LABORATORY MODELLING OF NATURAL VENTILATION VIA CHIMNEYS

G.F.LANE-SERFF, P.F.LINDEN, D.J.PARKER and D.A.SMEED

CERC Ltd
3D King's Parade
Cambridge CB2 1SJ
U.K.

DAMTP
Silver Street
Cambridge CB3 9EW
U.K.

ABSTRACT. In this paper we describe a study of the design for a new Engineering School at Leicester Polytechnic, a large building containing a range of spaces including auditoria, drawing studios, laboratories and classrooms. Natural ventilation is the use of naturally occurring pressure differences caused by the wind or by temperature differences to drive a ventilation flow. It is the latter type of natural ventilation (using the "stack effect") that will be considered in this paper. A particular feature of the proposed design is that it uses chimney vents to enhance the stack effect and one of the goals of our study was to establish the effectiveness of this type of system. The building design was studied by a laboratory simulation using a scale model. The experiments showed that the basic design of the ventilation system was sound and indicated areas that needed modification. The results demonstrated that it is generally better to have isolated systems with separate vents for each space rather than having different spaces sharing the same vents. This is because the flows between connected spaces are sensitive to small differences in the occupancy and vent areas of each space. Isolated spaces are also better for the containment of fires and smoke.

1. Introduction: Natural Ventilation

In this paper we describe the results of an investigation into naturally driven ventilation in the proposed building for the School of Engineering at Leicester Polytechnic. The expected heat gains in parts of the building are large, and it was necessary to investigate whether natural ventilation would provide adequate flow rates to maintain comfortable conditions. The study is confined to an investigation of buoyancy driven natural ventilation, ie where the flow is driven by temperature differences (the "stack effect"). In particular, the effect of the wind is not taken into account. The basic principle is to use the temperature differences to induce a flow which will bring cool ambient air into the space.

The ventilation flows found in naturally ventilated spaces can be split into two broad categories: mixing and displacement flows. If the incoming cool air is introduced near the top of a space containing sources of heat then it will descend into the space, mixing up the air and giving a fairly uniform temperature profile. If, however, the cool air is introduced near the floor, and warm air is extracted near the ceiling, a displacement flow will be established with a high degree of stratification. Above the heat sources (such as occupants, equipment, etc) warm air will rise as turbulent plumes, and spread out within the building on

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reaching the ceiling to form a warm upper layer. This layer will drive flow out of the upper vents and draw ambient air in through the lower vents. (See figure 1.) A steady state will develop with the lower part of the room containing air at close to ambient temperatures, and with warm air confined to the layer in the upper part of the room (and to the rising plumes). There will be an interface between the cool and warm air, and it is clearly desirable to have this interface above the occupied zone. For more details of this type of flow, including a mathematical analysis, see Linden *et al*, 1990.

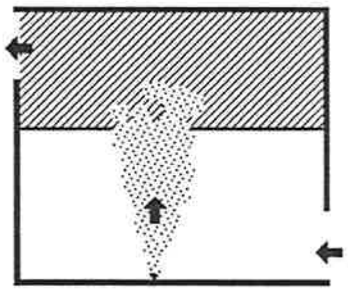

Figure 1. Natural ventilation: displacement type. Warm air rises from the heat source as a turbulent plume, entraining cooler air as it rises. The warm air from the plume forms a layer in the upper part of the space which drives a flow out of the upper opening and in through the lower opening.

2. Case Study: Leicester Polytechnic School of Engineering

The new Engineering School at Leicester Polytechnic is a large building containing a variety of spaces including auditoria, drawing studios, laboratories and classrooms (see figure 2). The building was designed with energy conservation in mind and so makes extensive use of natural light and natural ventilation. Some of the spaces are on the perimeter of the building and fairly shallow so that it is expected that natural ventilation through openable windows will be adequate for these spaces. Many spaces have large gains and little outside wall area and it was not clear that all of these could be adequately ventilated by natural means. The ventilation outlets from these spaces were in the form of tall chimneys to increase the effective stack height. In addition there were low level vents to allow outside air to flow into the spaces near the floor, and with the warm air leaving via the chimney vents this gives a displacement system. The use of tall chimneys is a radical new approach to natural ventilation design, and our work was aimed at assessing the performance of this system.

With the exception of the laboratories most of the heat gains within each space came from occupants. The spaces investigated were the auditoria (gains of 15kW each), laboratories (20kW), drawing studios (3kW), classrooms (3kW) and the central concourse (variable gains of up to 40kW). The effects of a fire in the concourse were also studied (5MW).

