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A study of the operation of a novel naturally ventilated building using computational fluid dynamics

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In response to an increased awareness of the impact of building related energy consumption on emissions of carbon dioxide, attention has turned to the task of making buildings more energy efficient. Although this is a key element in the design of a new building, it is important also that the occupants' expectations of a comfortable and healthy environment are met. Computer simulations of the airflow and thermal environment within a naturally ventilated building have been made using a finite-volume CFD model. Indoor climatic conditions and the effectiveness of cross-ventilation channels and solar-assisted ventilation shafts on a warm summer day, with a light breeze, have been examined. This case study facilitates a better understanding of some of the complex interrelated issues associated with natural ventilation.

Introduction

A growing interest in the application of natural ventilation design strategies has been driven by an increased awareness of the potential environmental benefits and energy savings of such designs and the encouragement given by the authorities for their uptake. However, to ensure the successful operation of a naturally ventilated building, the design must take into careful consideration a number of important issues. These include the external air quality and wind distribution, the dynamic thermal response of the building structure and the anticipated levels of internal and solar heat gain. The inter-relationship of the above issues is complex and difficult to predict, and requires a detailed thermodynamic analysis.

Physical measurements using laboratory-based models (e.g. salt water and wind tunnel) and computer models based on 'zone' or 'network' methods provide valuable assistance to the design engineer. However, the task of analysing the complex airflow and heat distribution patterns lends itself to the techniques of computational fluid dynamics (CFD).

The present contribution revisits the performance of the novel natural ventilation system adopted in the Environmental Building at the BRE, Watford, on a warm summer day with a light breeze.

The Building

A requirement for a new office building at the BRE's main site in Watford provided an ideal opportunity to put new construction and environmental design ideas into practice. Air conditioning has been avoided, with summer-time natural ventilation on the ground and first floors provided by a novel combination of cross-ventilation, a pre-cast concrete wave ceiling with cavity air channels and five external ventilation shafts.

The ground and first floor office spaces are 30 m long (east-west) by 13.5 m wide (north-south), with a 3.3 m distance from the floor to the ceiling crest. Nine cavity ceiling channels run in the north-south direction, each channel consisting of separate north and south sections opening into the office space approximately 5 m from the north façade. Whereas all north sections open, via Building Management System (BMS) controlled windows, to the external atmosphere, alternate south sections open into external ventilation shafts (again under the control of the BMS). Figure 1 shows the ventilation paths in a cross-section containing an external shaft, and shows also the division of the office space between an open plane area and cellular offices. Figure 2 shows, from inside the office, the air paths to a ventilation shaft, which in addition to the ceiling channel includes two low level 'hopper' windows which open directly from the open plane area.

Additional office ventilation may be provided by high-level windows that open to the outside at the ceiling crests mid-way between the channels, and from a provision of manually controlled low level windows. With the doors closed, the cellular offices are effectively isolated from the main office space, with 'single sided' ventilation provided locally by windows in these offices. Further information about the BRE's Environmental Building and its conceptual design can be found elsewhere [1,2].

The building is the subject of a European Commission THERMIE project [3], where various aspects of the building performance are being monitored. One conclusion from this project is that the operation of the ventilation shafts is complex, and that further study of their operation and their interaction with the office air space is required.

The CFD Model

Airflow and heat transfer within and around a building are governed by the principles of conservation of mass, momentum and thermal energy. These 'conservation laws' may each be expressed in terms of partial differential equations, the solution of which provides the basis for a CFD 'field' model. The mathematical expressions for the governing differential equations can be found elsewhere [4].

The appropriateness of the model, however, depends not only upon the characteristics of the fluid flow and related processes, but also the geometrical aspects of the problem. Although many buildings may be formed from simple rectangular shapes, others include more complex shapes (such as the office ceiling inside the Environmental Building) which require accurate numerical representation. The accuracy of the CFD solution relies heavily upon the quality of the computational mesh on which the discretised equations are solved. Therefore, in buildings with interconnected zones and geometrical complexities it is desirable to employ a CFD model which is capable of representing a complex, three-dimensional geometry using a boundary-conforming numerical mesh to fit irregular boundaries. An unstructured mesh CFD model was used for the study, allowing the geometry to be discretised with an irregular arrangement of tetrahedral and prism elements in an efficient manner.

