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BUILDING DESIGN ASSESSMENT THROUGH COUPLED HEAT AND AIR FLOW SIMULATION: TWO CASE STUDIES

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SYNOPSIS

This paper is concerned with the application of air flow simulation in design. It describes the real world application - and the results of this with respect to building design improvement - of a building energy modelling system, $ESP^{R\dagger}$, which supports the analysis of coupled heat and fluid flow as encountered in a building and/or plant environment.

The use of the system, and the design benefits to accrue, are demonstrated by elaborating two real world case studies. The first case study is also used to demonstrate some theoretical issues regarding coupled heat and mass flow, whereas the second case study is more concerned with practical issues.

The paper gives a brief overview of the theoretical basis of the modelling approach and it's use in a building performance evaluation context. In particular, it describes the necessary level of design abstraction, the choice of which simulations to perform, the results analysis and the design implications for the two case studies.

1 INTRODUCTION

ESP^R is a research orientated building and plant energy simulation environment. It's objective is to simulate the real world as rigorously as possible to a level which is dictated by international research efforts/ results on the matter in question. The current state of the simulation environment is the result of many years of evolutionary enhancements which seek to incorporate the latest state-of-the-art techniques to a feasible level. This means that the technique included must be more or less generally applicable and there must be a certain amount of international consensus about the technique. The program sets out to take fully into account all building & plant energy flows and their inter-connections. It also offers the possibility to assess building & plant performance in terms of thermal comfort. Thus it is specifically suited to do research on subjects in which inter-weaving of energy and mass flows plays an important role.

In order to be able to study the energy and comfort implications due to mass flows encountered in a building context, the system was recently extended so as to be capable of simulating the one-dimensional fluid (presently air and water) flow in a building and/or HVAC configuration. This involves solution of the mass balance in a nodal network in which the nodes represent either internal or boundary pressures and where the connections represent the distributed flow paths.

The system may be focussed on the fluid flow problem alone (by employing the stand-alone mass flow solver module *mfs*) or, to fuller advantage, on coupled problems (by activating the main building and plant energy simulation module *bps* and it's incorporated version of *mfs*). In the latter case, this enables energy and comfort studies of combined building and plant configurations in which the fluid flow rates may vary with time; for example due to changing boundary conditions (e.g. wind induced pressures) or as caused by changing flow path characteristics (e.g. some flow rate controller).

† In this context, the term ESP^R refers to the research version of the system as currently under development at various centres throughout Europe including the Universities of Strathclyde and Eindhoven. A separate version of the *ESP* system is being commercialised by a private company, ABACUS Simulations Limited.

This paper now continues with a brief outline of the approach. The use of the system, and the design benefits to accrue, will then be demonstrated by elaborating two real world case studies. The paper finishes with some conclusions towards possible future work.

2 THE APPROACH IN OUTLINE

In earlier publications a full account has been given of the internal workings of the system both with respect to energy simulation in general (Clarke 1985) and with respect to simultaneous heat and mass flow simulation (Clarke and Hensen 1991, Hensen 1991). An outline of the approach used within ESP^R could be: during each simulation time step, the mass transfer problem is constrained to the steady flow (possibly bi-directional) of an incompressible fluid along the connections which represent the building/ plant mass flow paths network when subjected to certain boundary conditions regarding pressure and/ or flow. The problem reduces therefore to the calculation of fluid flow through these connections with the nodes of the network representing certain pressures. This is achieved by an iterative mass balance approach in which the unknown nodal pressures are adjusted until the mass residual of each internal node satisfies some user-specified criterion.

Information on potential mass flows is given by a user in terms of node descriptions, fluid types, flow component types, interconnections and boundary conditions. In this way a nodal network of connecting resistances is constructed. This may then be attached, at it's boundaries, to known pressures or to pressure coefficient sets which represent the relationship between free-stream wind vectors and the building external surface pressures to result. The flow network may consist of several decoupled sub-networks and is not restricted to one type of fluid. However, all nodes and components within a sub-network must relate to the same fluid type.

