USE OF COMPUTER SIMULATION IN THE DESIGN OF A NATURALLY VENTILATED LIBRARY

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ABSTRACT Sustainable building design has received increased attention over recent years and the use of natural ventilation in non-domestic buildings has been integral to this forward-looking issue. Natural ventilation design has been assisted by the availability of computer-based simulation techniques capable of predicting aspects of building design such as thermal comfort and air quality. Such aspects require particular attention by architects and building designers as they are more difficult to determine, and subsequently to control, in buildings which are naturally rather than mechanically ventilated. This paper describes how computational fluid dynamics (CFD) and dynamic thermal simulation (DTS) programs were used to analyse an innovative new library design at Coventry University in the UK.

The building comprises four passively ventilated floors with an area of 8100m^2. Fresh air flows into the building via a lightwell in each quadrant of the floor plan. Buoyancy forces then drive stale air upwards and out through a central lightwell and perimeter exhaust stacks. The simulation work reported in this paper provides an insight into the complementary use of CFD and DTS programs and shows how their results were used to inform and corroborate the design of this building.

1 Introduction

During recent years, many architects and building designers have been turning their attention to naturally ventilated and daylit designs. Their striving for innovation and good practice has yielded large reductions in energy consumption (e.g. BRECSU (1991)) and this is likely to continue as new lessons are learnt.

One of the difficulties in designing innovative buildings is a lack of knowledge about how to design the various features required to ensure adequate ventilation and daylight, whilst maintaining acceptable thermal performance. Significant assistance is offered by computer-based simulation programs. These enable many design variations to be considered in relatively short periods of time. This not only guides architects but can also engender client confidence in the architect's proposal.

This paper illustrates the application of dynamic thermal simulation (DTS) and computational fluid dynamics (CFD) programs by describing their use at the design stage of a naturally ventilated library for Coventry University in the UK.

A brief description of the building is given followed by an explanation of the DTS and CFD simulations that were used to inform and corroborate the design. The results and their implications are then discussed.

2 Design description

2.1 The brief

Included in the client's brief were several issues that are in keeping with sustainable buildings. The client (Coventry University) requested that the new library, to have a net floor area of about 12 000m^2 (including basement), should be as energy efficient as possible and environmentally friendly. Full consideration was to be given to natural lighting, natural ventilation and combined heat and power. The client also wanted the proposals to be computer modelled to obtain the anticipated running costs and an indication of the level of control that the client would have over conditions inside the building. As the use of computers was thought likely to increase rather than to decrease, the client was keen to ensure that the library would perform satisfactorily under increased internal heat loads.

The building was also to be useable as a teaching vehicle for the University's School of the Built Environment, and, through its innovative design, provide the University with a flagship building which would attract national and international acclaim.

2.2 The site

The building's inner-city location imposed additional design constraints. Coventry, in the UK Midlands, suffered serious wartime bombing and its reconstruction has resulted in a car-oriented road network. The site itself is located very close to a raised main road accentuating the problems of noise and air pollution. The site is typified by the UK's temperate summer and winter conditions and is subject to the gusty and unpredictable wind conditions often encountered in inner-city areas. Surrounding buildings, both existing and planned, offered little solar shading to the site.

2.3 Preliminary design

Following a concept study by the architects Short and Associates, a Royal Institute of British Architects (RIBA) stage D design was established based on which detailed CFD and thermal simulations could be conducted. The design comprised: a half basement ( ); a ground, first and second floor all measuring ; and a third cruciform-shape floor with an area of 1620m^2. The basement, which comprises the book archive and provides 24 hour computing access, is not part of the natural ventilation concept and will not be discussed further in this paper. The four remaining floors are essentially open plan and are penetrated by five large lightwells, one in each quadrant and one in the centre which is tapered and only partially penetrates the ground floor (Fig.1a). This tapering assists daylight penetration. Around the perimeter of the building are sixteen vertical ventilation stacks and the staircases (Fig.1b). An additional ventilation stack is also included in each of the four corners of the building.

