Buoyancy Driven Flow Through an Open door

P.F. Linden and J.E. Simpson
Department of Applied Mathematics & Theoretical Physics
University of Cambridge, UK

Introduction

A good understanding of natural ventilation air-flows through open doors and windows can be obtained by using laboratory experiments in water tanks. Such flows are of great importance, since only very few houses in the world have any artificially driven and controlled ventilation systems. Most rely on mixing by convection currents produced by heating from internal sources, and on the use of open windows and doors for external ventilation. These open windows and doors can be responsible for excessive losses of heat in cold countries and invasion of hot air in hot climates, as gravity currents of dense or buoyant air pass through these spaces.

Even at quite small temperature differences (a few degrees) between the exterior and interior 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 indoor air flows along the ceiling. These flows account for a significant part of total heat losses in housing, and can also determine the distribution of indoor contaminants within a building.

Laboratory Experiments

Experiments can be set up in small scale laboratory apparatus which serve to demonstrate the kinds of flow which can occur and enable realistic calculations to be made about the full-size flows. In such experiments, rather than use hot and cold air, it is better to use water as the working fluid, with density differences produced by dissolved salt. By this means it is easier to achieve dynamic similarity by maintaining the correct range of the relevant dimensionless numbers concerned with viscosity and diffusion. These are:

		domestic–industrial
Reynolds No.	$Re = (g'H)^{1/2} H/\nu$	range $10^3 - 10^6$
Peclet No.	$Pe = (g'H)^{1/2} H/K$	$10^3 - 10^6$

where $g' = g\Delta\rho/\rho$, where g is the acceleration due to gravity and $\Delta\rho/\rho$ is the fractional density difference, ν is the viscosity and K the diffusivity.

Using air as the working fluid these parameters are smaller by a factor of $[H(\text{model})/H(\text{full size})]^{3/2}$ for the same temperature difference ΔT. Full scale values can be readily obtained using water tanks. It is worth noting that a temperature difference of 3K in air corresponds to a density difference of about 1%.

Two-dimensional Flows

The flow which takes place through an open doorway at the end of a passage is illustrated in figure 1. When the door is opened the dyed dense fluid enters the building as a gravity current. This current fills half the depth of the door and advances at a uniform velocity U along the floor. Outside the house at the same time the less dense fluid can be seen rising up the outer wall and mixing with the surroundings.

In this type of exchange flow the orifice (of height H) acts as a hydraulic control, and the speed of the intruding current is

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

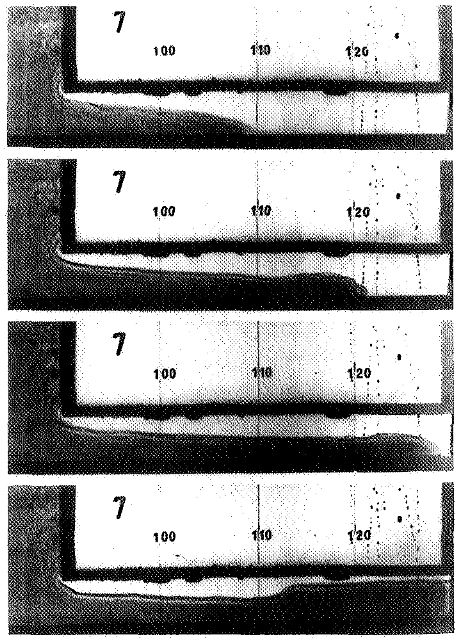

Figure 1: Four views of the advance of a dense flow through an open door in a laboratory experiment. The door height is 10 cm and the density difference $\Delta\rho/\rho$ is 1%. The separation between the vertical lines is 10 cm

When the front of the current reaches the end wall the flow is reflected and can be seen travelling back towards the door. The dense fluid almost fills the space, but there is a small space above filled with lighter fluid which appears to have difficulty in escaping due to frictional effects near the ceiling.

Figure 2 shows some of the experimental results, plotted on a log/log scale in non-dimensional form. The distance X is expressed non-dimensionally 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 $U = 0.47\,(g'H)^{1/2}$, close to the theoretical value stated above.

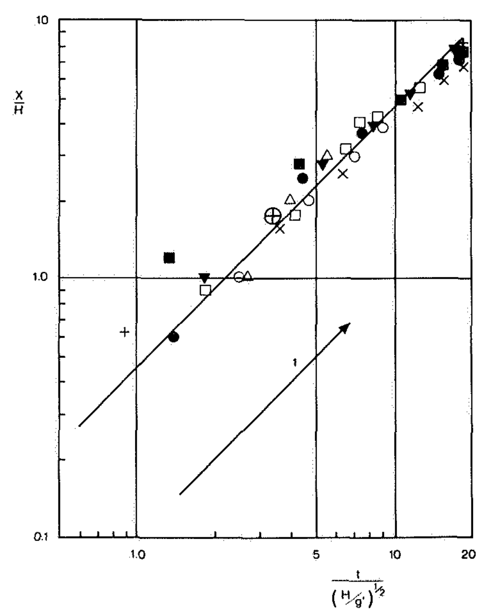

Figure 2 : Measurements from a series of experiments similar to those shown in figure 1. The point ⊕ corresponds to observations made in the house of one of the authors, and it agrees with the laboratory data showing that the experiments accurately represent the full-scale flow

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.

