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LABORATORY AND MATHEMATICAL MODELLING: THE DESIGN OF A NATURALLY VENTILATED BUILDING

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ABSTRACT

Heat sources within a building lead to temperature differences which can be used to drive ventilation flows using the "stack effect". These buoyancy-driven flows, and their implications for building design, are investigated in this paper. Water-filled laboratory models can be used to study the flow, with salt solutions of different concentrations representing air at different temperatures in the real building. A description of the use of laboratory models is given, together with the scaling laws necessary to apply the results to a full-scale building. An outline of a mathematical model is also given, and the general features of natural ventilation are discussed. These modelling techniques are applied to a proposed building project.

1. INTRODUCTION

Natural ventilation is the use of naturally occurring pressure differences to drive a ventilation flow. These pressure differences may be caused by the action of the wind or by temperature differences between the internal and external air. It is the latter type of natural ventilation, using the "stack effect", that will be discussed in this paper. Though wind-driven ventilation is important it generally results in increased ventilation rates compared with those observed on calm days, and will not be considered here. In recent years there has been increased interest in the use of natural, rather than mechanical, ventilation, especially for the ventilation of large spaces with high solar gains such as atria (1). Clearly the use of novel ventilation techniques requires extensive testing and modelling at the design stage.

In section 2 of this paper we describe techniques for the laboratory modelling of ventilation flows driven by temperature differences, using water-filled models with different concentrations of salt solution representing different temperatures. In section 3 we give an outline of a mathematical model of such flows (greater detail of this model is given in (2)). The application of these techniques to a particular building project (Department of Humanities at the University of Seville) is given in section 4, and in the final section, section 5, we conclude with a discussion of the general features of natural ventilation and the use of modelling in the design process.

2. LABORATORY MODELLING OF VENTILATION FLOWS

2.1 Scaling Laws

For the ventilation flows considered here the effects of viscosity and heat diffusion are small, as is evident from the values of the Reynolds and Péclet numbers (10^3 and greater). These numbers are given by UL/ν and UL/κ respectively, where U is a typical velocity, L is a typical length, ν is the viscosity of air and κ is the diffusivity of heat. At such large values the flow will be independent of these numbers, except at the smallest scales. To simulate these flows in the laboratory it is necessary to ensure that the values of the Reynolds and Péclet numbers in the experiment are sufficiently high. This can be achieved in the laboratory in small scale models using water as the working fluid and adding salt to produce density differences (3,4,5). Thus different salt concentrations represent different temperatures. Note that since heat is modelled by salt it is the diffusivity of salt in water that gives the relevant Péclet number.

The driving force in these flows is the buoyancy force caused by density differences 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 $g\Delta\rho/\rho$, if $\Delta\rho/\rho$ is small. This acceleration is known as the *reduced gravity*, and it will be denoted by g'. For air, it is useful to note that $\Delta\rho/\rho$ is approximately equal to $-\Delta T/T$, where T is the temperature measured in Kelvin. It is not necessary to use the same density difference in the model as in the real situation, rather it is chosen to give high enough Reynolds numbers. The relation between the experimental results and the real situation is found by considering the appropriate scalings. The subscripts M and F will be used to denote the scales in the model and real (full-scale) cases. Length-scales will be denoted by L, velocities by U, times by t and buoyancy fluxes by B. (The buoyancy flux is the flux of g'.) These scales can all be constructed from the length-scale and g' as shown in table 1.

		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 $(L_M g'_M)^{1/2} : (L_F g'_F)^{1/2}$. It is useful to note that the buoyancy flux due to a heat source of strength W (in kilowatts) in air is $B=0.0281W$, where B is measured in m^4s^{-3}. Further discussion of scalings will be given below with reference to the study of a particular building.

2.2 Experimental Techniques

The laboratory models are constructed from clear perspex, which allows visualisation of the flows. The concentration of salt solutions may be measured either by taking samples or by measurement *in situ* using conductivity probes. The latter technique makes use of the change in conductivity of salt solutions with changing concentration. Note that since salt water is denser than fresh water higher salt concentrations represent lower temperatures. In many cases, including the case described below, it is convenient to turn the model upside down so that higher salt concentrations represent higher temperatures and heat sources can be represented by sources of salty water.