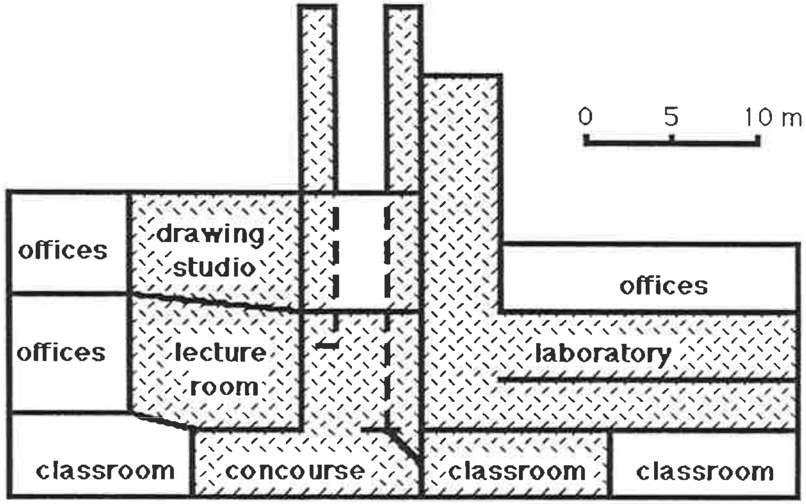

Figure 2. Simplified section of the Engineering School. The shaded rooms were those modelled.

3. Laboratory Modelling

3.1 EXPERIMENTAL TECHNIQUES

A 1:75 scale model of part of the building was used for these tests. The model was made from clear perspex to allow visualisation of the flows. Some features of the building were simplified but the larger spaces and the vents connecting them to one another and to the outside were included. The model was suspended upside down in a large tank of water. Heat sources were represented by sources of salt solution. The falling of dense salt solution in the model represents the rising of warm air in the real building.

The salt water ("hot air") was dyed and a side elevation filmed using an inverted video camera. Samples of fluid were taken during the experiments and the density of these samples determined. These densities can be related to the equivalent temperature for the full scale building.

3.2 SCALING LAWS

For the ventilation flows studied the effects of heat diffusion and viscosity are small compared with advection, as is evident from the high Péclet and Reynolds numbers (of 1000 and above). To simulate these flows accurately in the laboratory it is necessary to ensure that the Péclet and Reynolds numbers in the simulation are also large. This can be achieved in small scale models using water as the working fluid with salt providing density differences, since the viscosity of water is less than that of air and because larger density differences may be achieved without compressibility effects becoming important.

In general lengths, times, velocities and density differences are all different in the model compared with those in the real building. In the experiments described below the flows occurred five to ten times quicker in the model than they would in the real building. Length scales are obviously governed by the scale of the model; other scales are determined by this in conjunction with ratio of buoyancy fluxes between the model and full scale (the buoyancy flux is proportional to the heat flux). The buoyancy forces depend on the difference in densities between different parts of the fluid. A parcel of fluid of density $\rho+\Delta\rho$ surrounded by fluid of density ρ will experience an acceleration of approximately $g\Delta\rho/\rho$, where g is the acceleration due to gravity. This acceleration is known as the "reduced gravity", and will be denoted by g'. For air it is useful to note that $\Delta\rho/\rho$ is approximately equal to $\Delta T/(T+273)$, where T is the temperature in °C. It is not necessary to use the same density differences in the model as would occur in the real building, rather they are chosen to give high enough Reynolds numbers. The scales for times (t), velocities (U) and buoyancy fluxes (B) can be constructed from the length scales (L) and g' as shown in table 1. The model scales are denoted by the subscript M, the full-scale ones by F.

		model	full-scale
scale:	times	$(L_M/g'_M)^{1/2}$	$(L_F/g'_F)^{1/2}$
	velocities	$(L_M g'_M)^{1/2}$	$(L_F g'_F)^{1/2}$
	buoyancy fluxes	$L_M^{5/2} g'^{\,3/2}_M$	$L_F^{5/2} g'^{\,3/2}_F$

Table 1. Scales for other variables in terms of the length-scale and the reduced gravity ($g' \equiv g\Delta\rho/\rho$).

Thus, for example, the ratio of velocities in an experiment to those at full-scale will be $(L_M g'_M)^{1/2} : (L_F g'_F)^{1/2}$. The buoyancy flux due to a heat source of 1kW in air at normal temperatures is approximately 0.028 m^4s^{-3}. It should be noted that while the temperatures and flow rates depend on the strength of the heat sources, the basic flow patterns depend only on the geometry and positions of the sources and vents.