2.4 Intended operation of the building

All areas of the library (except the basement) are to be naturally ventilated using ambient air. Fresh air will be supplied to the four corner lightwells (pre-heated if necessary) via a plenum, by harnessing wind and buoyancy forces. From these lightwells the air will enter each floor at low level and traverse the floor plate. It will then be exhausted at ceiling level through the central lightwell and the perimeter stacks, where louvres will control airflow rates based on internal temperature and CO_2 levels (mainly temperature during the summer). The tops of the air supply lightwells, which will become heated by solar gain, will be separated by a glazed partition from the near-ambient air below to prevent warming of the supply air during the summer. A translucent, moveable shading device will also be placed at this partition, and heat will be passively vented out of the separated region. The Building Energy Management System (BEMS) will control louvre openings so that night air can flow through the building cooling the exposed thermal mass during the summer, thus providing a convective and radiant heat sink during the following day.

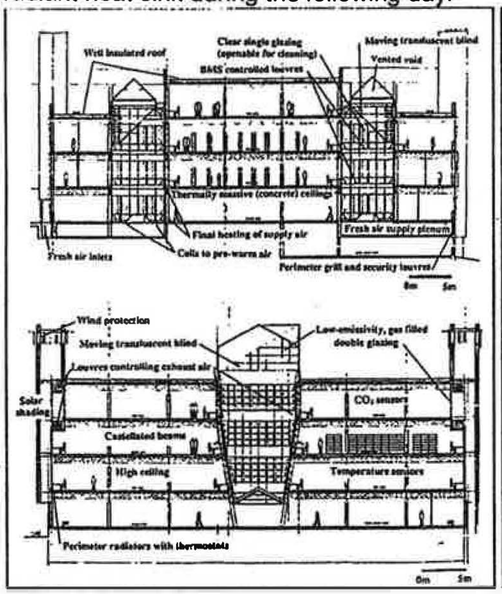


Fig. 1a **Sections through proposed library showing corner lightwells (top) and central lightwell (bottom).**

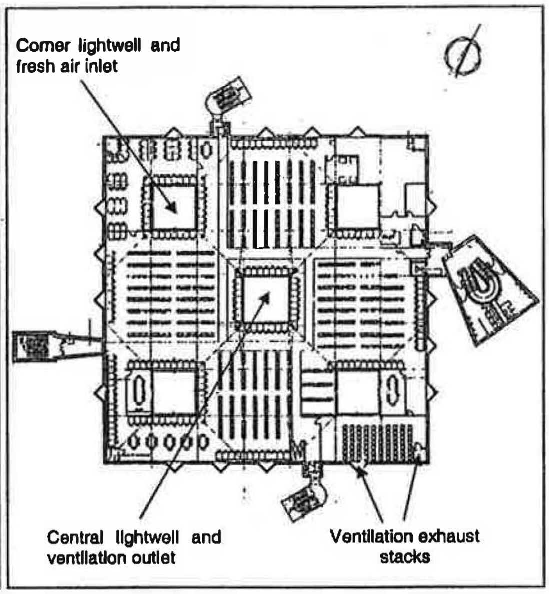


Fig. 1b Typical plan of a possible library layout (level 2) showing inlet and exhaust airflow routes.

At 4m, the floor-to-ceiling height is large. This allows warm stratified air to accumulate above head height where castellated beams enable air movement along the soffit to the air outlets. The central lightwell and perimeter stacks increase in cross sectional area up the building to accommodate the increasing volume flow of air as additional floors are exhausted.

During winter nights, the louvres and shading devices should be closed to prevent convective and radiant heat loss, and an (unoccupied) set-point or 'frost protection' temperature will be imposed.

3 Simulation studies

The success of the library hinges, most critically, on maintaining thermally comfortable conditions in summer, i.e. an adequate supply of air at an acceptable temperature. This issue was investigated using the CFD program CFX (CFX International 1997) and the thermal simulation software ESP-r (ESRU 1996).

CFD programs work by dividing the building up into many thousands of small three-dimensional cells and predicting air speed, air temperature and other physical air properties in each cell, according to a set of user-supplied boundary conditions. This provides a very detailed picture of how the air is likely to behave. However, due to the complexity of CFD programs, simulations over a long period of time are prohibitive. Instead, CFD is most commonly used to obtain a 'snap-shot' of the airflow pattern at an instant in time.

