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EFFECT OF THERMAL MASS ON THE AIRFLOW AND VENTILATION IN PASSIVE BUILDING DESIGN

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ABSTRACT

Air may be pre-cooled using thermal mass before it is supplied to an occupied space. One option is to pre-cool the air in a basement space and exhaust the air at high level through stacks. However, the thermal forces that determine the direction of airflow, including heat gains in the occupied space, thermal mass cooling and the external air temperature may counter each other, and result in flow reversal. This paper uses a combination of thermal dynamic and computational fluid dynamics (CFD) airflow modelling to study the ventilation and thermal performance of a hypothetical naturally ventilated 'mass cooled' auditorium.

KEYWORDS

ventilation, airflow direction, CFD, thermal mass, dynamic modelling

INTRODUCTION

Thermal mass and natural ventilation are often combined as part of a passive building design strategy. In particular thermal mass may be used to provide passive cooling in warm weather or when there are high levels of heat gains to the space. In recent years this concept has been applied to a range of building types in the UK. The thermal mass may be either directly coupled to the space, for example, as an exposed concrete ceiling found typically in offices such as Edinburgh Gate, DETR New Practice Case Study (in press), or it may be indirectly coupled, for example, in a separate adjacent space, through which the ventilation supply air is routed, as found in auditorium and theatres, e. g. Queens Building DeMontfort University and Contact Theatre in Manchester , Short et. al. (1998).

The driving forces of natural ventilation are temperature and wind effects. The temperature effects are due to the interaction of outside conditions and heating/ cooling systems, together with the internal heat gains from people, lighting and machines. The intended heat losses through the thermal capacity and transmission characteristics of the building fabric can however lead to negative buoyancy effects, which may counteract the intended ventilation strategy.

This paper examines the balance between the various factors associated with positive and negative thermal buoyancy effects. In practical ventilation design the dynamic nature of wind should also be considered in order to minimise any unwanted interaction with thermal forces. In addition to this, the air movement is influenced by resistance in the system to the airflow due to acoustic attenuators, heating coils, guidance of airflow, etc. However, for the purpose of this study these have been ignored in order to concentrate on the thermal mass effects alone.

The work is based on a series of thermal modelling studies using a dynamic building energy model and CFD airflow modelling. The paper takes an auditorium as an example case, with an underfloor thermal mass plenum, coupled to the supply airflow path.

MODELLING METHOD

In order to predict the thermal mass performance of coupled spaces both the dynamic effects associated with thermal capacity and the spatial variation of temperature and air movement must be considered. Computer models exist for both types of prediction. Previous research, Srebric et. al. (1999), has used coupled thermal dynamic and CFD modelling, with the CFD operated in steady-state mode at discrete hourly time intervals, to predict internal temperatures and air movement for a mechanically ventilated atrium. Time-varying CFD simulations are not yet practical for this type of application because of the short time steps needed (order of seconds) over relatively long periods (order of hours). One of the problems of coupling thermal dynamic and airflow models is the need to iterate between them to achieve a converged solution. The thermal dynamic model provides data for surface temperatures which take account of the time varying thermal mass effects, while the CFD model provides an instantaneous ventilation rate and pattern of air movement. Both models provide values of internal air temperature. In combining the models some ´start-up´ assumptions are needed, of either ventilation rate (if the thermal dynamic model is used first) or surface temperatures (if the CFD model is used first). The procedure is to iterate between the models until a converged solution is obtained. This can be assumed when the ventilation rate does not change for successive CFD runs. A criterion of good convergence is the agreement of the internal air temperatures of both models. Figure 1 illustrates the iterative modelling procedure. It is considered more appropriate to begin with the CFD simulation as there is likely to be more uncertainty about the ventilation rate than the surface temperatures. Initial surface temperatures may be estimated from an average of outside and inside temperatures, for the mass space and occupied spaces respectively.

