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PHYSICAL MODELLING OF AIRFLOWS - A NEW DESIGN TOOL

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Abstract

The geometry and the large glazed areas of atria with high solar gains in summer and large heat losses in winter, place severe demands on the design of ventilation. Usual rules of thumb and generic solutions cannot always be extrapolated with confidence, and the prediction of air movement and temperature distribution is beyond the scope of models based upon computed fluid dynamics calculations in all but the simplest geometries.

This paper presents a new approach to predicting the airflow and stratification within an atrium, based on reduced scale physical modelling. Water is used as the working fluid and accurate quantitative measurements can be made since the effects of frictional losses at full scale are correctly scaled in the model. Equally important, by using coloured dyes, the water modelling produces very graphic flow visualization which greatly assists the intuitive understanding of the architect and engineer.The use of this method as a design aid is illustrated by case studies of two large atria, one in the temperate climate of the UK, and one in the hot climate of southern Spain.

1.0 The Need for Airflow Modelling

Considerable progress has been made in the thermal analysis of buildings, using mathematical models,and also large scale test cells. Much less progress has been made in airflow modelling - indeed it is the modelling of convective heat flows in thermal models which remain their major weakness.

Mathematical airflow models tend to fall into two broad categories - those describing inter-zonal mass flows, and those describing three dimensional flow within a zone e.g. Computed Fluid Dynamics (CFD). Neither of these are familiar to building designers; the former kind require unfamiliar input data such as air leakage distribution and pressure coefficients whilst the latter requires specialist input and expert interpretation of output, and heavy computing resources.

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Furthermore, unlike certain other environmental processes such as lighting and acoustics, air movement is not readily perceived by the human observer. This has severely limited the development of intuitive design skills, even by the specialist.

The result of this is a general lack of familiarity in the building design profession of air movement behaviour. This has lead to several unfortunate trends in building design, for example, the lowering of ceilings in offices, schools and hospitals, and problems in heating and ventilating large interconnected spaces, and inappropriate positioning of inlets in naturally ventilated spaces.

One area where this lack of knowledge is particularly evident is in the design of atria. Here, the demand for this particular building feature has outstripped the development of our understanding of the environmental physics of these spaces. In particular, we are short of knowledge of air flow within the atrium and how this leads to thermal stratification and over- and under-heating. The large areas of glazing, characteristic of atria, result in both large and non-homogeneous heat losses, and heat gains due to solar gain. This accentuates the problem of predicting temperature distribution. We also lack understanding of air movement between the atrium and the parent building.

In a recent EC programme, Building 2000, where environmental analysis expertise was provided for designers of innovative low energy buildings, air-movement and ventilation were identified as the major uncertainties in almost every consultancy.

The response of the designer, and the consultant, has been to rely heavily on mechanical servicing of these spaces, under the impression that there is more certainty of their performance. This often leads to unnecessary investment in plant and running costs, and even then does not always guarantee success. More importantly it leads to high energy costs. This is particularly ironic in view of the often claimed association of the atrium with the 'green', environmentally friendly ethic.

With the growing concern for environmental issues, in particular the association of electrical energy use and CO_2 production, and the connection between refrigeration plant and CFC release, there is renewed interest in natural ventilation as an alternative to air-conditioning. The size and complexity of modern buildings, and the expectations for comfort of the occupants, will place heavy demands on designers who adopt natural ventilation as an option.

A parallel topic, that of daylighting, is already much better served. Daylight levels are relatively easy to calculate, image synthesizing models are being developed, and physical daylight modelling is a simple and well validated technique. Physical scale modelling of daylight is of particular relevance for comparison here. Its value lies in that it links a visual simulation which can be judged subjectively with accurate objective quantitative measurement. Experience with the new physical airflow modelling technique shows the same virtue.

The application of the method for a number of real building projects has lead to both useful quantitative "design proving" results, and "design leading" proposals. For example, the University of Seville Dept of Humanities on the EXPO 92 site, described later in this paper, is a four storey atrium building where the atrium is used to drive buoyancy ventilation of the surrounding rooms, at the same time as retaining a cool pool of air at the ground level, as a refuge from the intense summer heat. This idea was largely conceived as a result of watching fluid airflow modelling. The design was subsequently developed and ventilation concept tested quantitatively by the same method.