The flows are visualised by shining light through the apparatus onto a translucent screen forming a *shadowgraph*. Since different concentrations of salt solution have a different refractive index, changes in salt concentration are shown by this technique. Dyes are also used to mark different parts of the fluid as they are advected by the flow. The flow is recorded using video cameras and by taking still photos, and can be examined in detail using image processing techniques.

3. MATHEMATICAL MODEL OF NATURAL VENTILATION

In this section the main results of mathematical models of ventilation flows will be given. For a full decription of modelling of ventilation flows see (2,5), for flow through openings see (6,7,8,9), for turbulent plumes see (10), and for plumes in a closed space see (11,12).

3.1 Mixing Ventilation

Mixing ventilation occurs where a heated space is connected to cooler ambient air by openings near the top of the space. Warm air leaves through these openings and cool air enters, often mixing throughout the space as it descends giving a fairly uniform temperature throughout the space. A steady situation will develop, with the heat lost through the openings being balanced by the heat sources within the space. If there is a single opening, of height d and area A, connecting a space at temperature $T+\Delta T$ with ambient air at temperature T, then the air flow through the opening will be

$$F = kA\,(dg'\Delta T/T\,)^{1/2}, \tag{1}$$

where k is a constant equal to 0.25. For an opening in the ceiling, such as a skylight, the flux can again be found from equation (1) with k=0.05. If the space contains a heat source of W kW, and lengths are measured in metres, the steady temperature is given by $T + \Delta T_M$, with

$$\Delta T_M = 2.8\,(W/kAd^{\,1/2})^{2/3}. \tag{2}$$

3.2 Displacement Ventilation

If a heated space has openings near the floor and openings near the ceiling connecting the space to cooler ambient air, then warm air will leave through the upper openings and cooler air will enter through the lower openings. The air in the space will be highly stratified with cool air near the floor and warm air near the ceiling. We consider here the simple case of a single heat source on the floor of a space with an opening near the ceiling of area a_1 and an opening near the floor of area a_2. A turbulent plume will rise above the heat source, entraining ambient air and becoming cooler as it rises. A layer of warm air will build up near the ceiling, driving a flow through the openings due to the stack effect. Eventually a steady state will develop, with a stationary interface between warm air in the upper layer and cool air in the lower layer, as shown in figure 1. The only flow from the lower to upper layer will be within the rising plume, so the flux in the plume at the interface level must match the flux out through the upper opening, which in turn must be equal to the inflow through the lower opening. In addition, in the steady state the heat flux into the upper layer, due to the plume, must equal the heat flux out through the upper opening. Thus the temperature in the rising plume at the interface level must equal the temperature of the air leaving the space through the upper opening. Therefore, the temperature of the upper layer must be uniform throughout the layer, equal to the temperature in the plume at the interface level.

Writing H for the height of the space and h for the height of the interface, the steady state balances described above lead to a relation between the area of the openings and the interface height

$$A/H^2 = 0.04\,(h/H\,)^{5/2}(1-h/H\,)^{-1/2}, \tag{3}$$

where A is the *effective area*, given by

$$A\ = (a_1\,a_2)/(1/2(a_1{}^2/c\ -a_2{}^2\,))^{1/2}. \tag{4}$$

In equation (4) c is a constant lying between one half, for a sharp expansion at the inlet, to unity, for a perfectly smooth expansion. The effective area is dominated by the smaller of the total area of the upper and lower openings. Notice that the strength of the heat source does not appear in equation (3): the interface height is a geometric quantity determined by the geometric relation between the area of the openings and the height of the space. The temperature difference between the upper and lower layer, which will be denoted by ΔT_D, does depend on the heat source, being given by

$$\Delta T_D = 24W^{2/3}h^{-5/3}, \tag{5}$$

where h is measured in metres, W in kilowatts and ΔT_D in degrees Celsius or Kelvin.

