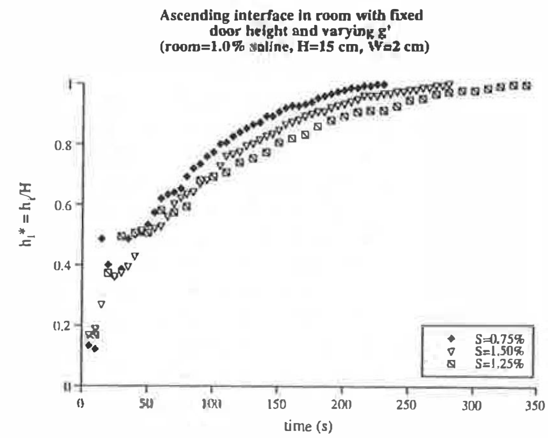
Previous studies of exchange flows through doorways have examined the initial stages of the exchange flow, before the stratified layer developed (cf. Dalziel and Lane-Serff, 1991) In the case of a smooth, slow opening, hydraulic theories have been proposed to quantify the magnitude of the exchange flow (Armi, 1986; Dalziel and Lane-Serff, 1991). For these theories, the fluid on each side of the doorway is assumed to have a fixed two-layer density stratification, and no mixing of the exchange flow with the ambient fluid is accounted for; in contrast, in the present case, the mixing of the exchange flow through the sharp doorway leads to significant mixing and so the density profile in the room becomes stratified below the top of the doorway. We have examined the impact of this evolving stratification on the mixing in the room by measuring the height of the top of the mixed layer, h_i, in the room as a function of time.

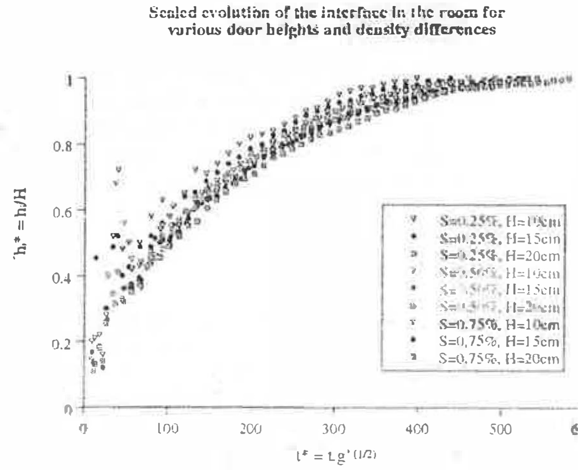
Figure 3a shows the raw data h/H as a function of time, t, for 3 experiments in which different values of H, the door height were used, but with the same buoyancy g'. Initially, the mixed layer deepens very quickly, corresponding to the initial propagation and reflection of the gravity current through the door, which leads to rapid mixing. However, once the mixed layer has ascended above about 0.5H, the rate of deepening of the mixed layer becomes more gradual. This is because the fluid subsequently entering the room is of very similar density to the fluid in the base of the room, so that the mixed layer then rises primarily as it is displaced upwards by the exchange flow, rather than through mixing within the room, which appears to dominate the initial stages of the mixing. The data collapse very well, suggesting that the door height has little impact on the time scale of the filling process.

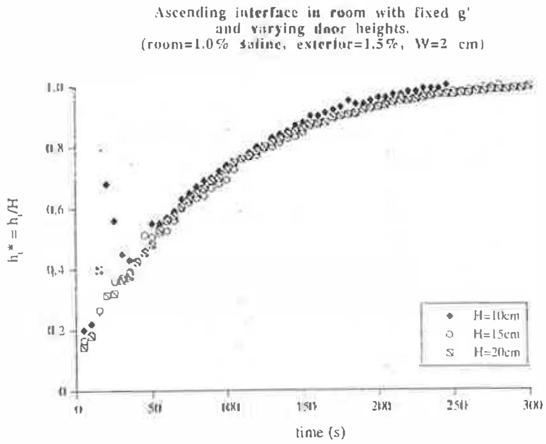
Figure 3b shows the data h/H for three experiments in which different initial density contrasts between the room and exterior were used with the same door height. The data are quite spread, suggesting an important time dependence of the filling of the room on the density contrast between the room and the exterior. Since g' depends on the inverse square of time and there are no other independent quantities controlling the exchange flow and mixing process which depend on time, we expect the time scale of mixing in the room to scale with $1/g'^{1/2}$. Therefore, in figure 3c, we have plotted the data from 9 experiments multiplying time by $g'^{1/2}$. The data from each set of experiments with a given value of g' appears to collapse to a single curve, confirming the independence of the filling process on H, and the data from experiments with different values of g' collapse much more closely than in figure 3b, as expected. Note, however, that there is a small but consistent increase in the time scale as the initial density contrast and hence buoyancy, g', across the doorway increases which may reflect a decrease in the initial mixing efficiency as the density contrast increases.