In contrast, the crude spatial subdivisions used in DTS programs enable only average temperatures to be predicted. However, simulations can be used to predict the hourly variation of internal temperatures in response to time-varying external climatic conditions and changes in internal heat gains and the on-off switching of heating systems. Because the internal temperatures are closely related to the airflows in this building, a combined airflow and thermal simulation was undertaken. In such a simulation the model predicts the current internal air temperatures, and based on this, the resulting internal airflows. These airflows are then used in the calculation of the air temperatures at the next increment of time. Thus the time-varying interaction of temperatures and airflows is modelled as closely as possible. This modelling approach requires an airflow network to be established as well as a thermal (heat flow) network. The heat flow network demands that the construction of all walls, ceilings, floors and windows be described so that heat storage within thermally massive elements and solar gain through windows can be accurately modelled. This also enables surface temperatures to be calculated, using which, dry resultant temperatures can be found. The detailed operation of the BEMS, which is usually used to tune the operation of buildings such as this, was not modelled. However, in the results that follow, the probable consequence of such tuning is indicated.

DTS simulations were undertaken for each of the floors for a whole year period. Heating set-points of 18°C (occupied) and 14°C (unoccupied) were imposed, and a climate file for Kew 1967 used.
CFD simulations were carried out for one quadrant of the four-storey library, making use of symmetry planes to represent the remaining floor plan. Simulations were undertaken for a typical warm summer day using an ambient temperature of 24.5°C. Two occupancy scenarios were considered: one for the expected occupancy, in which internal heat gains were 28W/m^2 (core) and 48W/m^2 (perimeter, to account for solar gain); and a second in which the library is much more heavily used (42W/m^2 core and 60W/m^2 perimeter). The 'perimeter' zone was estimated to extend a distance of 4m from the building perimeter. The simulations did not include the effects of night cooling and exposed thermal mass, and assumed calm (no wind) ambient conditions - because the building must work in the absence of assisting winds.

To encourage uniform airflow rates through each floor, openings higher up the building should be larger than those lower down. As a starting point in the CFD study, openings were sized according to the force acting on the stack outlet at that level. Using basic stack equations (e.g. Awbi 1991) it can be shown that for uniform airflow rates at all levels, openings should be sized in inverse proportion to the square root of the stack height acting on that opening.

4 Results and discussion

4.1 CFD simulations

The results for the expected occupancy scenario show air flowing out of the supply lightwell, across the floor plates, and exhausting via the central lightwell and perimeter stacks (Fig. 2a). Despite the crude approach to opening sizing, the air change rates through the lower three levels were fairly well balanced, having a range of 9.5 to 12ac/h. This yielded fairly uniform temperatures across each floor plate as desired. The predicted temperatures were just 2.5-3.5°C above ambient, which, given that the effects of night cooling and exposed thermal mass were not modelled, is encouraging. Dry resultant temperatures, which account for radiation effects and are indicative of thermal comfort, can be expected to be lower than the CFD-predicted air temperature provided an efficient night cooling strategy is in operation.

In the preliminary design, the top (third) floor was connected to the same central exhaust and the same perimeter chimneys as the floors below. It was observed that, under some conditions, the warm air rising up the central lightwell from the lower floors could flow out into the top floor (rather than continuing upwards to the outlet). This effect reduced the flow of fresh air into the top floor to around 7ac/h which raised the air temperature on this floor (Fig. 2b). As a result of the simulations, the design was modified to give the top floor dedicated exhaust stacks which would prevent this problem.

CFD simulations for the heavy occupancy scenario indicated that internal temperatures would only increase by about 1°C. This is because higher internal heat loads are capable of driving larger airflows which increases ambient cooling. This coupling between airflows and heat injection is a valuable characteristic of buoyancy-driven displacement ventilation systems.

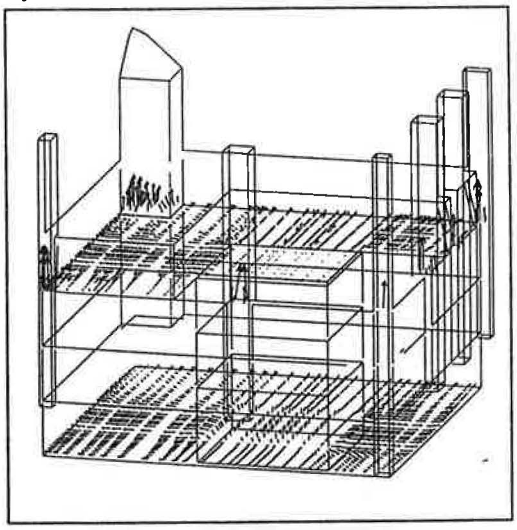


Fig. 2a Air flow predictions (CFD) at 0.1m above the ground and third floors (a vector length equal to 1m of the geometry corresponds to 0.5m/s)