If, instead of a point source, the heat source is a line source spreading the full length of the space, the interface height is given by

$$A_L/H\ = 0.2\,((h/H\,)^3/(1-h/H\,))^{1/2}, \tag{6}$$

where A_L is the effective area per unit length. The temperature difference between the upper and lower layer is given by

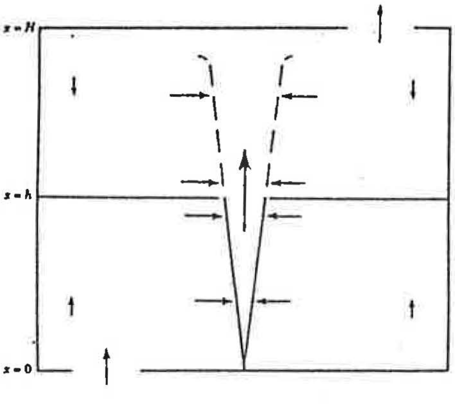


Figure 1. Steady displacement flow in a space containing a source of buoyancy.

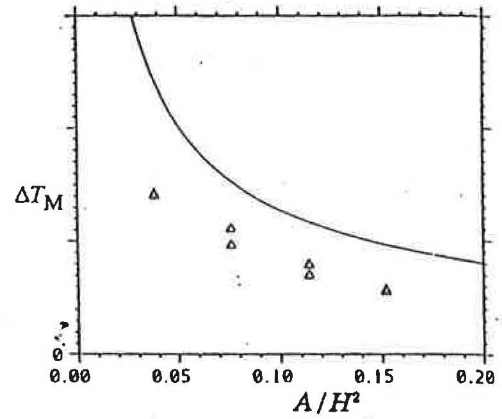
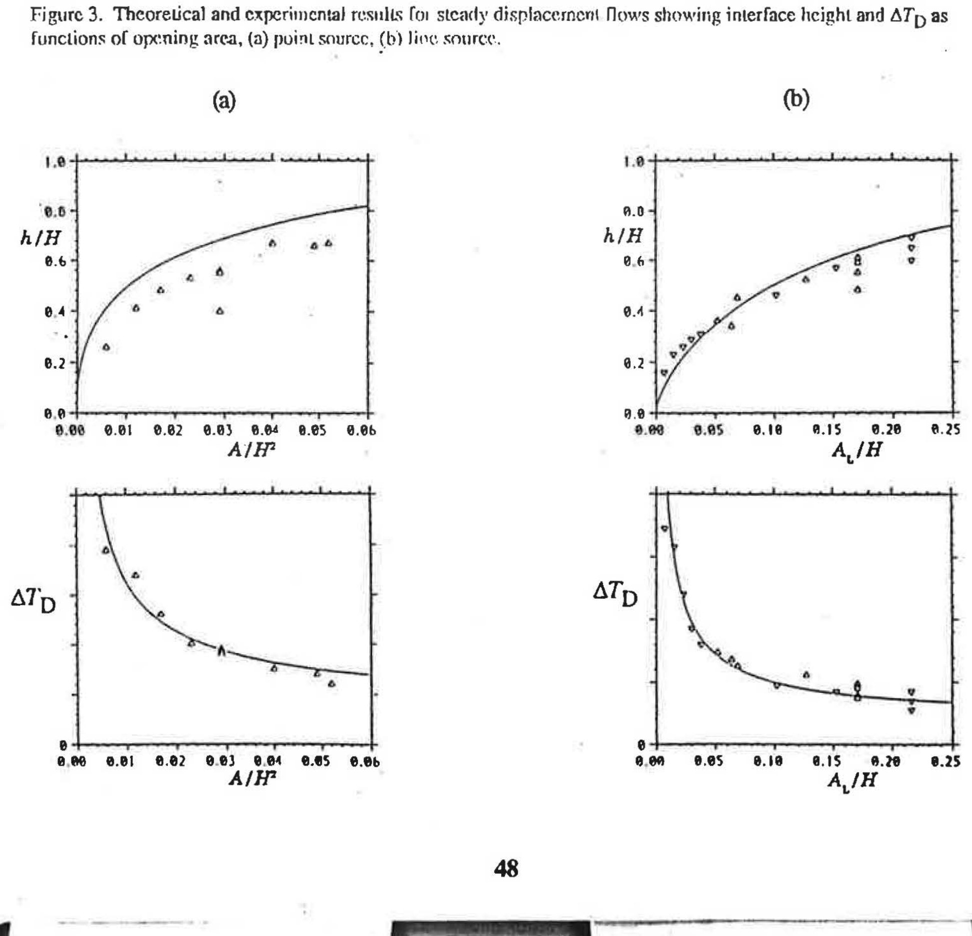


Figure 2. Theoretical and experimental results for steady mixing flows showing ΔT_M as a function of opening area.

