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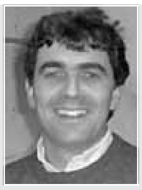

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Energy efficiency with natural ventilation: a case study

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Application of laboratory analogue modelling of air flow in a naturally ventilated shopping mall is reviewed in this paper. A detailed study of the ventilation was undertaken to establish the principles and to explore how natural ventilation might interact with a localised mechanical ventilation system designed to enhance the cooling of a high density food court area. The case study is used to show how the combination of laboratory modelling and simplified mathematical modelling enables one to rapidly identify the various flow regimes which can occur, to quantify the resultant flows and mean temperatures and to thereby develop appropriate ventilation strategies for the different external conditions which occur through the year.

1. INTRODUCTION

1.1. Energy use in buildings

The UK domestic energy gap is widening and national demand is set to outstrip indigenous supply. Crucially, there are major opportunities to close the gap by reducing the UK energy demand. The provision of energy to buildings accounts for 40% of all energy consumed and much of this is associated with heating and cooling. It is well known that energy inefficiency is wide-ranging in current UK building stock. Older buildings are typically less well insulated than newer structures, and have inefficient energy management systems and inefficient lighting. Improving the energy efficiency of existing buildings is important, but can be challenging owing to the limited budgets often allowed for refurbishment. However, even in new buildings that are intended to be low energy, there are considerable variations in energy efficiency. For example, air-conditioned buildings, which are increasingly becoming the norm, typically cost more and may consume tens of per cent more energy than those without air-conditioning. Properly designed non-air-conditioned buildings therefore provide a significant opportunity for minimising fuel consumption within the building sector. One of the key challenges for engineers is to design low-energy building systems that provide comfortable conditions by responding effectively to changes in external conditions (such as wind and temperature) and internal heat loads.

1.2. Design of naturally ventilated buildings

Buildings that do not rely on mechanical equipment to draw in fresh air and distribute it through the interior are described as naturally ventilated; forces of nature such as wind and/or buoyancy arising from temperature differences between the exterior and interior are used to drive air flows through the building. The design of a naturally ventilated building requires an understanding of the interaction between heat sources and sinks and the air circulation pattern. This understanding is important if a building is to be designed successfully and an appropriate control strategy that minimises energy use is to be developed.

The interaction between heat sources and sinks and building-scale air flows is a difficult issue to model accurately. For example, recent research has highlighted the potential for a building to exhibit multiple flow patterns for exactly the same exterior conditions and vent settings.[1] It is difficult and time-consuming to identify these phenomena during a normal design program with modelling tools such as computational fluid dynamics (CFD). Typically, CFD models predict a flow pattern given initial conditions and heating and cooling loads, but do not explicitly search for multiple states. Similarly, although some of the simpler zonal models may identify the occurrence of multiple flow regimes, they are not always geared for such an application but rather predict one possible flow pattern. Furthermore, zonal models are not designed to model the interaction of mixing ventilation, in which there may be bi-directional flow through some openings, with displacement ventilation, in which there is a net flux through some of the vents.

In order to address such flow regimes, new analogue laboratory techniques have been developed to model ventilation flow patterns that may arise in a building. Such models are now available for designers to rapidly visualise and quantify flow patterns in a proposed naturally ventilated building. The experiments involve using Perspex models immersed in a water bath, with hot wires to simulate heat loads and chilled water to simulate mechanical cooling. Appropriate quantitative models, based on the zonal modelling approach but accounting for both mixing and displacement ventilation, may then be built to determine air flow rates and thermal comfort conditions in naturally ventilated buildings. Such models can account for the benefits of thermal mass and the effectiveness of various control strategies in accord with the laboratory models.

The new laboratory modelling approach provides a complement to CFD studies in that, for large building projects, it is ideally suited to prediction of building-scale flow patterns and control of building-scale ventilation, whereas CFD studies are appropriate for determining more localised details of flow, perhaps within enclosed office spaces, or near inflow air distributors and

Fig. 1. Photograph of the experimental apparatus illustrating the model of the shopping complex, which consists of the main hall (right-hand side of photograph) and the food court (left)

doorways. Indeed, with the highly complex geometry of large buildings, it is difficult to readily visualise large-scale flow patterns using CFD. The output of such models is typically used to generate contour maps of flow through two-dimensional sections of a building. Furthermore, the solution of the time-dependent flow equations through a three-dimensional building geometry requires parameterisations of small-scale mixing processes, which limit the accuracy of such models.