These data emphasize the importance of the mixing and formation of a stratified layer in the room during the filling of the room through the exchange flow. This is readily seen by comparison with model predictions which neglect the mixing. In the absence of mixing and formation of a stratified layer, the results of Dalziel and Lane-Serff (1991) allow one to estimate the scalings for the volume flux through the doorway which would drive the ascent of the density front in the room. Their data suggest that the exchange flow scales with $(g'H)^{1/2}A$, where A is the area of the door, and so with no mixing the ascent speed of the lower layer would be $dh/dt = (g'H)^{1/2}A/A(room)$. In this case, the time scale of the exchange flow would scale as $A(room)/w(g'H)^{1/2}$.

Our new experimental data are in accord with the prediction of the time dependence on g', but indicate that to leading order the time-scale of filling in the room is independent of H. We are presently examining how the exchange flow and filling process is influenced by the aspect ratio of the doorway and the area and length of the room; initial data indicate that the precise geometry of the room and of the doorway influences the time for mixing through enhancement or suppression of mixing at the sides of the inflowing current as it spreads from the doorway.







Figures 3 a,b,c: a corresponds to door heights of 10, 15 and 20cm; b: corrresponds to salinity contrasts of 0.25, 0.5, 0.75 and 1.0% c: corresponds to 9 experiments using door heights of 10, 15 and 20 cm and salinity contrasts of 0.25, 0.50 and 0.75%.

(ii) STEADY STATE FLOWS

In a second sequence of experiments, we investigated the interaction between the steady exchange flow through the doorway and a buoyant release of fresh water from the base of the vessel. These experiments identified that a new steady flow regime becomes established in which the steady exchange flow through the doorway is exactly balanced by the flux of fluid entrained by the plume. The route to this steady state is complex and depends on the stratification in the room at the point when the plume of buoyant fluid is added to the base of the room. For example, if the plume is applied some time after the doorway exchange flow has produced a two-layer stratification, then the plume may mix with a large quantity of the the cold air in the lower layer. As a result, on reaching the top of the cold layer of air, the plume may be cooler than the upper layer of warm air and so the plume intrudes laterally atthis point, forming an intermediate layer (figure 4; schematic and photograph). With time this intermediate layer deepens towards the top of the room by the process of penetrative convection (Kumagai, 1984).

The final two-layer stratification which becomes established in the room is controlled by the strength of the plume supplied from the base of the room. Indeed, in equilibrium, the plume entrains from the lower layer exactly that volume of fluid which passes in to the room from the exterior as a result of the exchange flow. The precise scalings for height of the interface and the density contrast across the interface depend on the details of the plume motion and the exchange flow, which may in general be complex for a finite sized source of heat. However, by dimensional arguments, one may see that the height of the interface in the room between the hot air and the cold air does not depend on the buoyancy flux supplied from the source since this flux depends on time, yet the steady height only depends on position. Thus we expect that the height of the interface in the doorway should depend primarily on the aspect ratio of the door as well as the length scale of the source of heating.

In figure 5, we present data showing the height of the interface in the room as a function of the doorway aspect ratio. The data show a clear trend of increasing interface height with increasing doorway width. This occurs because a greater exchange flow is possible through a wider door of the same height. The data collapse to a single curve, suggesting that in these experiments with a fixed source geometry, the interface height depends primarily on the door-way aspect ratio, as expected.