Figure 3. Theoretical and experimental results for steady displacement flows showing interface height and ΔT_D as functions of opening area, (a) point source, (b) line source.



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4. CASE STUDY: I

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The distinctive feature of this buildin
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The design has been developed by the
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4.1 Design Considerations.

The basic strategy can be summed up
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4.2 The Role of the Physical Model Study

First it was necessary to show that
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the upper atrium.

$$\Delta T_D = 8 W_L^{2/3} h^{-1}, \tag{7}$$

where W_L is the heat strength per unit length. Note that all these results for displacement flows are for a source on the floor of the space: if the source is elevated then h and H should be measured from the height of the source. Note also that the height of the lower opening is immaterial, as far as the position of the interface is concerned, provided it is below the level of the interface.

The results for both mixing and displacement flows are shown in graphical form on figures 2 and 3, together with results from laboratory experiments conducted in a simple rectangular box. The results given in this section apply to a single point or line source, but the analysis can be extended to multiple sources and to area sources as shown in (2).

4. CASE STUDY: DEPARTMENT OF HUMANITIES, SEVILLE

Initially this building is to form part of the EXPO '92 World Exhibition Secretariat; its final use will be as the Department of Humanities for the re-sited University of Seville. It is a large building, approx 20,000 m^2, and is in the form of a linear slab of three and four storey accomodation on either side of an atrium, figure 4.

The distinctive feature of this building is that it is to be naturally ventilated and daylit with the intention of minimising energy running costs without compromising comfort. This is a significant challenge to the designers, bearing in mind that typical average daily temperatures rise to 28°C in summer with peak temperatures over 30°C. The design has been developed by the Architect Jaime Lopez de Asian of the Seminario de Arquitectura Bioclimatica, Seville. Under the CEC Project Building 2000, the architect has received technical consultancy from a number of European experts, and as part of this the natural ventilation design has been developed and studied by Cambridge Architectural Research Ltd and Cambridge Environmental Research Consultants Ltd. It is this study which will now be described.

4.1 Design Considerations.

The basic strategy can be summed up as follows. Ventilation will by driven by pressure differences induced by hot air high in the central atrium space above the occupied zones. When wind is present the flow pattern will be maintained due to negative pressures induced at the openings in the ridge of the atrium roof. Ventilation openings will be under intelligent control. Data such as external air temperature, temperature of the building structure, and internal gains will be input to a computer holding a thermal model of the building. This will minimise over-ventilation in the daytime when external temperatures may be above the temperature inside the building, and maximise ventilation at night-time.

The ground level of the atrium will form a cool refuge from the more densely occupied parts of the building. This will be achieved by encouraging stratification in the atrium and limiting ventilation as described above, together with evaporative cooling by vegetation and fountains, and the absorbtion of gains by the massive structure, cooled by night-ventilation.

A necessary adjunct to this strategy is the minimising of solar gains, but without compromising daylighting. This suggests that the shading devices should also be under centralised intelligent control.

4.2 The Role of the Physical Model Study

First it was necessary to show that ventilation rates sufficient to remove internal gains from the densely occupied spaces, such as the lecture rooms, could be induced by the buoyancy of the hot air in the upper part of the atrium. It was also important to investigate the position if the interface layer in relation to the occupied zones of the upper atrium.