1.3. Case study

Application of the laboratory analogue modelling approach to a new shopping mall in central Norwich, developed by Lend Lease, is reviewed in this paper. Large open spaces such as the interiors of large shopping mall complexes offer tremendous potential for natural ventilation owing to the very open and often tall interior space. However, such a natural ventilation system is complex to design and manage owing to the large number of heat sources within the space and the differing requirements of the ventilation system in different seasons. A detailed study of the ventilation was undertaken to establish the principles and to explore how natural ventilation might interact with a localised mechanical ventilation system designed to enhance the cooling of a high occupant density food court area. The study involved the development of theoretical models to determine the different regimes of ventilation depending on the seasons. A series of small-scale laboratory analogue experiments was then conducted to explore in more detail the flow patterns within the space, accounting for the effects of both natural and mechanical ventilation under a range of operating conditions (Fig. 1). The experimental tank shown in Fig. 1 was placed in a water bath and an electric current passed through wire to simulate the heat load. Chilled water was added to the food court area to represent mechanical cooling. The tank has openings at the top and the base to simulate the roof stacks and the low-level ventilation openings near the doors to the mall. Wires carrying electric current and for the thermocouples that monitor the temperature throughout the model can be seen in Fig. 1; pipes supplying chilled ventilation fluid to the food court can also be seen at the top of the food court area.

A laboratory simulation of flow through a model building using a water bath with heating and cooling of the water provides an analogue to real building air flows if the dynamical model flow regime is similar to that in the building. To establish equivalence, it is important to relate the dynamical regimes of the Reynolds number for the flow through the openings and the Rayleigh number of the convection with values appropriate for air flow in buildings. In a building, the Reynolds number is given by $R \sim UL/\nu$ for air, where the typical speed of air $U \sim 0{\cdot}1$–$1{\cdot}0$ m/s, the typical length scale of the building $L \sim 0{\cdot}1$–$0{\cdot}5$ m and the kinematic viscosity of the air $\boldsymbol{v} \sim 10^{-5}$ m^2/s, giving $R \sim 10^3$–10^5. The Rayleigh number, which measures the intensity of convective mixing and is given by $\Delta T \mathbf{g} H^3/T\boldsymbol{v}\kappa$, has a typical value of $\sim 10^{12}$–10^{13} (ΔT is the variation in temperature from the floor to the interior, T is the ambient air temperature in K, $\mathbf{g}$ is acceleration due to gravity, H is the vertical extent of the building airflow and κ is the thermal diffusivity of air). In the laboratory models, the flow through the openings has a speed of 0·1 m/s and the opening size is 0·01 m, giving a Reynolds number of about 10^3; this leads to flow that is just turbulent and hence is dynamically similar to the air flow in a building, although a little smaller in numerical terms. The Rayleigh number in the water bath model is $\Delta\rho\mathbf{g}H^3/\rho\boldsymbol{v}\kappa \sim 10^6$. This value is smaller than in the real building context but still corresponds to turbulent convective mixing in the space and hence leads to a dynamically similar flow regime.

One important difference between the laboratory model and real air flow is the Prandtl number for the flow, which represents the ratio of kinematic viscosity to thermal diffusivity. In air the Prandtl number is 0·7 while in water it is about 5; this difference means that the momentum boundary layer thickness dominates the thermal boundary layer in water, whereas in air they are closer in size, with the thermal boundary layer being a little deeper. The consequence of this is that the thermal structure of flow past obstacles is different in the model, and so the detailed flow pattern should not be interpreted as being directly analogous to the air flow in the real building, although the overall large-scale flow pattern and temperature distribution is analogous. In analysing temperatures within a building, it is helpful to focus on relative temperatures rather than absolute temperatures since it is temperature differences that control the buoyancy forces and dynamical flow regimes. In the laboratory models, the walls of the experimental tanks have relatively low thermal mass and so the models are strictly applicable to relatively lightweight and well-insulated buildings.

In the following, the heat budget in a typical shopping complex is described and its variation with season is discussed. The paper continues with an illustration of two flow regimes that might arise if the mall has a net heat load and is therefore warmer than the exterior air and if the mall has a net cooling load (including the effect of mechanical ventilation in the food court)—that is, the air inside the mall is cooler than the exterior. The discussion is illustrated with experimental results throughout. A simplified schematic diagram of the shopping mall is illustrated in Fig. 2. Entrances to the mall are openings on three sides of the food court. The roof of the main hall and the food court has a series of ventilation stacks in place. The side elevation of the building may be seen in simplified form in the experimental model shown in Fig. 1.