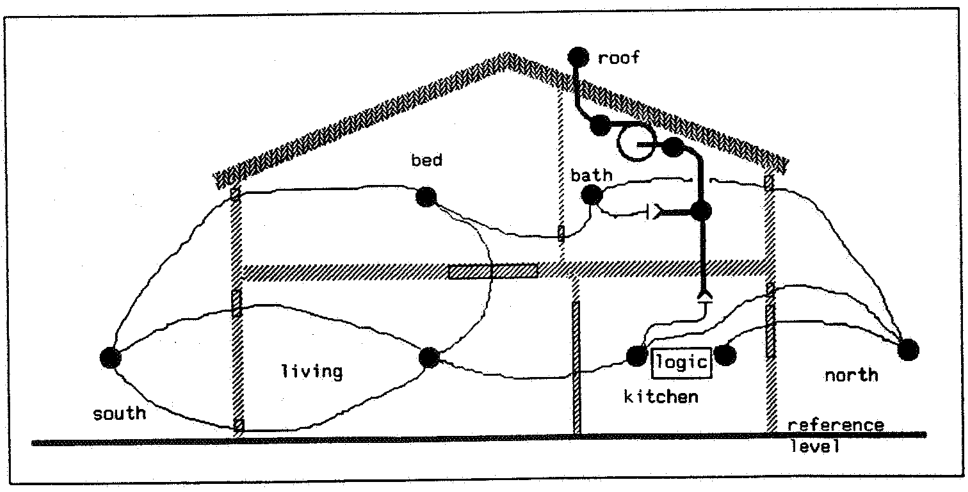

Figure 1 Example building and plant schematic

Nodes may represent rooms, parts of rooms, plant components, connection points in a duct or in a pipe, ambient conditions and so on. Fluid flow components correspond to discrete fluid flow passages such as doorways, construction cracks, ducts, pipes, fans, pumps, etc. As an example Figure 1 shows a schematic of part of a house consisting of four rooms, air flow connections between these rooms and to outside, and an exhaust-only ventilation system. In this case the building and plant configuration contains only one mass flow network, because there is only one working fluid, ie air. One possibility with respect to the translation of this configuration into a fluid flow nodal scheme is indicated by the dots.

Coupling of building/ plant heat and mass flow in a mathematical/ numerical sense, effectively means combining the energy and flow balance matrix equations for both the building and it's plant (Clarke 1985). (Note that in the case of building-side flows and for some plant, two flow balance matrix equations will be required to represent the two fluids present; air and water vapour for example). While in principle it is possible to combine all six matrix equations into one overall 'super-matrix', this is not done within ESP^R, primarily because of the advantages which accrue from problem partitioning. The most immediate advantage is the marked reduction in matrix dimensions and degree of sparsity - indeed the program never forms a two dimensional array but instead holds matrix topology and topography as a set of vectors. A second advantage is that it is possible to easily remove partitions as a function of the problem in hand; for example when the problem incorporates building only considerations, plant only considerations, plant + flow, and so on. A third advantage is that, potentially, different partition solvers can be used which are well adapted for the equation types in question - highly non-linear, differential and so on.
It is recognised however that there are often dominating thermodynamic and/ or hydraulic couplings between the different matrix partitions. If a variable in one partition (say air temperature of a zone) depends on a variable of state solved within another partition (say the inter-zonal air flow), it is important to ensure that both values match in order to preserve the thermodynamic integrity of the system. As elaborated in the above mentioned references, ESP^R incorporates a number of mechanisms which ensure this thermodynamic integrity, such as iteration mechanisms and time-step control.

2 DEMONSTRATING APPLICATION OF AIR FLOW SIMULATION IN DESIGN

The use of the system in a building performance evaluation context, and the design benefits to accrue, will be demonstrated in the following sections. This is achieved by elaborating two case studies showing the system's real world application, and the results of this with respect to building design improvement. The first case study is also used to demonstrate some theoretical issues regarding coupled heat and mass flow, whereas the second case study is more concerned with practical issues.
Both case studies were actually performed in a real consultancy context by an energy design advisory service (Emslie and Chalmers 1988).
Apart from anything else, such real world case studies signal the need in practice and the utilization factor of the kind of simulation tool described. From the developers point of view, real world case studies are important because they increase the insight in what is necessary from a practical point of view, and they assist in developing the system and making it more robust.

2.1 Case Study 1: Environmental Assessment of Hospital Spaces

This study concerns an environmental assessment of hospital spaces located in central Scotland, where air flow rates were judged to be critical in limiting summer overheating in zones with significant solar radiation gain (Hand 1990; Hensen 1991). Figure 2 shows the part of the hospital under consideration, which consists of a dayroom and adjoining dining room. As can be seen, the dayroom has very large glazing areas.