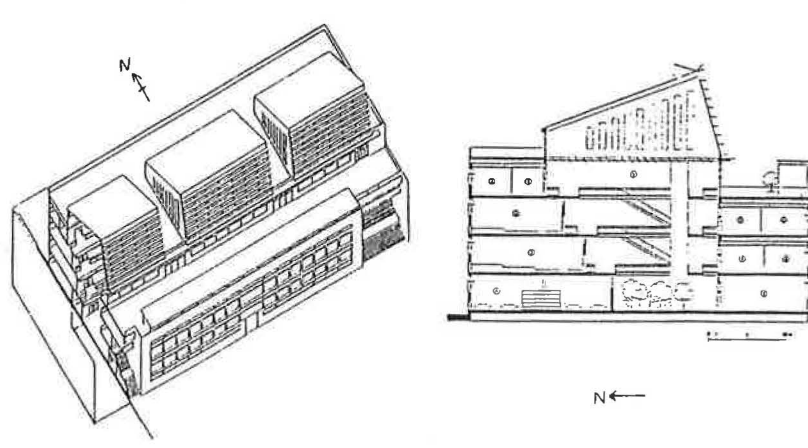
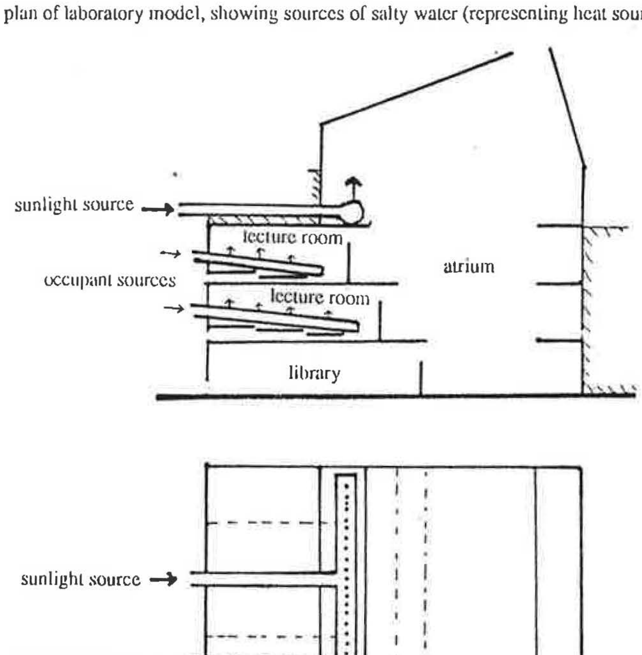


Figure 4. Perspective view and section of University building.

Figure 5. Section and plan of laboratory model, showing sources of salty water (representing heat sources).



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4.3 Modelling Studies

Modelling

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Results

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Preliminary buoyancy calculations established opening sizes in the outside walls of the lecture rooms and between the rooms and the atrium, which, with certain assumptions, would lead to a temperature increment in the rooms of 3°C. This, with an air movement of 0.1 ms^{-1} and an ambient relative humidity of 45%, would result in a Corrected Effective Temperature of about 27°C, which was considered an acceptable target. These opening sizes, which were quite large (about 4 m^2 in both external and atrium walls), were adopted in the scale model.

A further principle to be demonstrated was the introduction of fresh air via the stepped floor (figure 4). This served several purposes: it ensured that the fresh air was distributed more equitably to the occupants of the deep room (11m from outside wall to atrium), it also permitted the provision of blackout without impeding ventilation - not possible if conventional window openings are used.

Other concerns were mainly with conditions in the atrium. The main question here was whether the "cool pool" concept was viable. The maintenance of air below ambient temperature in the ground level of the atrium relied upon two conditions: first, that much warmer air exhausted from the library and the lecture rooms into the atrium should not mix with the cool pool and, second, that gains made in the ground floor zone (largely from occupants) could be absorbed into the massive structure (previously cooled by night ventilation). The first of these conditions could clearly be investigated with fluid modelling, the second was explored by mathematical thermal modelling.

4.3 Modelling Studies

Modelling

A perspex 1:100 scale model of the central third of the building was constructed. The lecture rooms and library space on the northern side of the building were included, as was the central atrium, but the offices on the southern side were not included. The lecture rooms and library had openings to the atrium and to the ambient fluid. In addition there was a large opening along the roof ridge of the atrium, some doorway openings at ground level in the atrium and openings on the southern wall of the atrium representing connections with the (unmodelled) offices. The model was suspended upside down in a large tank of water, illuminated by the shadowgraph technique and filmed with an inverted video camera. To avoid confusion the terms up, down, etc will be used with reference to the actual building.