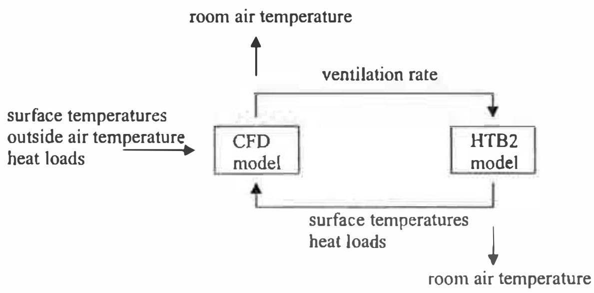

Figure 1: Diagram of iterative solution procedure

The steps in the procedure are then as follows:

1. Select the specific times for running the CFD simulations and the corresponding outside air temperatures.

2. Estimate the initial surface temperatures.
3. Run the CFD model to predict ventilation rate, airflow pattern and internal air temperatures.
4. Use the ventilation rate and direction of air flow to set up thermal dynamic model.
5. Run the dynamic model to predict the internal surface temperatures and air temperatures.
6. Update the surface temperatures in the CFD model and recalculate the ventilation rate, airflow pattern and internal air temperatures.
7. Repeat from step 4 until there is no change in the ventilation rate between successive CFD runs or until the internal air temperatures between the models agree.

The modelling procedure has been applied to a series of 3- and 2-dimensional case studies. The 3-dimensional case studies have been used to investigate the effects of external temperature, amount of exposed thermal mass, size of openings, and cooling and heating situations on the internal temperatures, ventilation rate and air movement for varied internal gains. The 2-dimensional modelling has been used to predict the impact of varying internal heat gains on ventilation rate and direction of air movement for two external temperatures in detail.

Figure 2 presents schematics of the geometry of the CFD model for both, the 2- and 3-dimensional case studies. In this study, the thermal dynamic model HTB2, Alexander (1996), and CFD model DFS-AIR were used, Jones & Waters (1993). In the dynamic model the main space is divided into two horizontal zones in a volume ratio of 4 (lower zone) to 1 (higher zone) in order to account for the temperature gradient as predicted by the CFD model.

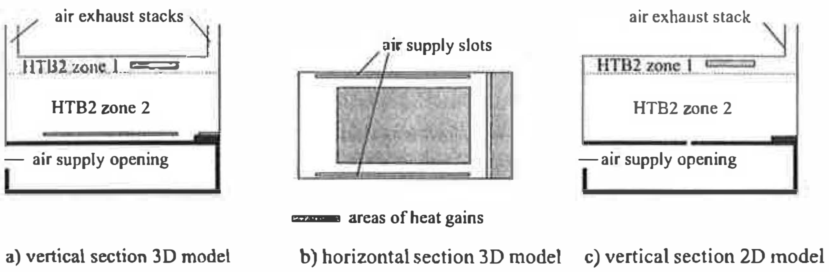

Figure 2: Schematics of the CFD models

Simulations were conducted for three outside air temperature conditions, corresponding to typical auditorium periods of use. This comprised a summer day and a summer evening in July, and a winter evening in January. The summer day simulation used the peak July outside air temperature, and the

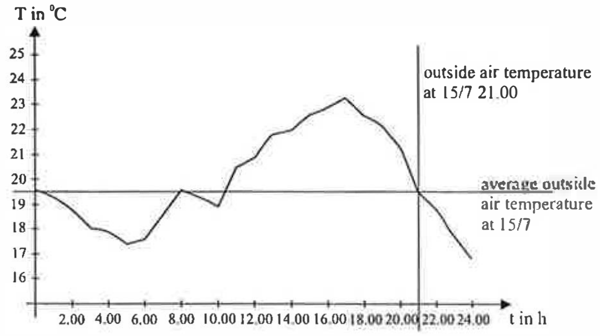

Figure 3: Diurnal outside air temperature profile at 15/7, selected for summer evening simulation

summer and winter evening simulations used the average monthly outside air temperature at 21.00 hours for July and January respectively. As an example, Figure 3 shows the diurnal outside air temperature profile for the day chosen for the summer evening simulation.

As an example, Figure 4 shows the values of internal air temperature and ventilation rate at each stage of the iteration for one summer evening simulation, case 4, described in more detail in figure 5. Convergence is achieved after three iterations.

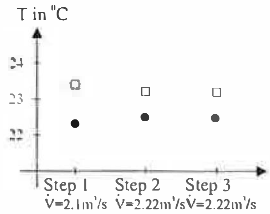

Figure 4: Iterative procedure

3-DIMENSIONAL CASE STUDIES

The modelled auditorium is 8 m high and has a floor plan area of 20 x 10 m^2, the underfloor thermal mass plenum is 4.25 m high. Thus, the volumes of the spaces are 1600m^3 and 850m^3 respectively. With a chosen construction of external cavity brick walls, carpet and ceiling tiles the auditorium has only a minor influence on the thermal mass storage performance of the model.