The Problem Considered

We report here the findings from airflow simulations of the first-floor open plan office on a warm summer day with a light breeze. It is in conditions such as these, where the external wind may be too weak to provide sufficient cross-ventilation, that the external ventilation shafts are designed to enhance air movement within the office space. The ventilation shafts also have a role to play during the night-cooling operation, again when the external wind is weak.

Three separate mechanisms, two passive and one active, can assist the flow of air from the office into a ventilation shaft, and thence into the external environment:

- Pressure induced flow generated by the movement of external air across the top of the shaft.
- Buoyancy induced flow generated by solar heating of the glass panels on the front (south face) of the shaft.
- A low speed fan installed near the top of the shaft.

The low speed fan operates only when the passive measures provide insufficient upward flow. This could occur, for instance, when there is no solar gain and no wind. We consider here, however, the case where there is a small airflow across the top of the shafts and the fans are not operating.

The interaction between the internal and external and conditions makes it preferable for the flow domain to include also the external environment. Ideally, the model should include the whole building as well as the influence of neighbouring structures. This would require, however, either a prohibitively large or a rather coarse numerical mesh. To investigate the interaction of the ceiling channels and the ventilation shafts, a reduced three-dimensional slice was modelled. While not capturing all the features of the flow, the office space is sufficiently periodic in the east-west direction for the simulations to capture the main characteristics of the selected scenarios and allow the main parameters, and their interaction, to be investigated.

The simulated domain was extended well beyond the building envelope, where inlet (wind) and free boundary conditions were imposed. The windows opening from the ceiling channels to the outside were included in the model, and were opened to 45°. A 470,000-element mesh was used, with a finer resolution inside the office and ventilation shaft and a coarser resolution elsewhere. Figure 3 illustrates part of the surface mesh inside the office, showing the ceiling slab, the lower 'hopper' window and part of the office furniture.

In a naturally ventilated building, the time-dependent interaction between the external conditions, the building fabric and the internal thermal load means the boundary conditions vary with time. In practice, however, CFD boundary conditions are often approximated as steady-state, based on the analytical, experimental or assumed values associated with a given time of day. In the present study the following steady-state conditions were imposed:

- Light breezes of 0.5 m/s and 1.5 m/s from the south. For this study a logarithmic wind profile was assumed, increasing from zero at ground level to the stated value 10 m above the ground. In practice, the wind could come from any direction, will vary with time and will depend also on the influence of the surrounding buildings. A more in-depth analysis of the effect of wind direction and the surrounding buildings awaits further study.
- An ambient external air temperature of 24°C was chosen, representing a scenario where ceiling channel cross-ventilation and the cooling effect of the ceiling slab would be expected to provide sufficient control of the office temperature. At higher temperatures the BMS is likely to activate trickle ventilation and possibly also the groundwater cooling system (summer-time cross-ventilation is active only if the external air temperature is lower than the internal office temperature).
- Two conditions of solar gain at the ventilation shaft were simulated. One where the internal faces of the glass panels had been heated to 5°C above ambient and one where there was no solar gain (representing a cloudy day).
- A source of exhausted air from the ground-floor office into the ventilation shafts (below the modelled first-floor office) was included. The temperature of this source was set to 24°C,

with a flow rate corresponding to two air changes per hour. The purpose of this was to make the conditions inside the ventilation shaft more realistic while not extending the CFD domain into the ground floor office.

- Two conditions of heat loss to the ceiling slab were imposed by assuming isothermal boundary conditions of 21°C and 23°C respectively (3°C and 1°C below ambient). Additionally, the case of no heat loss to the ceiling slab was modelled.
- A thermal load of approximately 20 W/m^2 (convected) was included, with individual heat sources to represent people and personal computers. Lighting was not included in the thermal load since this is minimal during summer-time operation.

The standard k-ε turbulence model [5] was employed and all solid surfaces were treated as hydro-dynamically smooth. Although radiation was not modelled directly, its effect can be considered to be included implicitly in the thermal boundary condition at the ceiling slab. A full matrix of simulations was performed, covering the various combinations of boundary conditions. This allowed the sensitivity of the boundary condition parameters to be assessed.