Sunlight falling on this section of the atrium will give a heat flux of about 150kW: this was modelled by a introducing salt water through a series of holes stretching the full length of the model at the upper walkway level as shown in figure 5. A heat source of 150kW in air gives a buoyancy flux of 4.125 m^4s^{-3}, and this was modelled by pumping in a salt solution 5% denser than fresh water (so, at the source, g'=0.49 ms^{-2}) at a rate of $15\times10^{-6}m^3s^{-1}$, giving a buoyancy flux of $7.36\times10^{-6}m^4s^{-3}$. Given this ratio between the buoyancy fluxes (7.36×10^{-6}:4.125) and the ratio in the lengths (1:100) this implies a ratio in the scales for g' of 0.317:1 (model:full-scale), from table 1. Cancelling g from the expressions for g' this gives $(\Delta\rho/\rho)_M/(\Delta T/T)_F = 0.317$, where T is measured in Kelvin. Thus a temperature difference of 1°C at full-scale is represented by a density difference of 0.1% in the model (since T is approximately 300K). This also sets the ratio in timescales, again from table 1, to be 0.18:1 so one second at full-scale is represented by 0.18 seconds in the model.

The heat due to occupants was modelled in two of the lecture rooms, representing a heat flux of 10kW (100 people) in each room. This was represented by introducing salt solution through a series of holes near the floor of each room, as shown in figure 5. For some experiments a cool pool of air on the floor of the atrium was modelled. This was done by introducing an alcohol solution, of density less than fresh water, into this part of the model before the start of the experiment.

Results

The results of the laboratory modelling are best appreciated by viewing a video of the experiments. Digitised images of the flow for various configurations of heat sources and openings are shown in figure 6. The warm air generated by sunlight falling on the interior wall of the atrium is seen to drive a flow through the building, with warm air flowing out through the opening in the roof being replaced by ambient air flowing in through the lecture rooms and other openings. An important result of this study is that an adequate ventilation flow can be driven in the lecture rooms by the heated atrium. The interface between warm and cool air in the atrium can be controlled by adjusting the area of the openings. In the lecture rooms the heat generated by occupants moves into the upper part of the lecture room, and thence out of the room into the atrium.

The mixing of the cool pool is caused, primarily, by entrainment into the warmer air above it. This entrainment is produced by the turbulent motions in the air above the cool pool and depends on a stability parameter $Ri=g'D/U^2$, the Richardson number, where D is the depth of the cool pool. The model scaling, given in table 1, preserves the value of Ri and so estimates of mixing found in the laboratory can be scaled to full-scale.