Figure 5 presents a selection of 3-dimensional case study results, where cases 1-8 are summer simulations and cases 9-12 winter simulations. For each case the results of the dynamic and airflow simulation is summarised. Cases 1-4 show the summer day performance for varied internal gains, ranging from 20kW to 1kW. There is a change of airflow direction from mixed to pure downward movement with decreasing heat gains. The agreement of the internal temperatures in both models is not very good for cases 1-3. This is considered to be caused by the demand of HTB2 for one distinct airflow direction, whereas the CFD simulations yield mixed directions. Cases 5 and 6 show summer evening performance for internal gains of 20kW and 1kW respectively. The direction of air movement is upward in both cases. The increased thermal mass case studies 7 and 8 correspond to cases 1 and 4, displaying summer day and evening performance for 20kW internal gains respectively. For the above mentioned reason the convergence of the internal temperatures is not satisfying for case 7, which shows mixed air flow directions. As examples for the winter simulations cases 9 and 10 (single storey mass plenum) as well as cases 11 and 12 (double storey mass plenum) show the influence of varying the supply and exhaust external opening areas - 50% and 30% of the summertime opening areas - and thermal mass on air movement and heat load. The heating is supplied at the point of entry or the air to the main space. All winter cases have rather high ventilation rates, indicating that even smaller openings could provide sufficient ventilation rates in winter.

Two further studies were carried out on the Case 1 situation, to investigate the effect of wind. Pressure gradients of 1 and 2Pa (corresponding to wind speeds of the order 2-4m/s) were applied across the supply and exhaust, with a relative negative pressure on the exhaust. The results show that the reversal in airflow at zero wind is corrected at low to moderate wind speeds.