Three-dimensional Flows

We have also carried out experiments in which the flow is no longer restricted to a parallel channel such as in a passage. For example in a more general case we may have a door in a much wider wall, so that the flow through it can widen out after passing through the doorway.

To illustrate some of the flows here, a series of experiments was carried out in a simple apparatus consisting of a box of perspex, just under a metre cube, with a vertical partition across it containing a door which could be opened. As before the tank was filled with water and salt dissolved on one side of the door to produce a density difference, corresponding to that produced by a temperature difference in the air.

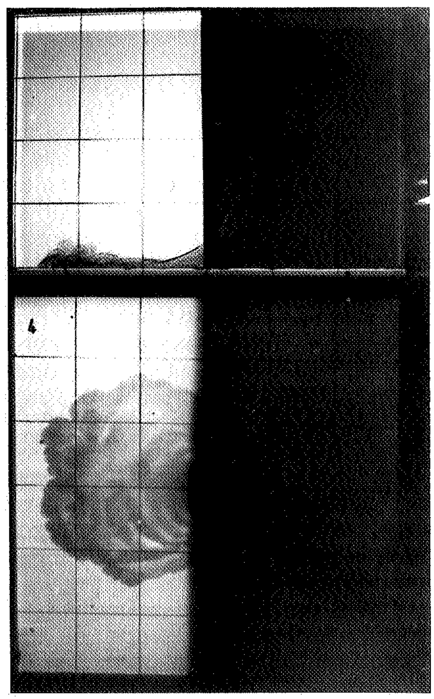

Figure 3: Simultaneous plan and elevation of the exchange flow through a doorway in a wall. Note the marked difference in behaviour between the dense fluid (on the left) and the buoyant fluid (on the right)

When the door was opened the dense flow issued through the door and spread out along the ground, while the less dense fluid rose up the wall as a buoyancy plume on the other side. The radial spread of the dense fluid is clearly visible in figure 3. The exchange flow provides a constant flux Q through the doorway

$$Q = 0.5\,HWU,$$

where H and W are the height and width of the door and U is the velocity of the leading edge of the front moving along the floor.

On the basis of dimensional analysis we expect that the position X of the foremost point of the leading edge be given by

$$X = c(Qg')^{1/4}\,t^{3/4},$$

where c is a constant, and this result is confirmed by the experimental results shown in figure 4.

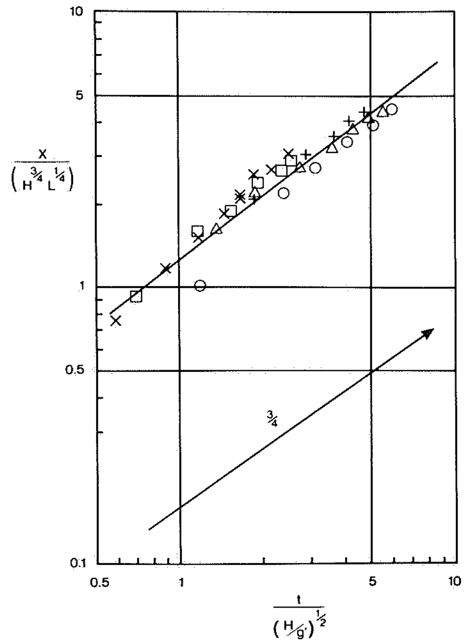

Figure 4: Measurements of the spread of the gravity current with time through a doorway into a large room

Summary of These Effects

a) After an initial acceleration phase ~ $(H/g')^{1/2}$ the flow takes on gravity current behaviour.

b) A doorway acts as a region of hydraulic control.

c) The transient effects – as the room fills with cold or warm air – are significant.

d) During gravity current phases, flow rates and heat losses can be accurately modelled using gravity current dynamics.

The technique described for these investigations has the advantage that it is inexpensive. Complicated patterns of doors and passageways and even separate floors as found in atria can easily be set up. Other effects such as turbulence in the outside air, or the effects of air curtains can readily be incorporated into these laboratory models. Most importantly the experiments give a clear visual picture of the flows concerned, and they are capable of producing realistic numerical results of both the rates of flow and the amounts of heat loss or gain. We believe these features will be of value to those interested in estimating the energy consumption of a building.

References

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