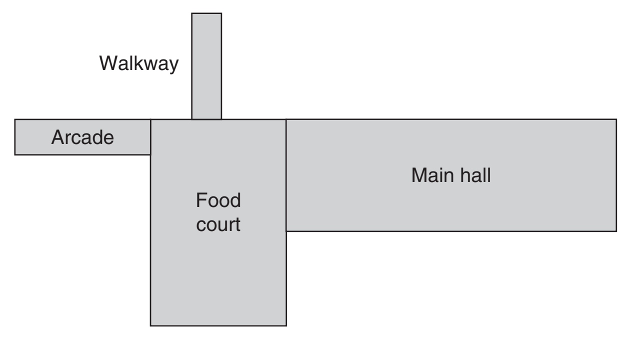

Fig. 2. Schematic diagram of the mall involving a two-storey long covered walkway bounded on both sides by shops

2. THERMAL REGIMES IN THE COMPLEX

2.1. Heat balance

The thermal regimes that may develop in the main shopping hall and the mechanically chilled food court may be identified by an overall thermal balance of the interior space. With some approximations and simplifications, an underfloor heating system, with a total heat load of about 100 kW, is used in winter to warm the space. Throughout the year, the heat load associated with visitors to the shopping complex represents a further 100 kW. In addition, solar gains and heat losses occur through the glazing and other radioactive heat fluxes may arise at the walls of the complex. Systems in the food court area of the mall have the ability to supply conditioned air at an air supply volume flux of 12 m^3/s with the purpose of achieving a temperature of around 22–24°C within the dining area.

In addition to these heat loads, a net ventilation flow through the mall brings in external air and exhausts air at the temperature in the vicinity of the exhaust vent. The analogue experimental models suggest that, although there is some lateral stratification in the mall, owing to large convection currents that develop along the mall (see below), the magnitude of these fluctuations is typically small relative to the difference between the mean internal and external temperatures. The magnitude of the heat flux associated with the ventilation flow may thus be estimated by assuming that the exhaust air has the mean temperature of the mall.

Figure 3 shows a typical prediction of the mean temperature in the mall that will develop with the above heat loads as a function of the external temperature. Plots are given for a series of values of the natural ventilation flow rate (shown on the lines) and assuming that the inlet temperature of the cooled air in the dining area is 14°C. Given this simplified picture of heat exchange and ventilation, the figure shows that, for much of the year, the temperature of the mall is higher than the external temperature. As a result, the natural ventilation flow could be an upward buoyancy-driven flow if the area of inflow and outflow vents is sufficiently large. In Fig. 4 the natural ventilation flow associated with a given temperature contrast and a given vent area is calculated and coupled with the heat budget calculation to predict the temperature excess of the building relative to the exterior as a function of the net convective heat load in the building (excluding the natural ventilation heat load).

The main exception to an upward displacement flow regime occurs in high summer if the external temperature increases to values in excess of 30°C. In that case, the supply of cold air to the food court may dominate the heating load within the mall, leading to a weak net cooling of the whole building. In such a situation, a downward natural buoyancy driven flow can develop, as indicated in the next section.

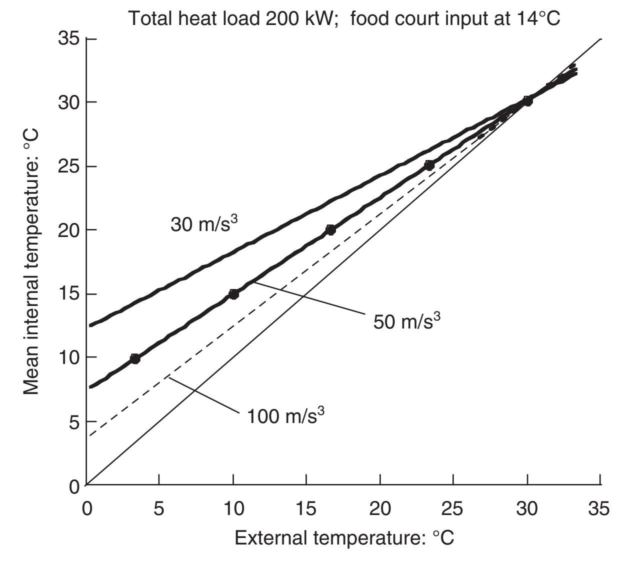

Fig. 3. Variation of the predicted temperature as a function of external temperature and ventilation flow. The line passing though the origin corresponds to the case in which the building temperature is neutral relative to the exterior. The small range of conditions for which the external temperature is in excess of about 30°C corresponds to the limit in which the interior is cooler than the exterior