Results

As expected, the combination of the stronger breeze (1.5 m/s) and greater cooling at the ceiling slab (21°C boundary condition) produced the best thermal comfort inside the office. The temperature was maintained at below 25°C throughout the accessible parts of the office space, i.e. not including regions such as directly above the computers. This is within 1°C of the ambient value. Figure 4 shows the temperature contours on two cross-sections through the office. The temperature rise is modest and within the building specification requirement that the temperature be maintained below 25°C for 95% of the working year.

The presence of a moderate solar gain inside the ventilation shaft had little bearing on the climate inside the office. The temperature was slightly higher with no solar gain due to a small change in the ventilation rate through the shaft. This was observed for all combinations of wind speed and ceiling slab temperature, and confirms the design concept that the pressure drop at the top of the shaft should induce an upward flow of air.

Increasing the ceiling slab temperature from 21°C to 23°C had the effect of increasing the office temperature by about 0.5 °C. Even taking the pessimistic case of no cooling by the ceiling slab, the office temperature remained below 26 °C, i.e. a temperature rise of less than 2 °C.

Reducing the wind speed from 1.5 m s^{-1} to 0.5 m s^{-1} increased the office temperature slightly, but only by approximately 0.5°C. As with the stronger breeze, the temperature rise inside the occupied office space in the situation of no cooling by the ceiling slab was still under 2°C.

The important difference between the results with the two wind speeds was in the ventilation rate inside the office. With the stronger breeze, approximately 7 air changes per hour (ach^{-1}) were observed for all combinations of thermal boundary conditions. With the weaker breeze this reduced to approximately 4 ach^{-1}. The predicted air change rate with the stronger breeze is certainly quite high. The maximum allowed in the building design specification is 10 ach^{-1}. Tests undertaken during the THERMIE project indicate that the air change rate could be this high when the ceiling channels and hopper windows are fully open.

The simulations showed the extent to which the ventilation shafts contribute to the overall air change. With the weaker breeze (0.5 m/s), all exhausted air passed into the ventilation shaft, with incoming air passing through all ceiling channels. With the stronger breeze, approximately 80% of the exhausted air passed into the ventilation shaft, with the remainder passing out through one of the leeward ceiling channels. In both cases, about 50% of the air entering the ventilation shaft passed via the hopper windows.

Figure 5 shows a typical airflow pattern inside the office on a cross-section that includes a ventilation shaft. The passage of air through the hopper windows can be seen. Furthermore, the division of the incoming (ceiling channel) air between the opposite channel section and the office space below can be observed. This confirms the observation from the THERMIE project that some of the incoming air may bypass the office space and pass directly to the ventilation shaft via the opposite ceiling channel.

Conclusions

The CFD simulations reported here have illustrated the effective performance of one mode of operation of the natural ventilation strategy adopted in the BRE's Environmental Building, namely a warm summer day with a light breeze and an internal thermal load of approximately 20 W/m^2 (convected). With the ceiling slab channels and ventilation shafts at full ventilation setting, and the ceiling slab surface at 3°C below ambient, temperatures inside the occupied first-floor office space remained everywhere close to the outside ambient value. Even with no cooling to the ceiling slab, temperatures rose by no more than 2°C above ambient.

Provided there is some breeze, the ventilation stacks were shown to operate effectively even in the absence of any solar heating. This supports the design assumption that in most situations the pressure drop at the top of the stack should help to draw air through.

The overall ventilation rate inside the office was correlated to the magnitude of the breeze. At the higher wind speed of 1.5 m/s, in particular, the predicted ventilation rate was quite high at about 7 ach^{-1}. At the lower wind speed of 0.5 m/s the value was reduced to about 4 ach^{-1}. These values could be reduced by partially closing the ceiling channel and hopper windows.

On hot summer days, with an outside temperature in excess of say 25°C, the building would most likely need to operate in a trickle ventilation mode and possibly activate the groundwater cooling system (as happens in practice).

