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SIMULATION OF NATURAL VENTILATION IN BUILDINGS BY MEANS OF FLUID FLOWS APPLIED TO THE CASE OF CROWN AND COUNTY COURTS

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ABSTRACT. The use of natural ventilation to provide air changes within a building is investigated. The driving forces for the flows considered are buoyancy forces produced by temperature differences within a building and between the interior and the exterior air - the 'stack effect'. Wind-driven ventilation, which usually produces increased ventilation rates is not considered here. The use of small-scale models is described in which water is used as the working fluid and variations in salt concentrations represent different air temperatures in the full scale building. A description of the use of laboratory models to investigate a building with internal heat gains is given and the scaling laws necessary to apply the results at full scale are derived. An outline of a mathematical model is also given and some general features of buoyancy driven natural ventilation are described. These modelling techniques are applied to a proposed design of a Crown Court.

1. INTRODUCTION

Natural ventilation is the use of naturally occuring pressure differences to drive a ventilation flow. These pressure differences may be caused by temperature differences between the internal and the external air - the 'stack effect' - or by the wind. We restrict attention here to the effects of temperature differences. Recently, there has been renewed interest in natural ventilation, especially for the ventilation of large spaces /1/. This interest has arisen partly because of considerations of energy conservation and cost, and partly from dissatisfaction with the performance of mechanical systems. Since these naturally driven flows are less easy to control, it is desirable to accurately determine flow patterns and ventilation rates and to determine how effective control may be established.
The laboratory modelling of these flows is described in section 2 and the outline of a mathematical model (described fully in /2/) is given in section 3. The application of these techniques is the Crown Court design which is described in section 4 and the concluding section 5 contains 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 large values of the Reynolds and Peclet numbers (10^3 and greater). These numbers are given by UL/ν and UL/k respectively, where U is a typical velocity, L is a typical length, ν is viscosity and k 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 Peclet 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/. 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 Peclet 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. These scales can all be constructed from the length-scale and g' as shown in table 1. (The buoyancy flux is the flux of g'.)

		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 enables the 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. Two main kinds of ventilation flow occur: mixing ventilation and displacement ventilation and we shall treat each case in turn.

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. 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

$$F=kA(dg\Delta T/T)^{1/2}, \qquad (1)$$

where k is a constant approximately equal to 0.25 for a window /4/ and 0.05 for a skylight in a horizontal roof /5/. If the space contains a heat source of W kilowatts, and lengths are measured in metres, the steady temperature is given by $T+\Delta T_M$, with

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

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 and drive 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 volume flux in the plume at the interface level must match the volume flux out through the upper opening, which in turn must be equal to the inflow through the lower opening. In addition, 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. Consequently, the temperature of the upper layer must be uniform throughout the layer, and equal to the temperature in the plume at the interface level.

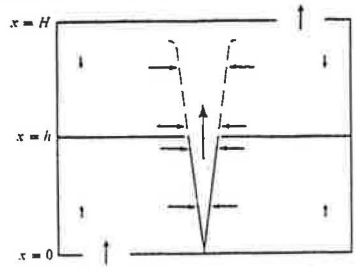

Figure 1. Steady displacement flow in a box with an internal source of buoyancy. The rising plume entrains fluid both above and below the interface. Outside the plume and below the interface the vertical component of velocity is upward: outside the plume and above the interface the vertical component of velocity is downward. Buoyant fluid leaves the space through the upper opening and ambient fluid enters through the lower opening.

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.

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

where A is the effective area, given by

$$A=(a_1 a_2)/(1/2(a_1^2/c+a_2^2))^{1/2}. \qquad (4)$$

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 upper and lower openings. Note 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, and is given by

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

where h is measured in metres, W in kilowatts and ΔT_D in degrees Celsius or Kelvin.
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 source but the analysis can be extended to multiple sources and to line and area sources /2/.

4. CASE STUDY: CROWN COURT BUILDING

4.1 Design Considerations

A courtroom has a number of restrictions to the possible ventilation openings. In the majority of cases all windows are above head height. There is also separate access to the main courtroom for the judge, jury, defendants and public. As a result high level vents were placed in the walls and ceiling of a raised roof section as shown in figure 4, to simulate the effects of windows and skylights. Two possible roof heights were examined viz 6m and 8m. Low level vents in both the walls and the floor were included (see figure 5) so that a range of opening configurations could be tested.