The general principle that there will be a period of time when the building is cool relative to the exterior and a complementary period when the building is warm relative to the exterior is typical of naturally ventilated buildings. In many cases, diurnal fluctuations in external temperature, the diurnal usage pattern of the building or the presence of any thermal mass in the building can lead to such variations. One of the interesting features of the

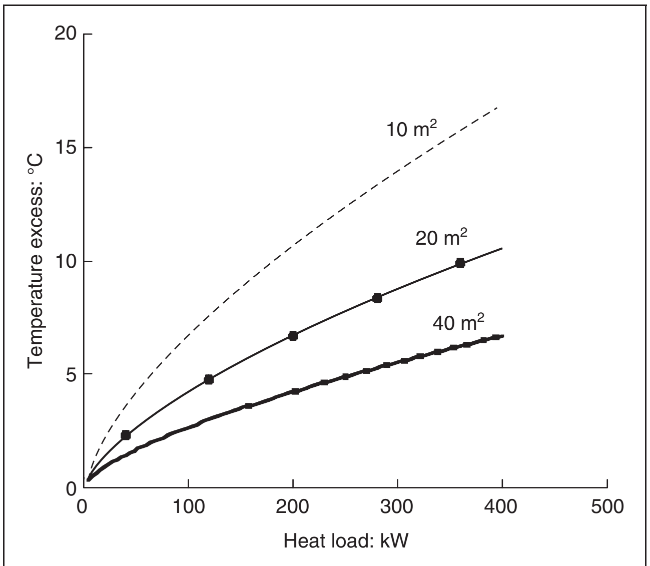

Fig. 4. Excess temperature in the mall as a function of heat load applied to the mall, for vent areas ranging from 10–40 m^2 and an effective height difference between inlet and outlet vents of 10 m

mall complex considered here is that cooling is applied locally relative to the scale of the mall. As shown in the following sections, this leads to substantial horizontal flows throughout the mall and some lateral temperature gradients. As mentioned above, this reduces the accuracy of the heat budget presented here in which we assume that the space is well mixed; however, this does not impact the general principle of upward and downward ventilation flows.

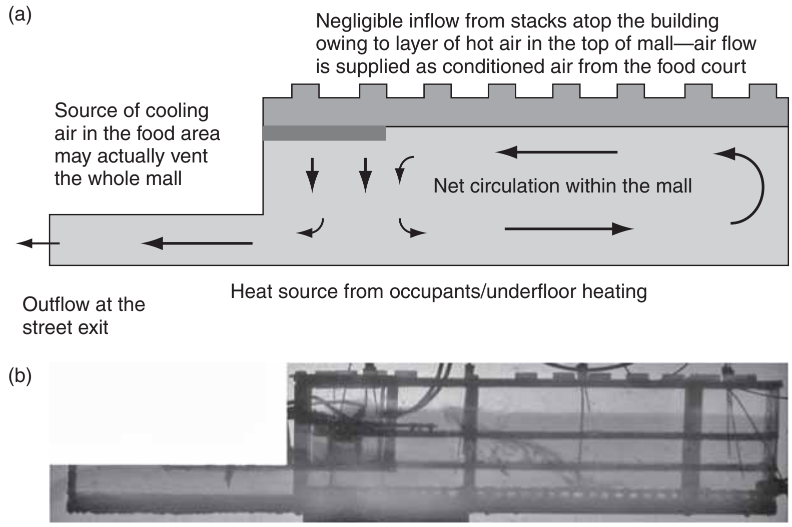

Fig. 5. (a) Schematic diagram of net circulation pattern and net downward flow. (b) The net circulation pattern may be seen in the photograph by the inclined streaks of dye within the fluid. This blue zone corresponds to the layer of cool air in the mall associated with the supply of air from the mechanical cooling system and the natural ventilation flow

2.2. Basic ventilation flows

Given the heat loads within the mall, the mall temperature as a function of convective heat load and the overall ventilation rate in the mall can be calculated (Fig. 4). Some of the most challenging conditions for such a building are those in a very still environment, when the natural buoyancy of air is the only mechanism available to drive air flow. The calculations presented here (Fig. 4) correspond to this case, and lead to a prediction of the mall temperature in terms of convective heat load and total ventilation flow (see also work by Gladstone and Woods[2]). The calculation applies to the case in which the effective height between the vents is 10 m. If this value is increased, then the ventilation rates increase and the excess temperature falls. The calculations indicate that it is possible to achieve very comfortable indoor conditions in a UK climate, in both summer and winter, by suitable adjustment of the interior heating provision; further control is available by varying the size of the effective area of the vents for ventilation flow.