References

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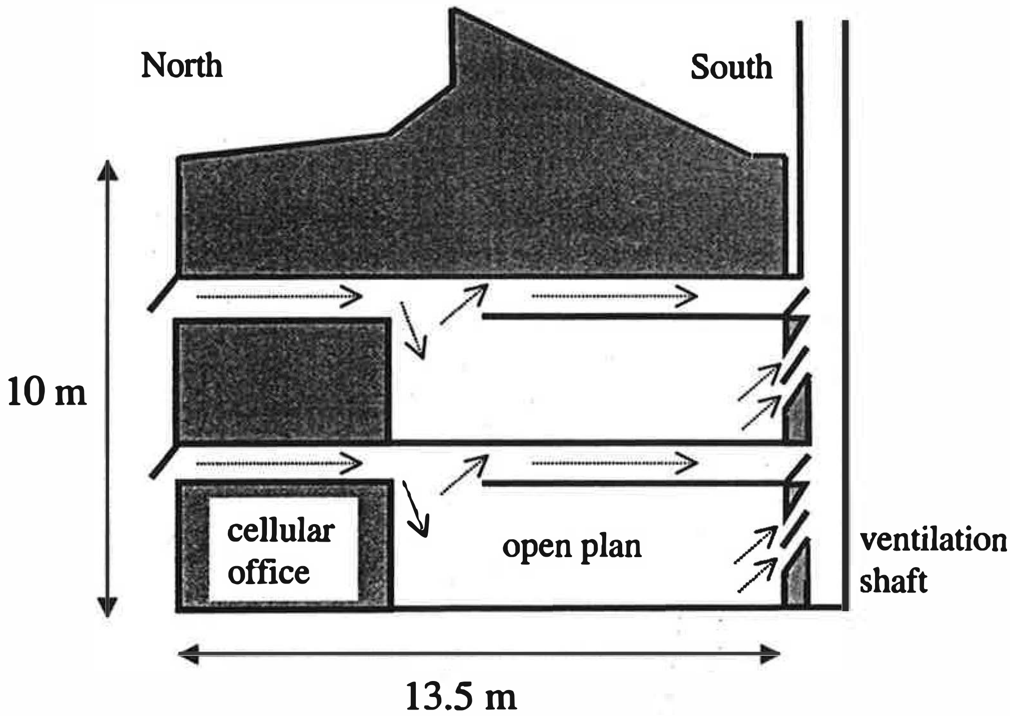