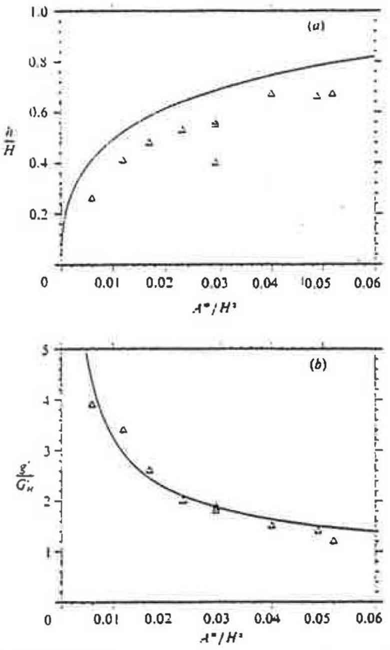

Figure 2. Theoretical and experimental results for displacement flow (a) interface height (b) buoyancy of heated layer.

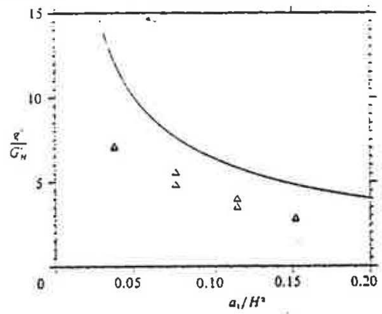

Figure 3. Steady-state buoyancy of space in mixing ventilation: comparison of theory and experiments.

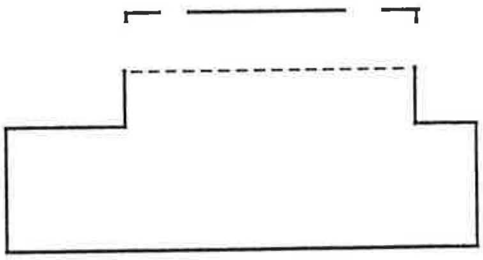

Figure 4. Courtroom model: section.

4.2 Modelling

A 1:30 scale model of a medium size courtroom (see figure 6) was constructed from perspex. Solid perspex blocks were used to represent the interior furniture. The model was completely transparent so that the flow within it could be visualised. Openings in the walls and floor were in the form of 18mm diameter circular holes. In the roof there were 4 square roof lights measuring 25mm x 25mm and windows were constructed in the ends of the roof above the judge and the defendents. These windows measured 50mm x 160mm and were constructed in two parts so they could be either fully or half open. All openings were sealed by plastic plugs or perspex covers and could be opened as desired. The model was suspended upside down in a large tank of water, illuminated by shadowgraph and filmed with an inverted camera. To avoid confusion the terms up, down, floor etc will be used with reference to the actual building.

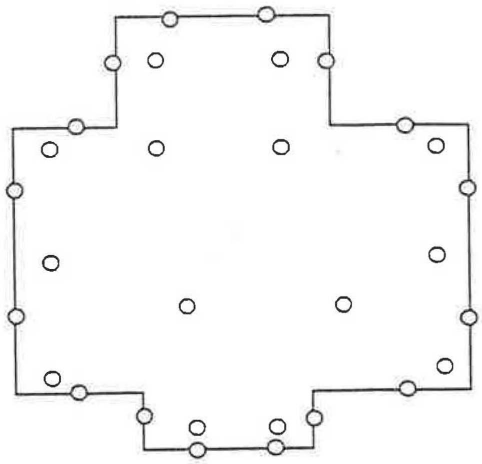

Figure 5. Courtroom model: plan.

Two main series of tests were carried out. In the first, the model was filled with salt solution and the transient flows that developed when one or more vents were opened were observed. The initial density difference was 26kg m^{-3}, and since $L_F/L_M=30$, the velocities at fullscale are 6 times faster than in the model and the real timescales are 5 times longer when the initial temperature differences are 10 degrees Celcius. In the second series, the effects of occupants were investigated. Three equal sources were placed on the floor to represent the judge and jury, the defendents and counsel, and the public. The strengths of these sources were equivalent to a total of 8 kilowatts (80 people each producing 100W) with the same ratio of velocities and timescales as in the first series.

4.3 Results

4.3.1 Openings in roof only

When windows were opened an exchange flow was established with warm air leaving the building through the upper part of the windows and cooler air entered through the lower half of the window. The cool air descended as a turbulent plume and mixed the interior. This was a mixing ventilation case with very weak stratification within the courtroom. When roof lights were opened the exchange flow was much less organized with interleaving and mixing of the incoming and outgoing air as it passed through the opening. The combination of roof lights and high level windows resulted in outflow from all openings, but inflow only through the windows. Measurements of temperature were in agreement with the predictions of (1) which implies that ΔT decreases as $1/t^2$ as shown in figure 7.

4.3.2 Low level openings only

In this case cool air enters the building with very little mixing and spreads out over the floor. It rises to the top of the highest open vent, and then further ventilation ceases. The details of the flow through the vents depends on the configurations of the openings.