2.0 Methodology

A small scale (typically 1:20 - 1:100) model of the building is constructed. The model is usually somewhat simplified, but the essential features controlling the ventilation are retained. This simplification requires an appreciation of the physical principles, but usually involves ensuring the main openings are accurately represented. The model is constructed from transparent perspex which allows the flows to be readily visualised.

Water is used as the working fluid and sources of heat within the atrium are represented by sources of salt solution. If the internal gains and solar gains produce buoyant rising air, the model is inverted and then viewed through an inverted video camera so that the dense salt solution appears to 'rise' within the model. Dense flows produced by cooling can be represented by water-alcohol mixtures which have a density less than fresh water. This arrangement is simply one of convenience. The model is completely immersed in a large tank of water which represents the outside, ambient air. This method avoids having to add salt to this large body of water.

The reasons for using water are three fold. Firstly, flow visualisation is straightforward and provides a very graphic way of illustrating the flow patterns to the architect and the engineer. The flows are visualised using shadowgraph imagery which shows density variations within the flow. These density variations cause refractive index changes which focus the light onto a screen. (These refractive index variations cause the air above a road to shimmer on a hot day). Dyes may also be used to mark different air flows, so that flow trajectories and mixing regions may be observed. Both still photography and video filming of the flows are used.

Secondly, quantitative measurements of flow velocities may be made, and temperature measurements can be obtained by measuring the density of samples of salt solution taken from within the model. A number of standard techniques exist (see Linden et al 1990) for these measurements. Recently developments in automated image processing of the video films allow the measurements of dye intensities to give the instantaneous temperature distribution over the complete section of the building. In addition, automated particle tracking allows the trajectories of seeding particles to be determined from which flow speeds can be determined.

Thirdly, the use of water allows the effects of friction and diffusion to be accurately modelled at small scale. 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/v and UL/k respectively, where U is a typical velocity, L is a typical length, v is the viscosity of air and k is the diffusivity of heat. At such large values the flow will be independent of these numbers, except at the smallest scales. In order 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 is achieved in the small scale model using water as the working fluid and adding salt to produce density differences (Linden & Simpson, 1985). Note that since heat is modelled by salt it is the diffusivity of salt in water that gives the relevant Péclet number.

Quantitative comparisons between laboratory models and full-scale measurements (Lane-Serff 1989, & Kalyani 1990) have confirmed that the large scale flows are accurately represented at small scale.

2.1 Scaling Laws

The driving force in these flows is the buoyancy force caused by density differences between different parts of the fluid. In a gravitational field with acceleration of a parcel of fluid of density $\rho+\Delta\rho$ surrounded by fluid of density p will experience an acceleration of approximately $g\Delta\rho/\rho$, if $\Delta\rho/\rho$ is small. This acceleration is known as the <u>reduced gravity</u>, and it will be denoted by g'. For air, it is useful to note $\Delta\rho/\rho$ 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 ($g' = g\Delta\rho/\rho$).

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 heat source of strength W (in kilowatts) in air is B = 0.0281W, where B is measured in m^4s^{-3}.

For example if $L_M/L_F = 1/100$ and density differences are set so that $\Delta\rho/\rho = 1\%$ corresponds to a temperature difference of 10.4°C, timescales in the model are 5.4 times faster than at full scale.

3.0 University of Seville Department of Humanities

This scheme is notable in that it proposes a daylit, naturally ventilated building for a location with one of the hottest climates in Europe. This is a bold proposition, bearing in mind that many buildings of this size and use type would be air-conditioned in locations in mid and northern Europe, where summer temperatures are far less extreme.

A central feature of the building is the long four storey height atrium. This permits almost full daylighting to all but the deepest spaces, and also performs a key role in the natural ventilation of the building. A simplified section is shown in figure 1.

Quite early on in the development of the design, three main features of the natural ventilation were proposed. These were -

1) to ventilate the lecture rooms by suction generated by heated buoyant air in the upper atrium,
2) to introduce the fresh air to the lecture rooms via underfloor voids,
3) to minimise the daytime ventilation rate at the floor level of the atrium in order to maintain a pool of cool air at temperature below outside ambient.

these proposals posed, in turn, crucial questions -

1) would temperatures in the upper atrium attainable by realistic solar gains remain tolerable, and yet create sufficient ventilation rate in the lecture rooms to displace the casual gains of the occupants, with a mean temperature rise of less than 3°C?