3. REGIMES OF FLOW

The previous section explored the overall thermal budget of the complex. A series of laboratory experiments is now presented to indicate some of the wide range of flow regimes that may develop when there is a local source of cooling within a large naturally ventilated space.

3.1. High summer mode

In this regime, the building is cooler than the exterior and a net downflow would be expected. However, as cooling is produced by localised sources (in the food court), the cooled air is mixed around the whole mall through the establishment of a net circulation pattern. This is shown schematically in Fig. 5(a) and in a photograph of an experiment in Fig. 5(b).

In the experiment, the cold water supply representing food court cooling is dyed blue. This water is allowed to descend through the mall from a local source near ceiling level. As it descends, it forms a turbulent plume that mixes in some of the ambient fluid prior to reaching the base of the model. This represents an analogue of air mixing that would occur if cooled air had been pumped through a high-level air diffuser and descended through the space. In this high summer mode, the cooling load dominates the heating provision from the hot-wire system on the floor of the experimental tank. The cold supply fluid therefore descends to the floor of the mall and then either vents through the different openings at the base or recirculates through the mall, being heated as it spreads to the far end of the mall. It then rises and flows back toward the food court zone, where it mixes with the continuing supply of pre-cooled air and descends to the base of the mall once again. This mode of downward displacement ventilation arises as a result of cooling in the food court (Fig. 3) in very hot exterior conditions. This simplified model of a well-mixed interior provides a good leading-order estimate for the heat budget in this case. However, with more temperate exterior conditions, it is likely that the mall will be warmer than the exterior, leading to a separate class of upward displacement flows, as described next.

3.2. Upward displacement ventilation

This regime of ventilation is most likely to apply to winter and spring/autumn conditions. Again, owing to the local source of cooling, a net circulation tends to become established in the main mall complex. The cold air in the food court descends and mixes along the mall, is heated to temperatures above that of the exterior and then rises out of the building. As well as inflow through the lower vents and air supply from the food court, there is in fact a large-scale exchange flow in the roof of the mall, driven by the large-scale circulation flow (Fig. 6).

The pattern of flow shown in Fig. 6 shows that the large-scale lateral circulation that develops in the mall tends to drive outflow at the far end of the mall; near the food court there is some high-level inflow that complements the inflow through the lower openings and the inflow supplied mechanically in the food court. The additional high-level inflow becomes established since the area available for ventilation in the roof structure is much greater than that in the lower-level inflow vents. This may be understood by considering the limiting case in which the low-level vents are all closed: the mixing ventilation flow regime through the roof becomes established, with the net circulation, in order that the mall can ventilate.[3] As the low-level vents are gradually opened, this mixing ventilation flow