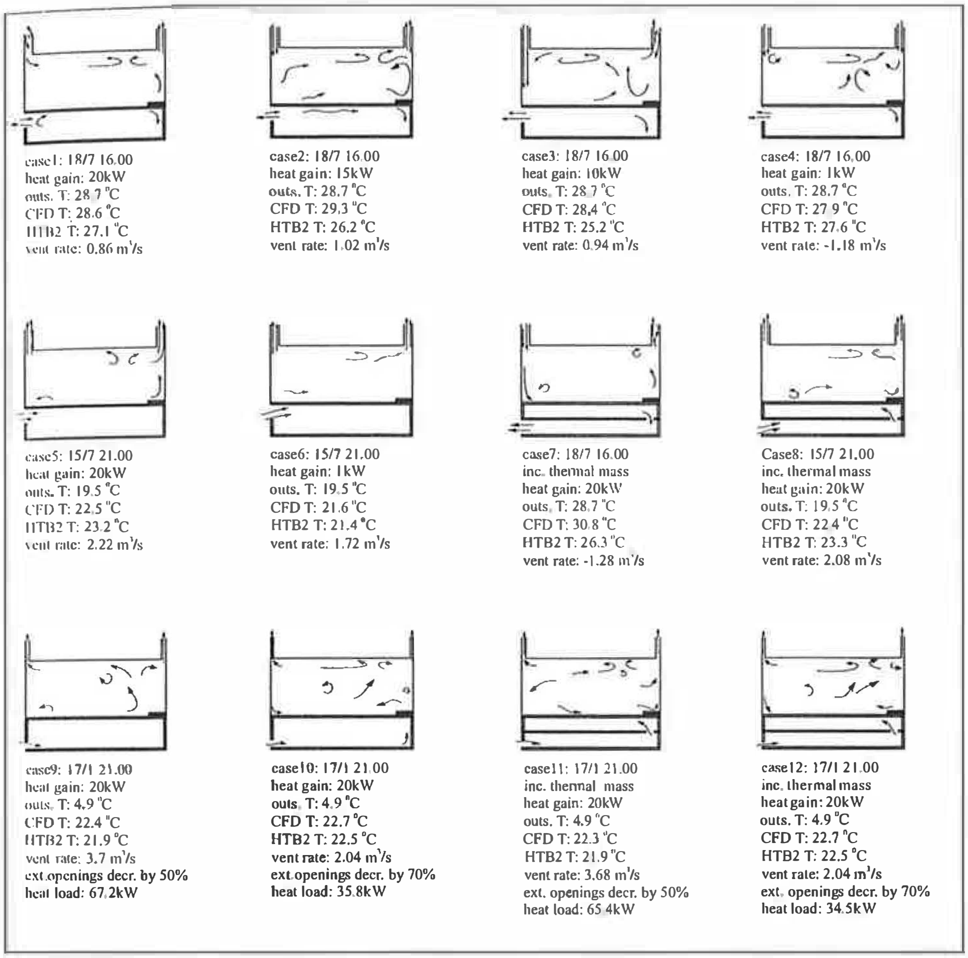

Figure 5: Selection of 3-dimensional case study results

2-DIMENSIONAL CASE STUDIES

Thus the 2-dimensional study was carried out to investigate the direction of airflow for increasing internal heat gain, and for two external air temperature conditions. The 2-dimensional case studies were carried out by CFD simulations - since HTB2 demands the direction of ventilation as an input, it was not used for this study. Figures 6 and 7 present the results of the summer day and summer evening simulations respectively. For the summer day, with a high outside air temperature, the direction of air movement is downward for low internal gains. With increasing internal heat gains, the downward ventilation rate decreases causing a rise in the internal air temperature. The direction of airflow switches from downward to upward for internal gains between 0.25 and 0.3 kW/m^2. At this point the temperature drops considerably due to the pre-cooling of supply air by the thermal mass, rising again slowly with increasing heat gains. For the summer evening case with a lower external temperature the movement of air is upward, independent of the level of heat gains.

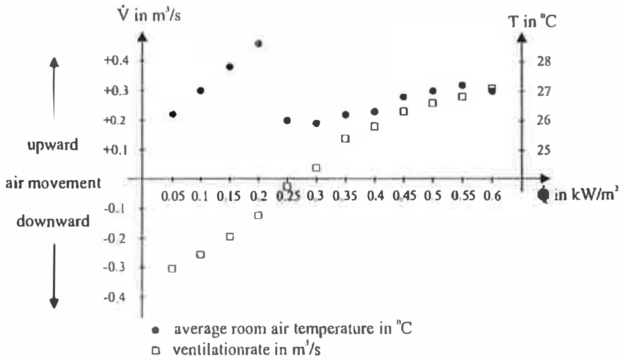

Figure 6: Diagram of ventilation rate and internal temperature versus internal heat gains for 2-dimensional summer day study

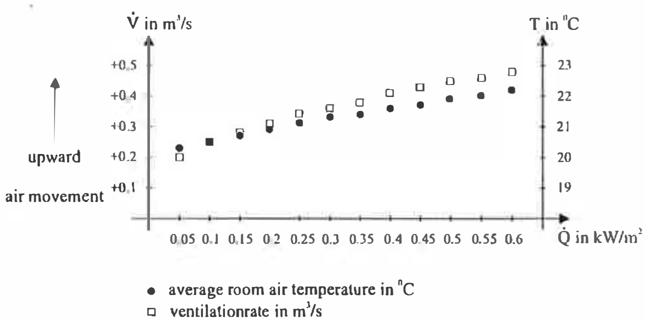

Figure 7: Diagram of ventilation rate and internal temperature versus internal heat gains for 2-dimensional summer evening study

CONCLUSIONS

The main conclusions of the research are as follows:

- For high external air temperatures there is a risk of flow reversal with air entering through the stacks and leaving via the mass plenum. The cooling of the air in the underfloor plenum creates a negative thermal mass effect. This may be countered by high internal heat gains, although these also create higher internal air temperatures, though not necessarily in the occupied zone.
- When it is cooler outside the air flows in the intended direction, with the air supplied to the occupied space about 1°C higher than the external air temperature. Increasing the thermal mass in the plenum reduces the temperature only marginally because of the reduced ventilation due to the increased negative buoyancy.
- In winter, with heat supplied to the incoming air, the flow is always upward. The openings at supply and exhaust should be controlled to avoid excessive ventilation.
- When there is wind, a pressure gradient of 1-2Pa is sufficient to ensure upward airflow for the high external air temperature situation.

- Thermal mass would be best placed above the occupied zone for warm weather cooling, where the thermal buoyancy effects would work together – of course the wind pressure gradient would need to be reversed, with devices to create a relative positive wind pressure at high level.
- The main limitation of the modelling technique is the weak convergence of internal air temperatures for mixed airflow directions. This is an area of further study.

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