(External design conditions were taken as 31°C and RH 46%. This gives a Corrected Effective Temperature of 26.5°C at 0.1 m/s. A 3°C rise on this to 29.5°C was considered to be just tolerable for a worst case.)

2) how would the underfloor introduction of ambient air effect the temperature distribution in the lecture rooms?
3) to what extent would the pool of cool air in the lower part of the atrium remain undisturbed whilst high rates of ventilation were permitted in the upper atrium?

3.1 The main results

These were the main questions which prompted the physical modelling study. The 1:100 model is shown in figure 2. An example of the flow visualization is shown in figure 3. Black and white reproduction seriously reduces information content. The main conclusions from the study were as follows -

1)
The solar heated upper atrium is sufficient to drive ventilation through the lecture rooms of sufficient rate to meet the criterion of a $\Delta T < 3^oC$ for a heat input in the lecture rooms equivalent to occupancy gains. This occurs with a hot layer temperature in the atrium of about 7^oC above ambient with a solar input of 150kW, as calculated from the proposed glazing area. The height of the boundary between the hot layer and the cool layer can be controlled by the opening areas, as predicted by theory, and generally the hot layer is above the occupied part of the atrium, with the exception of the offices on the north side.

2)
The underfoor ducts in the lecture rooms show a good distribution of fresh air. Heated (and humidified) air from the occupants appears to move vertically into the upper zone of the room creating a stratified layer close to the ceiling, (which is at 4m). The hot air exhausting into the atrium is replaced by cooler air via the underfloor ducts. This displacement ventilation leads to stratification which will probably result in better comfort conditions at occupant position than predicted. The predicted 3^oC criterion assumes perfect mixing.

3)
The pool of cool air, initially at 5.4^oC below ambient, warms to about 3^oC below ambient after two hours due to mixing. However this is based upon an assumed initial condition. Furthermore the physical modelling cannot show how in the real building, the night-ventilation cooled structure will contribute to absorbing these gains from mixing, and those (small gains) from occupancy of the atrium.

An interesting result of the visualization was to demonstrate the erosion of the cool pool by the plume of air emerging from the rooms. If the rooms were occupied, this air was buoyant and made its way immediately upwards with little disturbance to the pool. Air emerging from an unoccupied room at neutral density was far more destructive and, therefore, should be avoided. This confirms the need for intelligent controls of the building ventilation, to maintain optimum passive performance.

Openings at floor level in the atrium also caused major disturbance to the cool pool. This prompted the suggestion that the main circulation routes connected to the outside which were to have entered the building at ground floor level, should if possible enter at first floor level.

4.0 Engineering School at Leicester Polytechnic

This design departs from the original idea of an atrium space by reducing the horizontal area of the atrium to produce a chimney. The high elevation shell provides a large stack effect which enables the warm air accumulated in the chimneys to drive a naturally convected flow through the other parts of the building.

For these tests a 1:75 scale model of part of the building was used. 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.

4.1 Basic features of the building

Part of the central section of the building was modelled, containing one lecture room, one drawing studio, one general laboratory and several classrooms and offices. In the proposed building the drawing studio and lecture room have curved seating but this was modelled by straight seating, preserving the overall volume of the space. This was for ease of building the model and also to make the visualisation of the flows clearer.

The section modelled is shown in figure 4. Five principle areas of the building were tested -

(a) Drawing Studio
(b) Lecture Room
(c) Laboratory
(d) Classrooms (those with little outside wall)
(e) Concourse

The main cause of internal gains is occupants (100w per person) with some additional heating by equipment in the laboratory. The major areas of concern were the lecture room, the laboratory (partially the effect of the mezzanine floor) and the combined influence of the concourse and the adjoining areas. Tests were made with each area separately and then with combination of spaces.

4.2 The main results

As a result of these studies it was found that natural ventilation provides adequate ventilation in most of the spaces. Most areas operate with displacement ventilation with cool ambient air entering at low levels and warm air leaving at high levels eventually exiting the building via the tall chimneys. Typically the occupied zones are maintained at ambient temperatures and flow rates above 10 l/s/person are achieved.

As expected the mezzanine flow in the laboratory was found to be a problem area. In the original design this floor received little fresh air; instead the air was mixed first with hot air rising from the area directly beneath the mezzanine. As a result the design of this area was charged and further tests were carried out.

It was found inadvisable to use the same chimney vents for venting both the lecture room and the concourse. This is because the direction of flow between these spaces and the chimney is unpredictable, depending on the precise heat gains and openings in each space. Thus there may be flow from the lecture room to the concourse or vice versa.