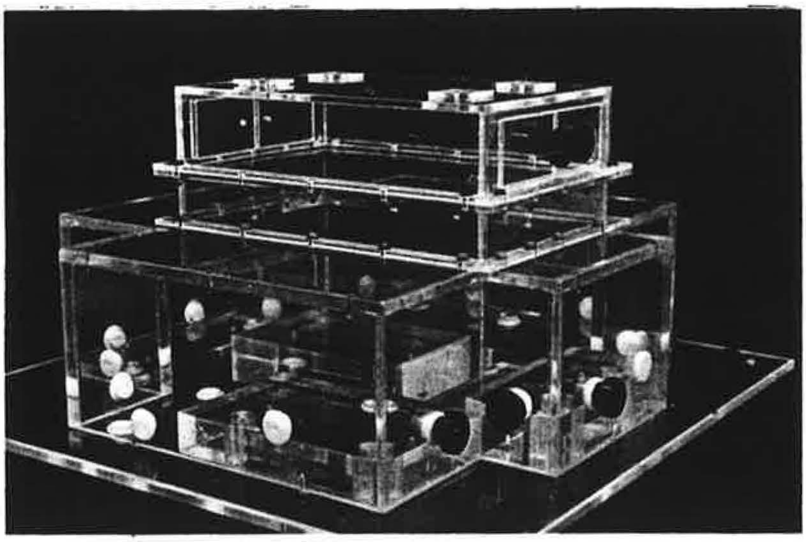

Figure 6. 1:30 scale model of courtroom showing the vents and the interior furniture .

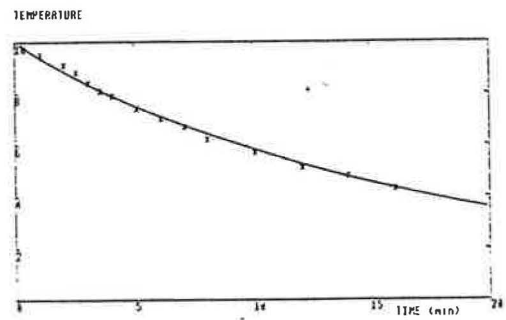

Figure 7. Decay of temperature in model.

4.3.3 High and low level openings

In these circumstances displacement ventilation is established with cold air entering at low level and warm air leaving the courtroom through the roof openings.

As predicted by (4) the rate of ventilation is determined by the vents with the smaller total area. The flow is a two-layer stratification with relatively little mixing between the incoming and interior air. If the total area of the upper level vents exceeds the low level vents by a factor of approximately 5 there is also some inflow through the high level windows. In this case the ventilation is a combination of the displacement and the mixing modes.

4.3.4 Effects of occupants

These tests were carried out with both high and low level openings. A displacement flow was established and a steady-state achieved as described in section 3. As successive low level vents were opened the level of the interface between the incoming air and the warm layer was raised. It was possible to control the level using the openings, so that the judge, at the highest point in the courtroom, remains in the cool air. As predicted by (3) the depth of the cool layer depends of the geometrical arrangement and location of sources and not on the heat flux.

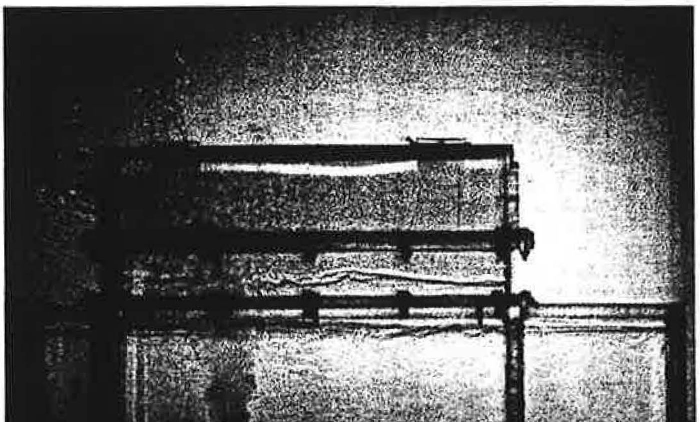

Figure 8. Photograph of displacement ventilation. Several vents near the floor, a window near the ceiling and a skylight are open.

5. CONCLUSIONS

This study has shown it is possible to naturally ventilate a courtroom, and that laboratory and mathematical modelling provides insights and quantitative information on the ventilation rates. Displacement ventilation is a controllable mode and works efficiently provided the ambient air is at a comfortable temperature. On cooler days, some preheating of the incoming air can be achieved by using high level inflows. Laboratory modelling allows the ventilation regimes to be delineated and the mathematical model is confirmed. It is, therefore, possible to predict the effects of other design changes and to decide on other configurations to test. The scaling laws which enable the quantitative results to be extrapolated to full-scale are also given.

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