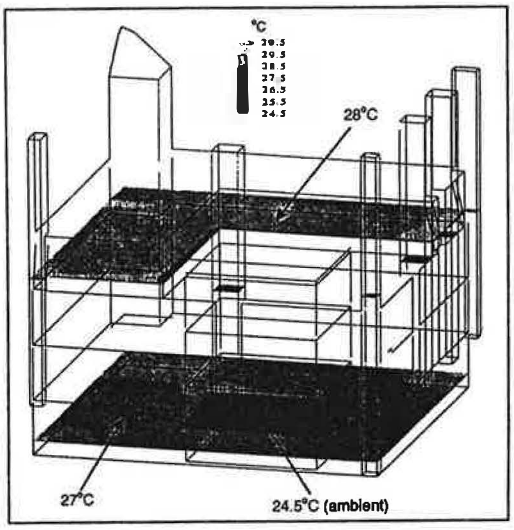
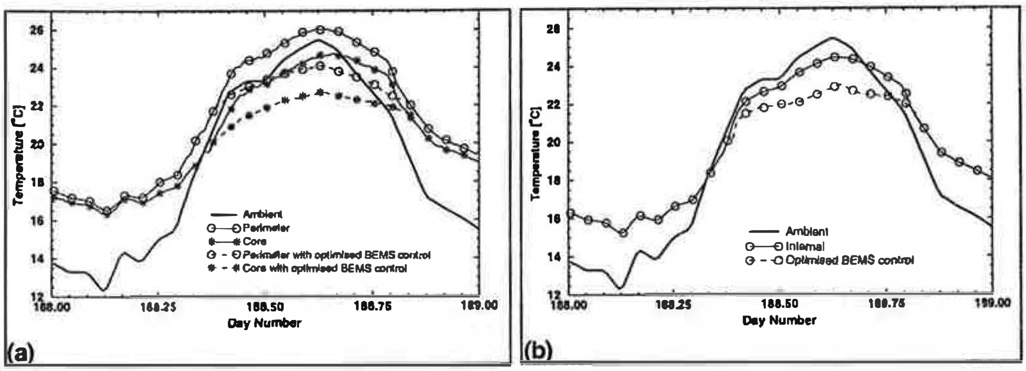


Fig. 2b Air temperature predictions (CFD) at 1m above the ground and third floors

4.2 Thermal simulations

Thermal simulation results for a typical summer day show peak dry resultant temperatures ranging from 26°C at the perimeter to 24°C in the core (Fig.3). These predictions, which account for the cooling effect of the exposed ceiling slab, are consistent with the CFD predictions. Although these temperatures are already below that which is generally considered to be thermally uncomfortable, i.e. about 27°C, it is anticipated that the refined control of airflow possible with a BEMS would be capable of lowering these by a further 1-2K.



(a) (b)
Fig.3 Predictions of ESP-r for the (a) ground and (b) third floors for a typical hot summer day (internal heat gains of 30 W/m² from 0900-1900h)

(Fig. 3). This control would reduce the opening sizes to the minimum commensurate with fresh air requirements at times when the ambient temperature is higher than internal temperature.

Over the course of the whole year, the simulations predicted that a dry resultant temperature of 27°C would only be exceeded for 11 hours of the year at normal occupancy, and the temperature would always be below 28°C.

5 Conclusions

It has been demonstrated that in the UK it is possible to design large, nominally deep-plan, buildings which do not require air-conditioning to maintain comfortable conditions, despite internal heat gains up to about $40W/m^2$.

The power of computer modelling to inform and corroborate a building design, and the complimentary use of CFD and DTS programs has been illustrated. A simple method of estimating the relative sizes of openings in exhaust stacks has been suggested as a starting point for CFD simulations.

The simulation work engendered client confidence that a new library is likely to remain thermally comfortable and well ventilated under conditions which are experienced during a typical UK year. It has also been shown that the design is reasonably robust to increases in library usage.

Once completed, the library at Coventry University will provide the region with a fine example of passive and low energy environmentally friendly architecture.

6 Acknowledgements

The authors wish to acknowledge the architects Short and Associates, and the client Coventry University for granting permission to publish this work.

7 References

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In the DTS simulations, the same internal heat gains were assumed in both the core and perimeter zones. In the CFD simulations higher values were imposed at the perimeter because the effects of solar gain need to be modelled explicitly.