In spaces where there are both upper vents and chimney vents the upper vents act as inlets if the chimney vents are open. The incoming air through such upper vents mixes down warmer air into the occupied zone and so it was recommended that they not be used in conjunction with chimney vents.

5.0 Conclusions

In both these examples, quantitative answers were found to questions which would have been difficult to answer by other means. Due to the geometrical complexity of the designs calculation methods would be unreliable. The study also served to increase the confidence in the concept, of the specialist consultant, the architect., and even the client. The ability to record the testing on video, greatly assists in the latter function.

However, we feel that the value flow modelling is not limited to one-off tests on specific design proposals. Generic studies could be carried out covering a range of configurations, which would assist in the development of parameterised (simplified) models which would predict temperature stratification and ventilation rate etc. Set in an interactive computer environment, these models, together with illustrative use of the videoed laboratory tests, could provide a valuable tool for atrium design.

Acknowledgements

We are grateful for the contributions made by Dr G F Lane-Serff and Dr D A Smeed to this work. We also acknowledge the CEC DGXII for the funding of the Seville modelling study, and the Energy Technology Support Unit, UK Department of Energy, for the funding of the Leicester Polytechnic study.

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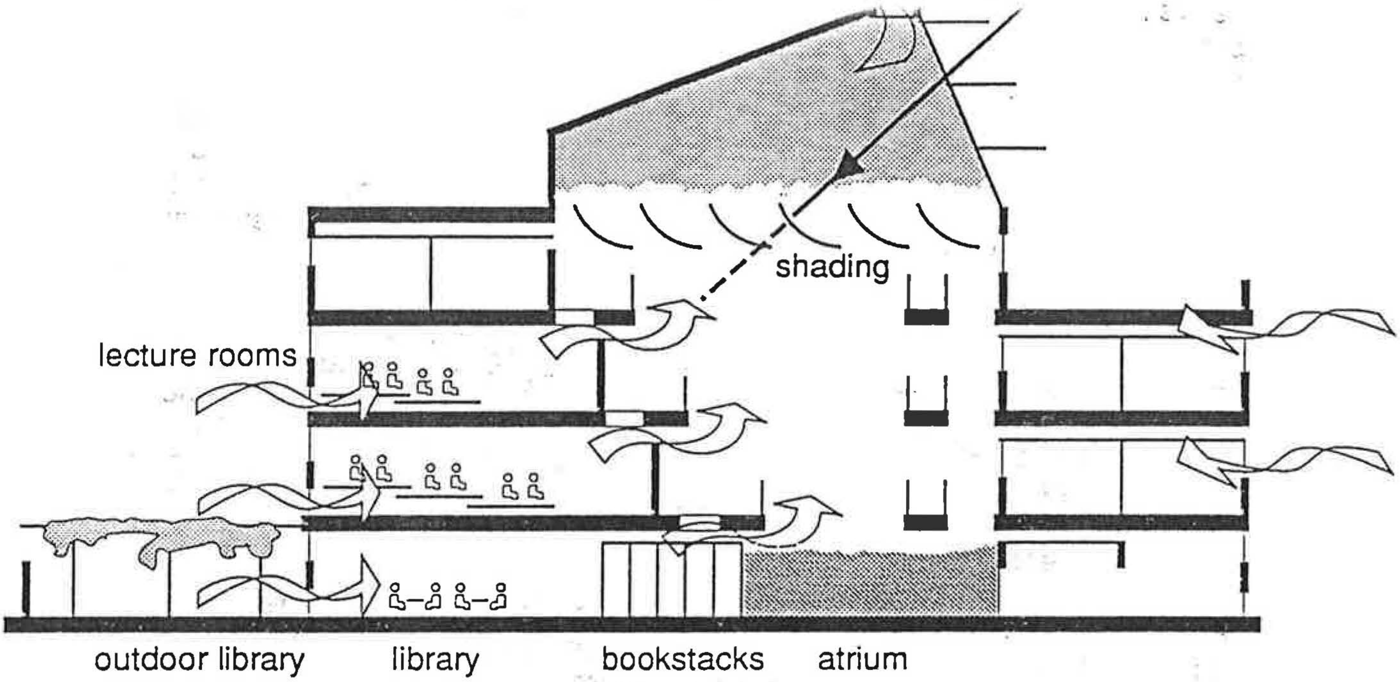
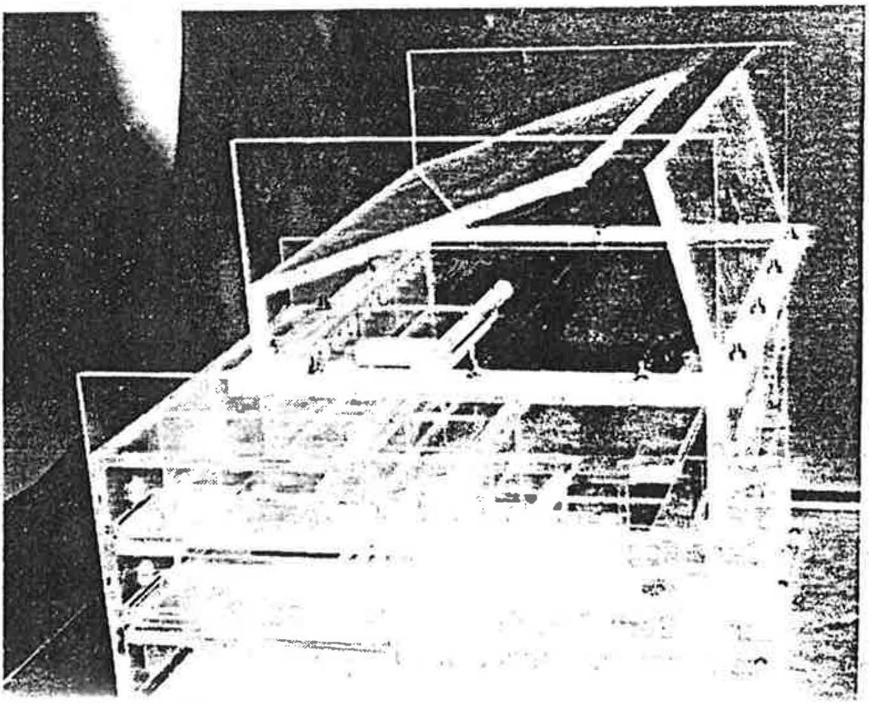