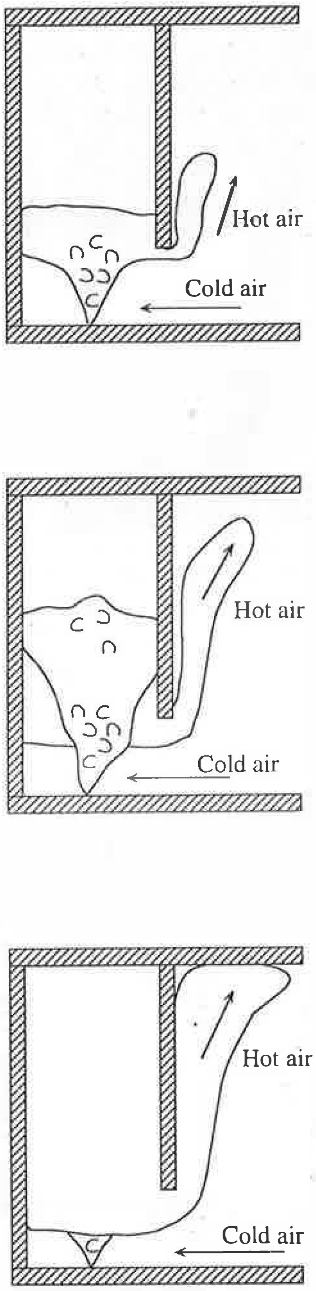


Figure 4a: Illustration of the route to steady state when a heat source is supplied at the base of the room.

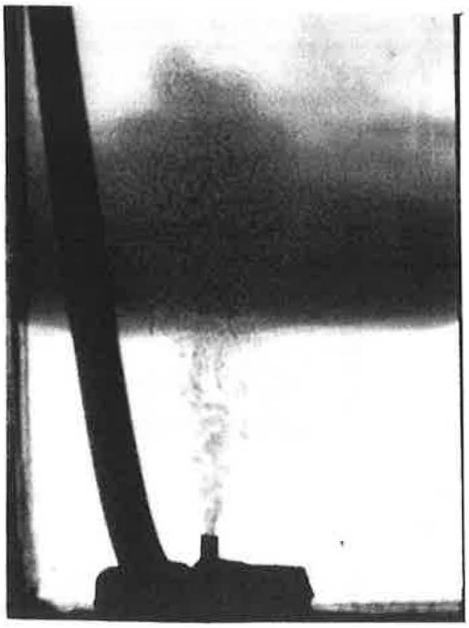


Figure 4b Photograph of exchange flow interacting with a plume of buoyant fluid released at the floor.

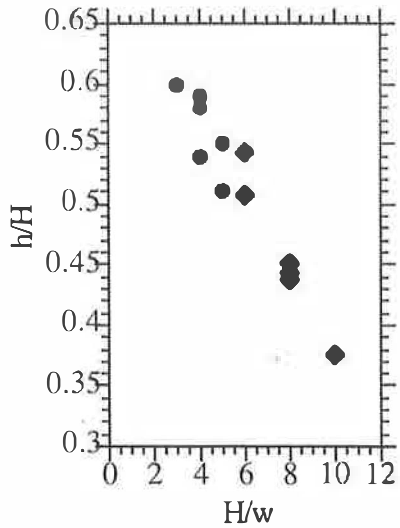


Figure 5: Steady interface height as a function of the doorway aspect ratio

DISCUSSION

We have presented a series of experiments on the transient and steady exchange flows between rooms of different density. The striking feature of our results is that there is a considerable amount of mixing after the onset of a transient exchange flow into a confined room. For the typical aspect ratio of our model room (18.5 x 37 cm) this leads to mixing of the room fluid in the region below the top of the doorway with the inflowing exchange flow. Experimentally, the time of mixing appears to be independent of the height of the doorway, but depends on the doorway width and room geometry. We are presently developing a model for the mixing along the sides and top of the inflowing exchange flow in an attempt to account for these experimental findings.

With a buoyancy flux applied at the base of the room, we have shown that a steady state flow becomes established, with the interface between the lower cold region and upper warm region forming below the top of the open doorway. The height of this interface is independent of the buoyancy flux and depends primarily on the aspect ratio of the doorway, as well as the source geometry. For tall thin doors, the interface is well below the top of the door while in wide, short doors, the interface ascends close to the top of the door.

The transient stages in which this steady state is established may involve the plume of warm air rising through the lower cold layer but being denser than the upper warm layer of air, and hence forming an intermediate intrusion of fluid near the top of the doorway. This has important safety implications for the dispersal of fire smoke or noxious gas: in a room which is ventilated with an open doorway, the plume of buoyant contaminant or smoke rising from the floor may remain trapped in the centre of the room, with a fraction flowing out of the room, for some time before reaching the ceiling. Hence, it may not always be optimal to locate fire alarms/gas detectors on the ceiling.

ACKNOWLEDGEMENTS

This work is sponsored by the EPSRC Built Environment Program.

REFERENCES

Armi, L. (1986) The hydraulics of two flowing layers with different densities. *J.*

Fluid Mech 163, 27-58

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

Kumagai, M. (1984), Turbulent buoyant convection from a source in a confined two-layer region. *J. Fluid Mech.* 147, 105-131.

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

Linden, P.F. & 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*, CUP.