As advection provides the dominant part of the heat fluxes in this building, the laboratory model gives reliable estimates of the fluid flow. The details of the fluid flow can then be used in a thermal model to give heat flows between massive parts of the building and also to give the temperature perceived by occupants.

3.3 EXPERIMENTS

Most of the flows observed were displacement type flows with cool ambient air entering through vents near the floor of a space and warm air leaving through vents near the ceiling. There were, however, cases with some mixing caused by incoming fluid entering at high levels or due to high inlet velocities disturbing the stratification in the space. The flow in various spaces was investigated, with both isolated spaces and sets of interconnected spaces being considered. The model incorporated a range of ducts and vents for each space, so that the best strategy for each space could be determined, and detailed recommendations about the size and position of vents could be given. In addition to tests under normal loads, some fire tests were carried out, simulating a fire of 5MW in the concourse.

4. Results

4.1 VENTILATION EXPERIMENTS

A variety of vent areas and positions was tried for each space, and some examples of the results for isolated spaces are given in table 2. Adequate flow rates could be achieved in all spaces, indeed the classrooms proved to be overventilated with uncomfortably large air speeds. However, flow rates do not give the complete picture. From studying the video and from the samples taken during experiments it was clear that there would be a problem with the mezzanine floor in the laboratory. Due to the stratification that built up the temperature on the mezzanine could reach 8°C above ambient even with all the available vents open. In a space ventilated by natural displacement ventilation there is always a problem in keeping the upper part of the space cool, and it is generally necessary to have a "dead space" above the topmost occupied zone that can be allowed to get hot.

Room	Occupancy (people)	Gains (kW)	Vent area (m^2)	Stack height (m)	Flow rate (l/s)
Drawing studio	30	3	4.5	6.5	1300
Lecture room	150	15	3	19	2200
Laboratory	50	20	6	16	5400
Classroom	30	3	1	22	4000
Concourse	100	10	3	22	2100

Table 2. Examples of results from the modelling study for various rooms. The stack height is the distance from the floor of the space to the upper vents. This height is generally bigger than the height of the room because of the use of chimney vents.

As well as experiments with isolated systems, experiments were conducted where different spaces shared the same vents. Problems were found especially when the concourse and lecture room shared the same chimney vents. Hot air flowed from one space to the other depending on only slight changes in the heat gains and vent areas of the two spaces. Given this, and the implications for smoke movement in the case of a fire, it was recommended that the concourse and lecture room have separate vents.

4.2 FIRE TESTS

The results of the fire tests depended on the location of the fire. If the plume from the fire rises close to a wall then entrainment is impeded. This results in a hotter plume but of smaller volume. In all cases there was a rapid build up of a smoke layer at the top of the space which would reach the occupied zone in about 3 minutes. We recommended that there would need to be additional emergency vents (of area at least $15m^2$) to clear the smoke by natural means.

5. Conclusions

The experiments showed that the basic design of the natural ventilation system was sound, and indicated areas that needed modification (design modifications have since been made, particularly to the laboratory and for coping with fires in the concourse). The results demonstrated that it is generally better to have isolated systems with separate vents for each space rather than having different spaces sharing the same vents. This is because the flows between such spaces vary significantly for small differences in the occupancy and vent areas of each space, making the flow effectively unpredictable. Isolated spaces are also better for the containment of fires and smoke.

Laboratory modelling is a very useful tool in the design of naturally ventilated buildings, it is possible to model complicated geometries that are beyond the scope of present computing power. The amount of quantitative information that can be recovered from a laboratory experiment is increasing with the advent of powerful image processing facilities. This type of modelling is also useful in giving a qualitative understanding of the flows, and is especially useful for conveying information about the basic fluid dynamics to non-specialists.

6. References

Lane-Serff, G.F. (1989) "Laboratory models of transient, buoyancy-driven flow", in J.H. Vincent (ed), Ventilation '88, Pergamon, Oxford, pp391-396.

Lane-Serff, G.F. (1989) "Heat flow and air movement in buildings", PhD thesis, Cambridge University.

Lane-Serff, G.F., P.F. Linden, M. Galtry, N.V. Baker (1990) "Laboratory and mathematical modelling: the design of a naturally ventilated building", in F. Lunau and G.L. Reynolds (eds), Indoor air quality and ventilation, Selper, London, pp45-54.

Lane-Serff, G.F., P.F. Linden and D.A. Smeed "Laboratory and mathematical models of natural ventilation", in proc. Roomvent '90, Oslo, 13-15 June, 1990.

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