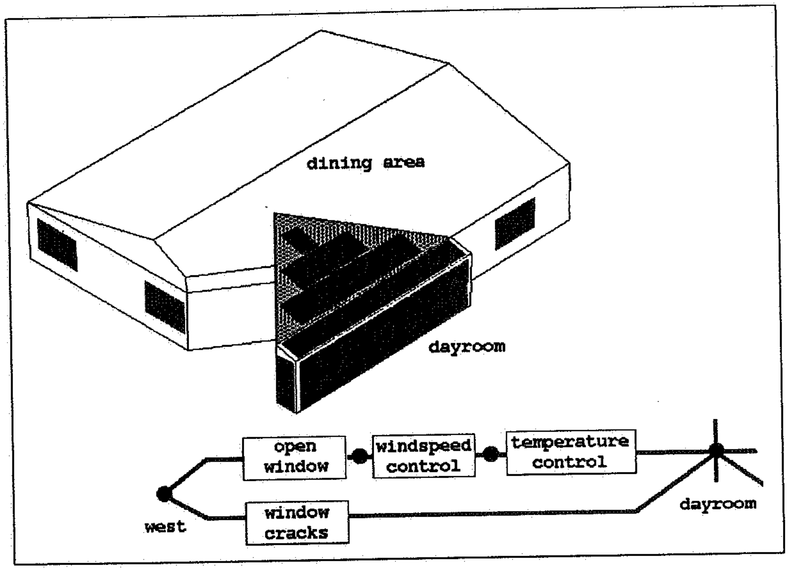

Figure 2 Schematic representation of the dayroom and adjoining dining room, when viewed from the south-west. Diagram of a fraction of the fluid flow network representing the west facade dayroom window.

It was requested to advise on useful operating strategies and/or possible modifications to the building in order to better control it's summertime indoor thermal environment. The actual case study involved a number of building thermal performance simulations regarding several aspects including shading analysis. However, here we concentrate on one issue only, namely infiltration analysis by simulation of coupled heat and mass transfer.

After reduction of solar gain, the primary means of preventing summer overheating is 'free cooling' by increasing the infiltration of ambient air. This may be achieved by, for example, opening of windows. Both the resulting cooling load by infiltration air and the indoor temperature, are influenced by the temperature difference between outside and inside, and by the actual air flow rates. In building thermal performance simulations, it has thus far been very problematic and time consuming to realistically incorporate the air flow rates. The main reason for this is that the rate of air flow depends on pressure differences which may be caused by wind or by stack effects due to temperature differences. Especially with a free floating indoor air temperature problem - like in the present case study - heat removal and air flow are closely coupled.

For the dayroom and dining area, a building thermal simulation model had been set up. In addition to this, a flow network was created with nodes representing the dayroom and the dining area on two levels to account for temperature stratification, and with nodes representing the wind induced pressures on the various facades. These nodes are inter-connected by flow components representing internal connections (doors etc), and infiltration openings (cracks etc) in the exterior envelope. The windows are also represented by flow components. In order to investigate the effects of their opening or closing, additional flow components representing logical control are incorporated in series with the window flow components, as indicated in Figure 2 for the dayroom west window only. Incorporation of these logical controllers allows the study of occupant interactions with respect to opening and closing of windows. Various options were examined. In one case, for example, it was envisaged that the windows would be opened whenever the air temperature of either the dayroom or the dining exceeds 24°*C* during the period between 11:00 and 18:00 hours, and that the occupants will not open the west and south orientated windows whenever it is very windy. Therefore, for these windows additional logical controllers are incorporated to prevent window opening in case the wind speed exceeds 6 m/s. Of course these specific control strategies are just examples and may be changed at will.