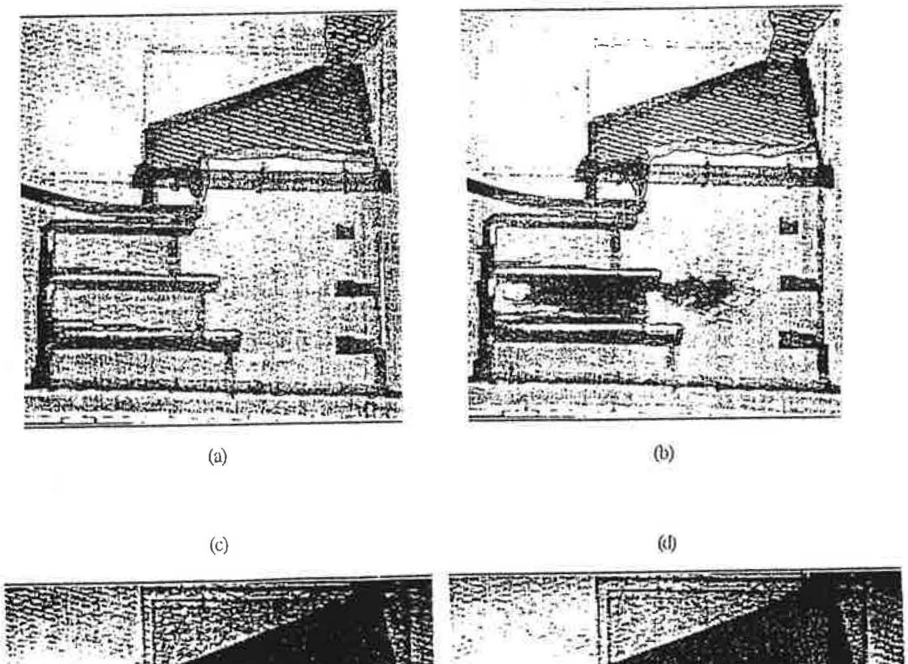

Figure 6. Digitised images from videos of the experiments. (a) & (b) Sunlight source only, no cool pool. Displacement flow drives fluid out through roof ridge opening and draws fluid through lecture rooms, in (b) fluid entering one of the lecture rooms and flowing into the atrium has been dyed. (c) & (d) Sunlight source, occupant sources and cool pool. Note that the flow from the lecture rooms rises on entering the atrium, rather than mixing throughout as in (b). The opening area is larger for (d) than (c), giving inreased interface height and more disruption of the cool pool.

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5.1 Models of Natural Ventilation

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5.2 The Use of Laboratory and Mathemat

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This work was supported by the C
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The cool pool of air at the bottom of the atrium is only slightly disturbed by the ventilation flows, the most disruption occuring when unheated side rooms are ventilated. This is because if the flow is from heated rooms it rises on entering the atrium, whilst if it comes from an unheated room it mixes throughout the atrium. Cool air can be prevented from escaping through ground level openings by the ventilation flow drawing in air through these openings at a fast enough rate to prevent outflow.

5. CONCLUSIONS

5.1 Models of Natural Ventilation

We have shown how ventilation flows may be modelled in the laboratory, giving an accessible qualitative description of the flow as well as quantitative details. It is possible to model flows due to a variety of distributed heat sources in a complex geometry. This type of modelling is particularly suited to flows where the advection of heat is the most important means of heat transport, but does not include the effect of wind on the ventialtion flow. The scaling rules necessary to interpret the implications of the results of laboratory experiments for full-scale flows have also been given . We have outlined a mathematical model of ventilation flows and shown how it gives reliable estimates of the observed flows.

5.2 The Use of Laboratory and Mathematical Models in Design

Physical models have a distinct advantage over mathematical models in that they are visual. Although a mathematical model may yield accurate quantitative results, which can be used to inform design, they will not have the same impact on the designer, unless very sophisticated computer visualization of the results is made. Why is "impact" important if the quantitative information is available?

In our view, it is because the process of design is not a purely rational one in a mechanistic sense. When a designer asks a question he does not want only the answer: he wants information about and around the question. Physical modelling techniques nearly always have this characteristic: for example whilst looking into a daylighting model, constructed to measure Daylight Factor, the designer will see the subjective effect of his proposed design and may spot good and bad characteristics. The flow visualisation is a striking demonstration of a rather mysterious and usually invisible process, and both architect and technical expert have found the visualization to have suggested new ideas as well as confirmed proposals. Indeed the proposed "cool pool" strategy was suggested after watching flow visualization of another quite different building.

More obvious advantages of the physical model is that it can deal with more complicated boundary conditions and, in this case, geometries. Computer codes could in principle solve similar problems, but with codes available at present there would be very large demands on computing power and data preparation. However, the effort involved in the preparation of the physical model, and the laboratory testing, must not be underestimated. It seems likely that as computer models and visualization of output improve more of these kinds of problems will be investigated using mathematical models. Furthermore, the laboratory model has technical limitations: for example heat flows into the structure cannot, at present, be modelled and for the this project a mathematical thermal model has had to be used to investigate the absorbtion of heat gains made to the cool pool.

One further point must be made. Although in this case the modelling has been applied to a specific building, in our view principles can be established which could be applied to other buildings where conditions are similar and the effect of small departures from these conditions is understood. We believe that physical modelling of this type offers a valuable educative tool providing both "design-proving" and "design-leading" roles.

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of its failure, exploring for new
The main reason of pollution
comfortable indoor climate versus

Adaptation to the Climate

In nature's ecosystem, pla
without polluting the air but e
plants methods of adaptation to
architecture.(1)

In this paper, an effort is ma
climate and search for new solut

In general the classifica
Xerophilous and Hygrophilous grou
and light structures in traditio
distribution of Hygrophilous and
humid and very arid areas.(2)

1) Xerophytes grow in conditi
water. They form devices for a
Factors favouring transpiration
temperature, (3) Rarefaction of t
(4) Light (or radiation).

2) Hygrophytes grow in conc
stagnation of water. They form d