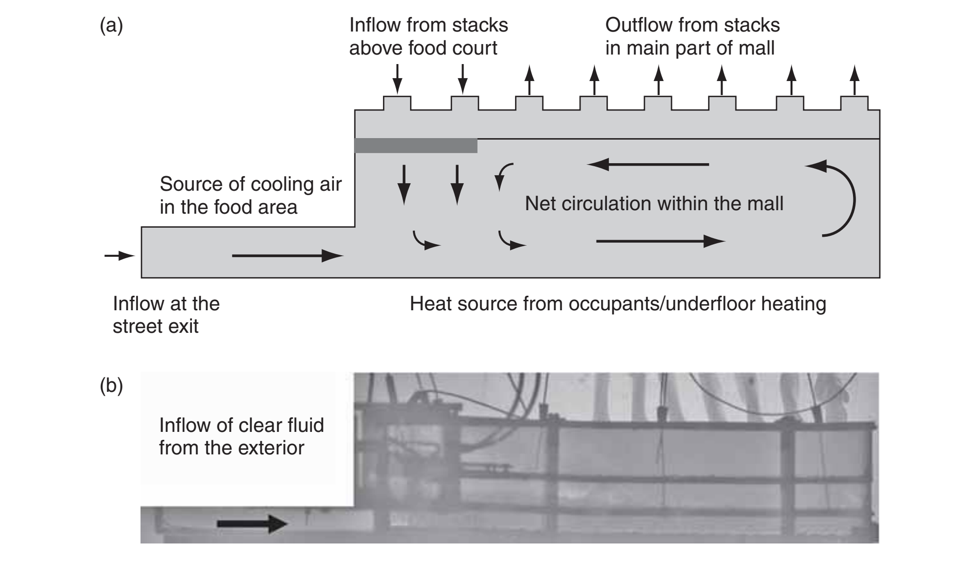

Fig. 6. (a) Schematic diagram of the net circulation pattern that develops in the case that the mall is warmer than the exterior; (b) photograph of experiment

large department stores that connect onto the main mall typically have their entrance doorways fixed open, offering a large area of 30–40 m^2 for exchange of air between the mall and the store. Measurements made at the Touchwood Mall in Solihull suggest air flow speeds through such openings may be as large as 1 m/s owing to the temperature contrast between the shop and the mall air. Such flows may have a large and even dominant contribution to the cooling load in summer (if the store is air-conditioned) or to the heating load in winter. In order to understand the importance and impact of such flows on the overall circulation pattern within the shopping mall, a further series of experiments was conducted in which there was a source of cool fluid issuing into one end of the mall, from a notional department store, with a corresponding balanced sink of mall fluid, while further cooling was supplied in the food court at the opposite end of the mall. Fig. 7 shows air supplied to the food court by the air-conditioning system modelled with blue water and air exchanged from the department store at the right-hand end dyed red. This red fluid forms a circulation cell that recycles air back into the department store. The blue fluid that ventilates from the left-hand end of the building originates from the food court air-conditioning. There is little exchange of fluid between the two convection cells.

persists until the low-level vents provide sufficient inflow area that a pure upward displacement ventilation regime is able to reverse the flow in the upper stacks. The large circulation pattern within the hall leads to some temperature gradients in the space.

4. EFFECT OF HEAT LOAD FROM NEIGHBOURING STORES

Although Figs 5 and 6 illustrate the principal ventilation regimes that arise in the building when analysed using design guidelines, these guidelines are somewhat curious in that they assume there is no heat exchange between individual shops and the large public mall space. In practice, some heat exchange does occur, both through conductive/radiative transfer through the fabric of the shop walls and windows and also owing to ventilation flows that exchange large volumes of air when the doors are opened. Indeed,

In the experiments (Fig. 7), each of the currents of cold air ran along the floor of the mall and was heated by the heat load in the mall. Eventually the currents met, and adjusted to that point at which both had the same temperature. They both rose to the top of the circulating zone at this point and then returned to each end of the mall. In this way, a steady double-circulation system became established.

Somewhat surprisingly, the interaction of the mechanically chilled stores and the ensuing exchange flow with the mall (with chilled air supplied to the food court in the main mall space) leads to an essentially mechanically ventilated building in the summer even though the mall was designed for natural ventilation. In this mode of ventilation, the development of a hot stable zone of air at the top of the mall, with a temperature