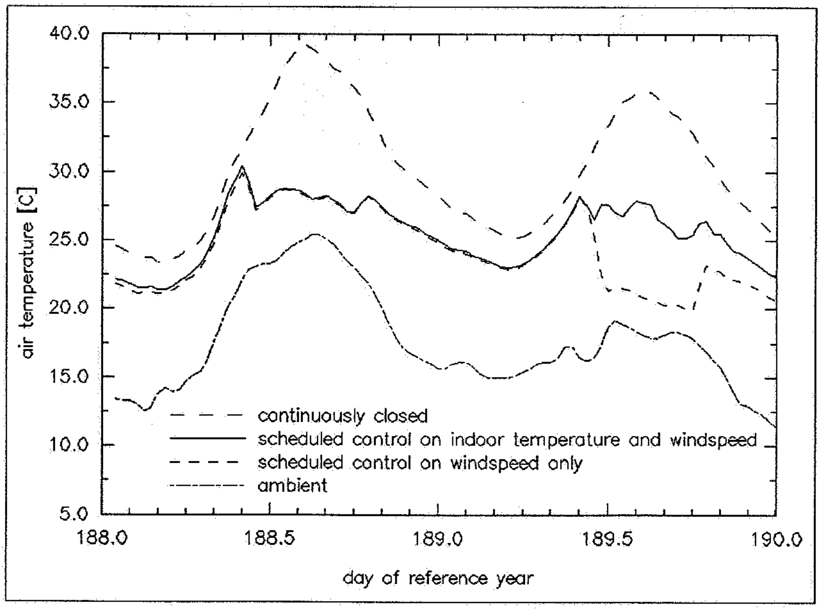

Figure 3 Predicted dayroom air temperature for July 7 and 8, assuming various window control strategies.

In order to demonstrate the effect on predicted air temperature, several simulation studies were performed. All these simulations were performed using *bps* and it's incorporated version of *mfs*, and are thus based on simultaneous and continuous simulation of heat transfer and air flow. It should be noted that this is already a more refined approach than building thermal simulation using infiltration/ventilation rates estimated by independent means which has been common practice up to now.
Figure 3 shows predicted dayroom air temperatures for July 7 and 8 of a reference year, and assuming various window control strategies. The first two (imaginary) window control strategies investigated are: (1) windows continuously closed, and (2) window opening controlled on the basis of time of day and wind speed. These two cases would have enabled prediction of at least upper and lower levels for the air temperatures to be expected, when coupled heat and mass transfer simulation would not have been possible.
With the present system the effects of more advanced controls can also be predicted. For example, a third window control strategy involved scheduled control both by wind speed and indoor temperature which is deemed to be more realistic than the previous strategies. The results for this control strategy are also shown in 2. As can be seen, the results for July 7 are almost identical to the control by wind speed only case because the indoor temperature was above 24°*C* throughout the period between 11:00 and 18:00 hours. For July 8 however, there are marked differences because this is a day where the

temperature control was actually activated.

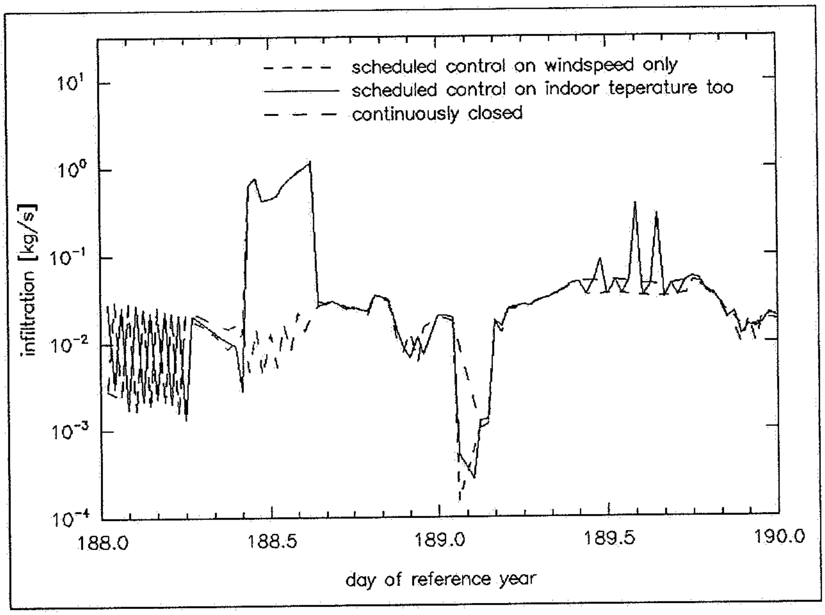

Figure 4 Predicted dayroom infiltration rates for July 7 and 8, assuming various window control strategies.