Figure 1: University of Seville Department of Humanities. Simplified section.



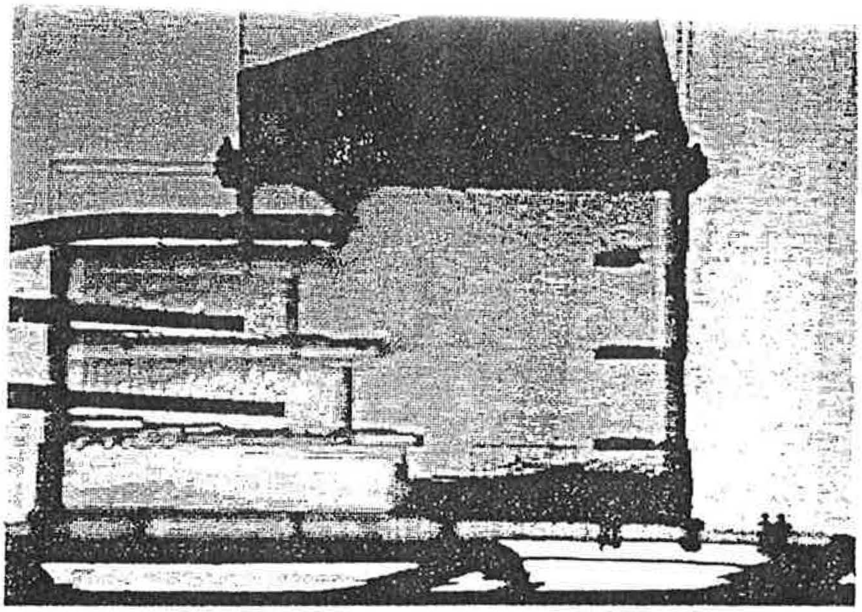


Figure 3: Shadowgraph photo of model of University of Seville building. The dark zone at the top of the atrium is hot air generated by solar gain. Plumes of warm air can be seen rising from the occupied lecture rooms. Fresh air is being drawn into these rooms via underfloor ducts. Plumes from the modelled occupants can be seen rising to a warm air layer under the ceiling. The dark layer at the base of the atrium is the cool pool. Slight erosion is occurring by neutral density air being drawn through the unnoccupied room on the left.