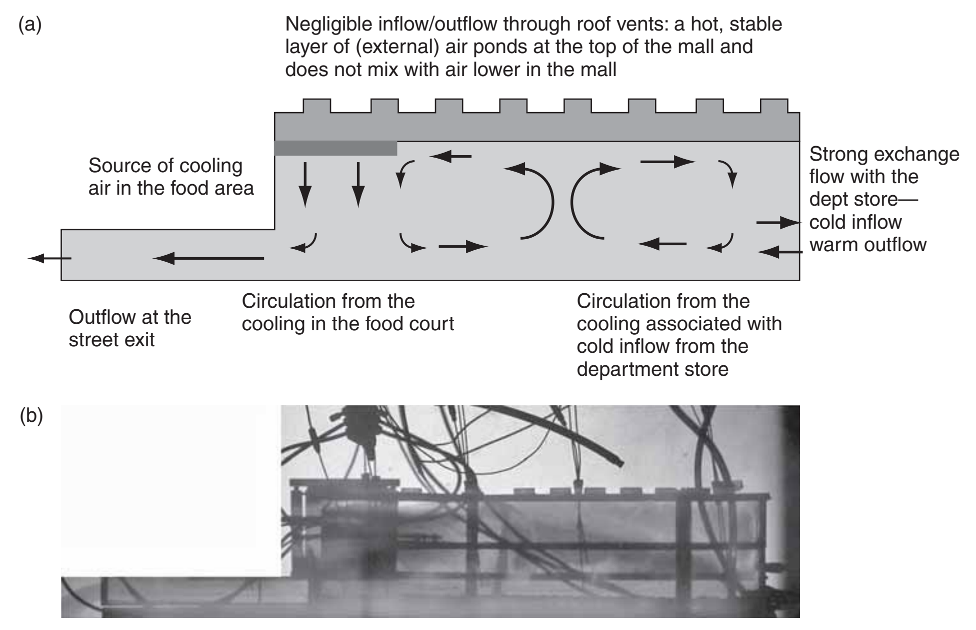

Fig. 7. (a) Schematic diagram and (b) photograph of an experiment showing the interaction of two cooling loads at different ends of the mall, leading to the formation of a double-circulation system

similar to that of the exterior, can render the roof stacks inactive in summer even though their main design purpose is for summer natural ventilation. The experiments identify the complexities of coupling mechanical and natural ventilation. It may be that, in future designs, a fully integrated natural ventilation system for both public mall space and stores could be designed to use vents/stacks and any mechanical heat loads or cooling system in the different spaces to maximum effect. In this way, by combining thermal mass, solar shading and good insulation with natural ventilation design, a very sustainable and non-mechanical system could be developed.

5. CONCLUSIONS

The different ventilation flow regimes that may develop in a naturally ventilated shopping complex with a localised zone of cooling have been explored using a combined approach of analogue laboratory modelling and simplified calculations for the thermal budget of the building. It was found that under high external temperatures, there may be a net cooling mode in the whole complex that leads to downflow and a large circulation flow within the mall. With lower external temperatures, there is typically a net heating mode, with upflow displacement ventilation developing. Despite these qualitative differences in flow patterns, the detailed mall geometry and the relative distribution of ventilation openings at high and low level can lead to considerably more complex flow patterns. In particular, owing to the distributed heat load at low level, net circulation along the length of the mall typically develops and this may induce inflow through some of the upper stacks at the cooler end of the circulation cell and outflow through some of the stacks at the warmer end of the circulation cell. This tends to increase the overall ventilation flow compared with the pure displacement mode. This study also identified that much more complex flow patterns can emerge if the heat exchange between individual shops surrounding the mall and the mall itself is taken into account. Indeed, owing to the mechanical conditioning of large department stores around the mall, there may be large convective exchange flows that develop in the very large doorways between the stores and the mall. The associated heat transfer of either cooled or heated air from the store into the mall may dominate the thermal budget of the mall, leading to very different circulation patterns in the mall.

Natural ventilation can play an important role in reducing the energy demand of new and ideally refurbished buildings. The combination of laboratory and simplified mathematical modelling can provide design teams with a rapid and relatively inexpensive means of identifying the various flow regimes and quantifying the resultant flows and mean temperatures. A hierarchy of models of the dominant building-scale flow patterns then emerges, and these can be used to inform the design by identifying the dominant controls on the flow in different seasons. Once the building-scale strategy is understood, through an analysis of the kind identified in this paper, more detailed CFD-type calculations may then provide key information about the detailed temperature gradients and air distribution patterns in the vicinity of the air inflow diffusers, heating units and mall–store exchange flows, where local zones of cooling or heating can lead to discomfort. This enables the team to develop an appropriate and robust strategy for ventilation using a combination of tools for different stages of the design.

As this laboratory modelling tool has evolved, the capability to explore the transient evolution of ventilation flows has also been developed. This may be important, especially if there are significant time constants for thermal evolution or air change rates in the building compared with occupancy patterns.

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REFERENCES

1. Woods A. W., Chenvidyakarn T. and Short A. Reversing flow in a naturally ventilated building with multiple stacks. *Proceedings PLEA*, 2003, **20**.
2. Gladstone C. and Woods A. W. Buoyancy-driven natural ventilation of a room with a heated floor. *Journal of Fluid Mechanics*, 2001, **441**, 293–314.
3. Chenvidyakarn T. and Woods A. W. Multiple steady states in stack ventilation. *Building and Environment*, 2005, **40**, No. 3, 399–410.