On July 8 the wind speed exceeded 6 m/s throughout the control period, and so the west and south orientated windows were not opened. The sharp air temperature decrease in case of the scheduled control on wind speed only, is also not due to an increase of infiltration but is caused by air flow from the dining area to the dayroom (because north and east facing windows were opened the air flow through the building changed from predominantly south-west to north-east to predominantly north to east). This is evidenced by Figure 4, which shows the predicted infiltration rates for the dayroom. Obviously as with the air temperatures, there are marked differences between the various control strategies. Infiltration is defined here as ambient air which enters the zone directly; ie in case of the dayroom excluding air flow via the dining area. Because the ambient air may enter the dayroom via the roof and the east and west window, infiltration rates may occur which seem to be out of order at first glance. For example the two peaks on July 8 (control incorporates temperature), are due to the fact that the east window is opened because of high indoor temperature. In that case air enters via this window, while at that point in time the air would leave via this window in the other two control strategy cases due to the prevailing environmental conditions.
This example may serve to illustrate the complexity of air flow paths through the building as a function of wind speed, wind direction, indoor temperatures, and control behaviour. From the analysis it was possible to define an operating regime and minimal change in equipment which would allow a zone to meet mandated environmental conditions.

In the previous cases, the air flow rates were calculated starting from the actual indoor air temperatures thus coupling heat and mass transfer. To illustrate the importance of this, some additional simulations were performed in which two cases were compared: (1) the indoor temperatures are at some fixed value, and (2) the indoor temperatures are as predicted by the thermal building simulation. So the pressure difference due to inside/outside temperature difference are accounted for in both cases, but it is only in

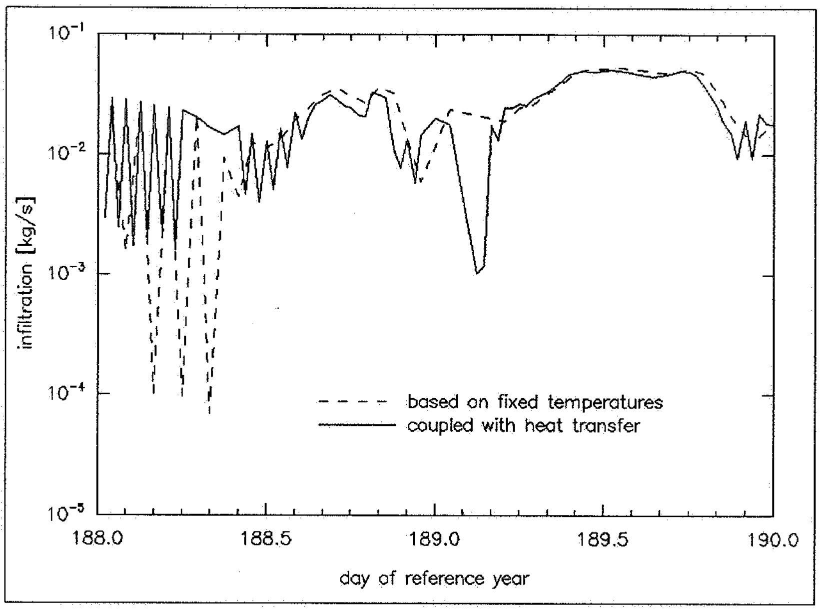

Figure 5 Effect of coupled/decoupled heat and mass transfer on predicted dayroom infiltration rates for July 7 and 8, assuming all windows closed.

the second case that varying indoor temperatures - both with respect to ambient as between the various zones - are taken into account. The first case exemplifies the case where buoyancy forces are fixed, while the second case exemplifies a case where heat and mass transfer are handled simultaneously. In both cases it was assumed that the windows are continuously closed. The corresponding indoor and ambient temperatures are shown in Figure 3. Figure 5 shows the simulation results for the dayroom infiltration rate. The differences are clear, thus stressing the importance of simulation of coupled heat and mass transfer especially when buoyancy effects play an important role or are strongly time varying.