Fig. 1. Building cross-section showing ceiling channels and ventilation shaft

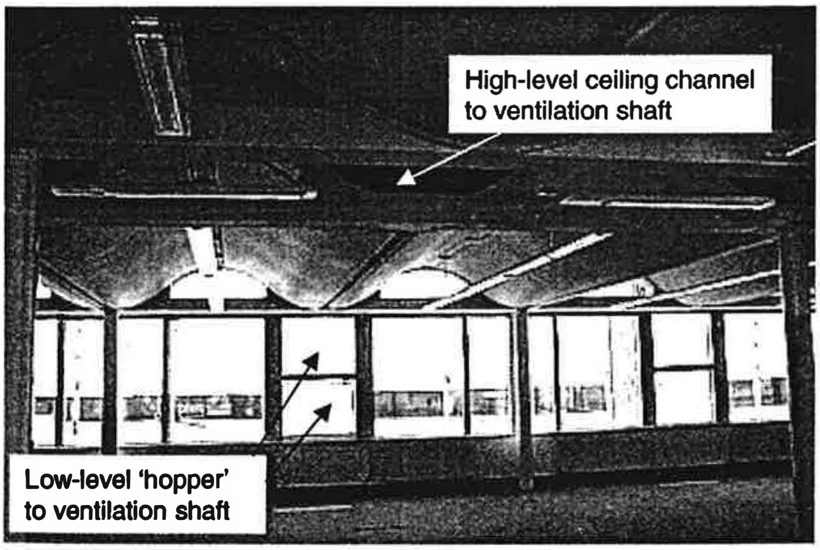

Fig. 2. Airflow paths to a ventilation shaft

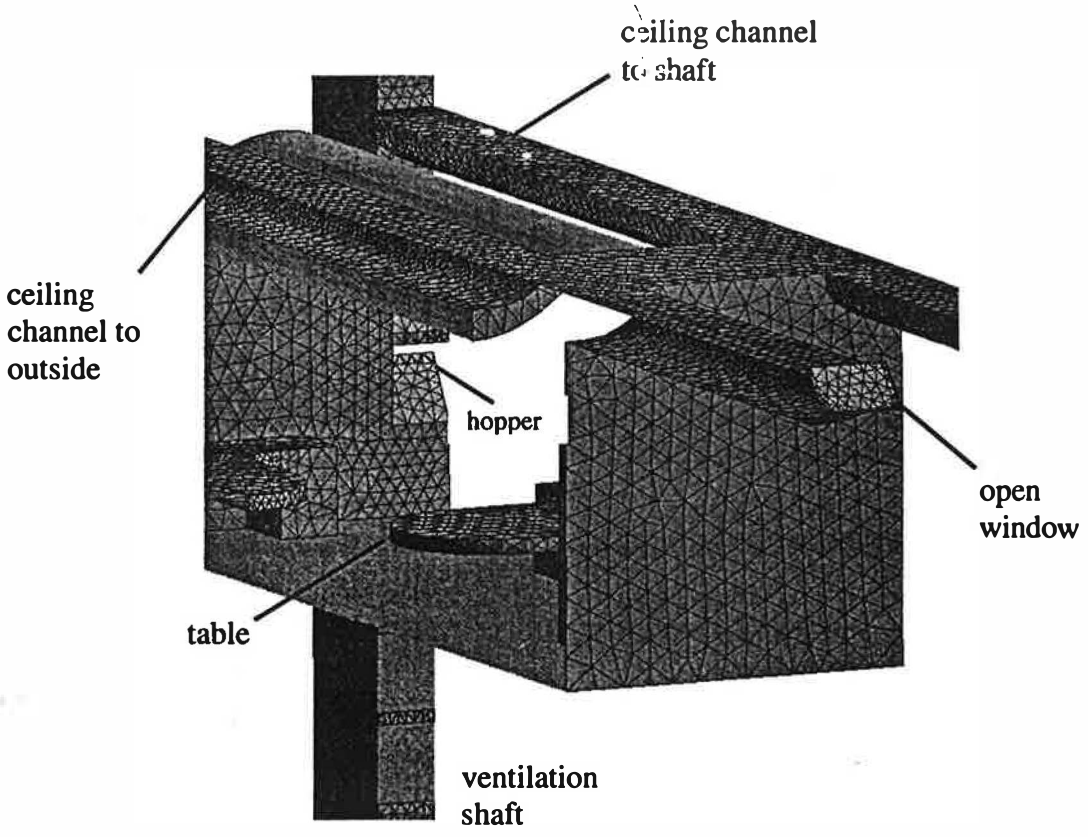

Fig. 3. Part of the surface mesh inside the office

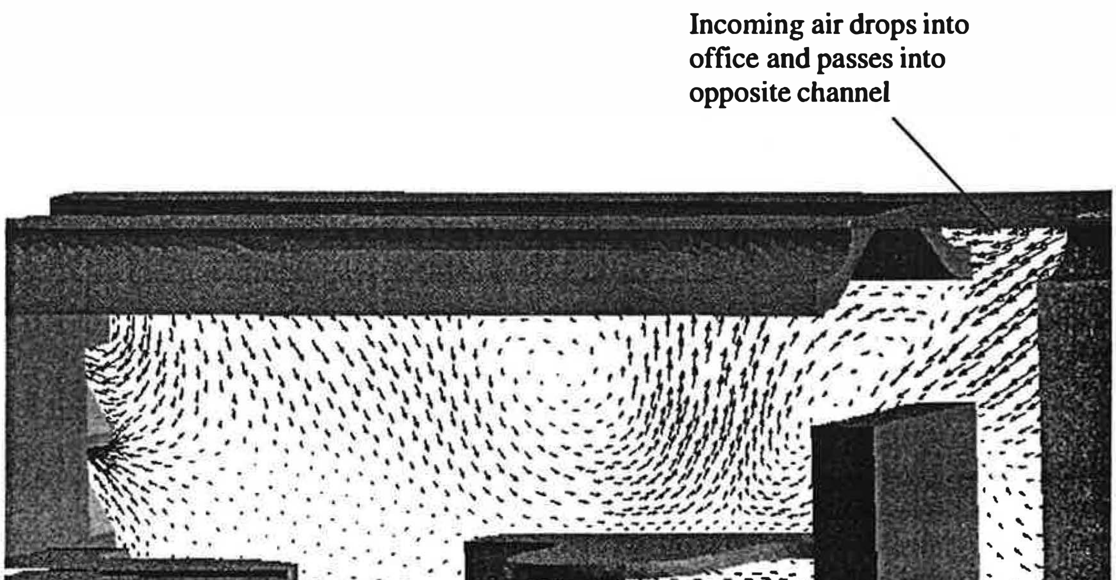

Fig. 5. Flow vectors inside the office