2.2 Case Study 2: Environmental Analysis of Office Spaces

The second case study concerned a comfort and energy impact assessment of three multi-storey atria in a proposed office block. Given the time-scale and financial resources available it was decided to carry out the analysis on three section of the office building rather than attempt to model the building as a whole. Each section was abstracted from the plans and sections provided. The occupancy and casual gains were taken from documents supplied as well as interviews with office staff.
Air flows were affected by buoyancy, asymmetrical radiant and convective heat injection and the use of each atrium as an exhaust for fresh air injection. Each atrium was subdivided into thermal zones on fixed levels, each with a core and a perimeter. The flow network included one or more nodes in each atria zone as well as connections to adjacent zones and boundary conditions. The connecting elements for the atrium nodes consisted of a number of large area air flow openings which are actually based on the common orifice flow equation which assumes uni-directional turbulent flow. This is a simplification of reality, which approximates the bulk flow through the atrium. Clearly,

a CFD approach might give more detailed information, but due to practical reasons such an approach would have to be restricted to a single, fixed, moment in time and probably to just one single enclosure as well. However, in the present case the problem involved an extended period in time and a large number of enclosures. Thus, the above mentioned network approach was chosen. It is worth noting that in the immediate future a research project will start with the objective to reduce the above mentioned practical limitations (Te Velde and Hensen 1991).

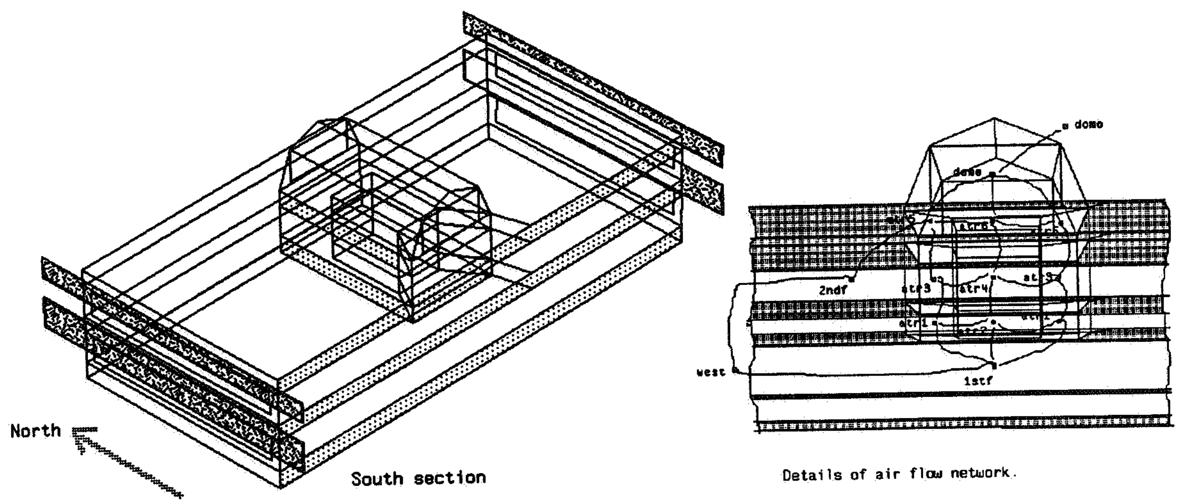

Figure 6 Schematic representation of one of the atria and the associated part of the air flow network.

Figure 6 shows the geometry of one of the atria and the associated part of the air flow network. Based on this, a combined heat and mass transfer analysis was carried out for a winter Sunday-Monday period (ie. starting up after a weekend) and for a Friday in July. The results for early in the morning and at noon are shown in Figure 7. For each branch of the network the upper value is the volume flow rate in m^3/s and the lower value is the velocity in m/s.

Beginning with the winter early morning graph, the flows at the left side are constant volume (equal to fresh air supply). Moving to the right, the four vertically stacked nodes are adjacent to the edge of the atrium while the second set of four stacked nodes represent the centre of the atrium. The diagonal at the top is adjacent to the glazing in the atrium dome and shows a downward flow of air as would be expected. This flow carries downwards until the middle of the atrium where it is met by the upwards flow from the first floor. At the base of the atrium there is a clock-wise circular flow as the unheated atrium air mixes with the first floor air.

The winter noon graph is similar in it left portion, however at this time the flow at the edge of the atrium is upwards with a strong current downwards at the centre of the atrium. Both the velocities and volume flow rates are quite high and are likely to be due to the cooler temperatures at the top of the atrium. As with the early morning there is a clock-wise mixing between the first floor and the atrium, however this time it extends to midway up the atrium. Since this analysis assumed that the only induced flow was due to the fresh air component, and this quantity was calculated based on the volume of the

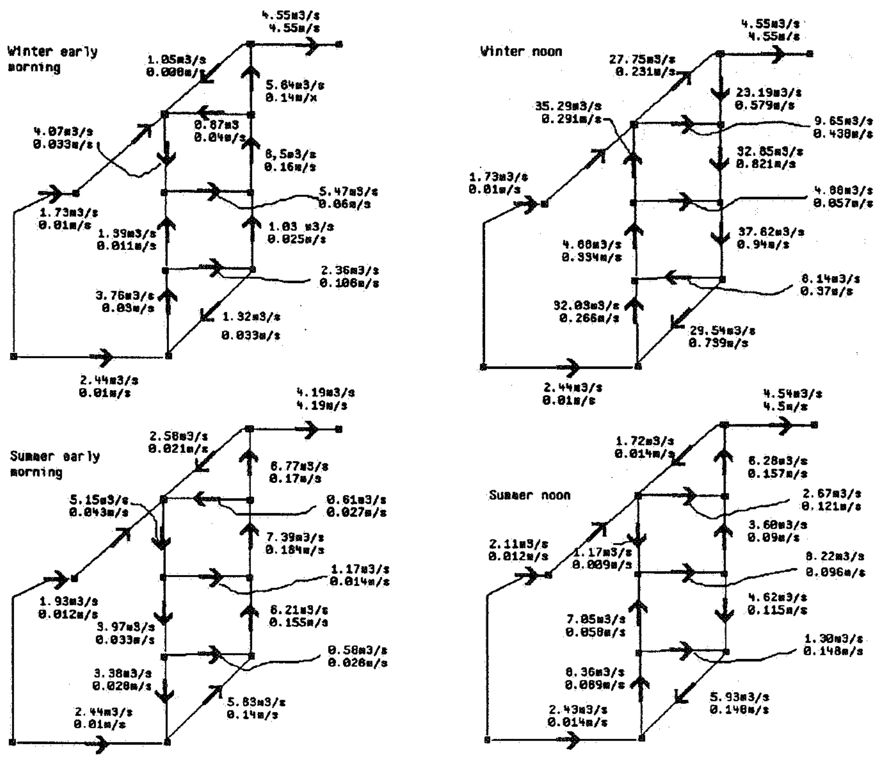

Figure 7 Predicted volume flow rates and velocities in each branch of the air flow network, for early morning and noon conditions in winter and in summer.

section, actual flows will be higher and there may be less of a temperature difference between the top and the bottom of the atrium.

The winter analysis does indicate that cold air trapped at the top of the atrium will have a tendency to flow downwards, either at the boundary of the atrium or in the centre. If care is taken to extract air so that pockets of still air are not allowed to form, then it may be possible to reduce such buoyancy driven flows.

The early morning summer flow patterns are dominated by a clear anti-clockwise flow which extends the full height of the atrium. As the high velocities are found in the centre of the atrium, the implications for thermal comfort are minimal. By noon this pattern has deteriorated into a series of circular patterns in various directions.

The analyses showed flow velocity and volume within the atria to be in the order of one magnitude greater than surrounding zones during winter start-up periods. The impact on plant capacity and comfort for occupants at the base of the atria were studied in detail and resulted in recommendations for top-up radiant heating and pre-conditioning.

3 CONCLUSIONS

By elaborating two real world case studies, this paper has demonstrated the use, and the design benefits to accrue, of a mass flow network method integrated in a building and plant energy simulation system, which is thus capable of simulating coupled heat and mass flows in buildings. The performance of the model indicates that it is practical to

solve complex building/ plant heat and mass flow problems with complex control regimes within large buildings for simulation periods of up to one year on the current generation of workstations.
It is felt that the model reflects the current state of the art in the field of network modelling approach to simulation of coupled heat and mass flows in buildings. Development and use of the model did reveal however that research is still needed in several areas. These include development of additional fluid flow component models (especially improved large opening models), modelling of intrazone effects by simplified methods and by integration with CFD modelling methods, expansion of the wind pressure database, expansion of the actual building and plant components 'database', and experimental validation of the simplifying assumptions in the flow component models and the network method.

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