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The use of heat pumps to induce airflow on hot days in otherwise passive ventilation systems

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Synopsis

The paper presents results from a wider study into providing displacement ventilation in urban areas by taking air into buildings from the top without the use of fans. Results from large scale experimental work are given. These results indicate that ventilation airflows can be induced using gravity chillers and heaters in conditions where this type of installation would otherwise fail. The paper also describes initial experiments undertaken to see how far the same equipment can be used in heat recovery.

One test installation is modelled using a proprietary zonal model. Experimental results are also compared to the results which could be inferred from CIBSE data. The authors argue that both the zonal model and the CIBSE data are very conservative tools for predicting low speed gravity driven airflows and suggest that more accurate methods of modelling airflows would enhance the take-up of this type of technology.

List of Symbols

Δp	pressure difference driving airflow
ha	air column height
t(int)	internal temperature ˚C
t(cold)	temperature of cold column of air ˚C
t(hot)	temperature of hot column of air ˚C
t(ext)	external temperature ˚C
R	resistance of system
Δp (RG)	effective pressure difference driving gravity airflow after resistances have been taken into account.
K(RG)	pressure loss of a complete gravity system expressed as a maximum velocity pressure in the system

INTRODUCTION – 'TOP DOWN' VENTILATION

Indoor air quality has been the subject of an intensive national and international research effort because poor air quality is seen to be a health risk, reducing working efficiency and encouraging absenteeism. Much research has focussed on developing natural ventilation as an alternative to mechanical ventilation and air conditioning. This is generally thought to be healthier than ventilation achieved by forcing air through ducted systems, especially when these systems re-circulate air in a building. Natural ventilation can offer direct local user control. Natural ventilation is quiet if there is no external noise. Natural ventilation can be induced without the need for electrical energy.

Natural ventilation presents considerable problems in urban areas. It has been demonstrated that high concentrations of atmospheric pollutants, especially fine particulates, occur at lower levels in urban street canyons and car parking areas[1]. It has also been demonstrated that atmospheric pollution can be drawn into buildings through ventilation openings[2]. The problems are such that special ventilators incorporating filters have been prototyped for natural ventilation systems[3]. Natural ventilation presents further problems in urban areas. In many urban areas, road noise levels make it undesirable to provide natural ventilation through opening windows. Opening windows and louvres placed at low level can be an invitation to burglary.

In general urban air pollution falls to an ambient or background level. This occurs above the roofs of buildings and in sheltered back-land areas that do not contain pollutant sources. Ventilation engineers are advised to site air intakes to mechanical systems in these locations, and this advice is likely to become mandatory on an EC wide basis[4]. When buildings under different ownership face common back-land areas it is difficult to ensure that these will remain pollution free; it is consequently more reliable to site air intakes at roof level, although there is evidence that pollution can also occur at this level, arising from rooftop plant and secondary transformation of gasses as a result of oxidation. Rooftop air intake is however regarded as best practice in mechanical ventilation systems. It has not been generally undertaken in passive systems in the UK. The only examples of passive roof intake are traditional and modern split duct wind-catcher systems and, in hot dry climates, the use of downdraught evaporative coolers. Both have been the subject of recent research[5][6].

In order to make the most of valuable land, developers and public clients will often seek to create deep plan buildings with rooms that cannot be ventilated or naturally lit from the sides of buildings. Atria have been created to act as extract ducts – but the question of intake air remains to be answered. Suggestions have been made, notably by Sir Michael Hopkins & Partners and Ove Arup & Partners in the new Parliament building at Westminster[7] that large scale wind driven intakes may be feasible, but this approach only works when the wind is blowing.

Gravity displacement ventilation has been extensively adopted in passively ventilated and cooled building. The addition of an intake duct increases the resistance of the system, but otherwise make no difference to the principles involved (see Figure 1). Cooling can be achieved in a passively ventilated building by passing large quantities

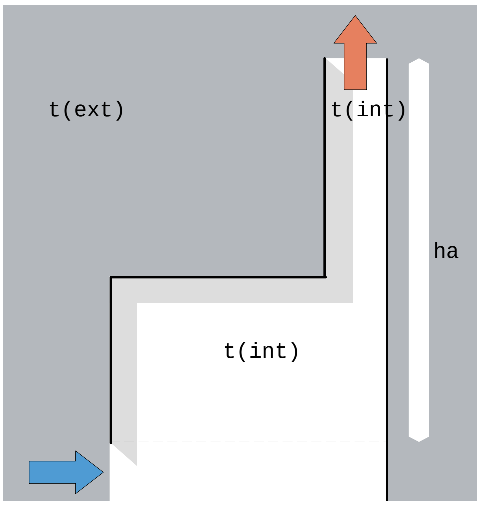

Fig 1a. Gravity displacement ventilation

Conventional gravity displacement. Ventilation occurs when the internal temperature t(int) is greater than the external temperature t(ext). The rate of ventilation is proportional to the temperature difference and the height of the hot column of air, ha.

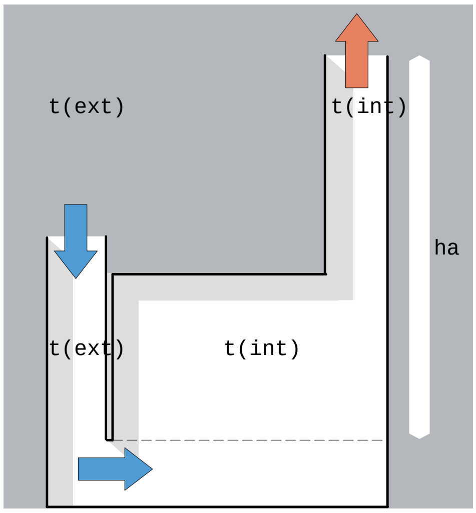

Fig 1b. Gravity displacement ventilation

'Top-down' gravity displacement. The principle is the same as a, but the intake duct increases the resistance of the system.

of air through the structure during the night to cool it down so that it can absorb occupancy and fabric gains during the day. The aim of night cooling is to achieve conditions where the internal air temperature is less than the external air temperature during the hottest part of the day in summer. In these conditions air will cease to move in the gravity displacement proposals shown in Figure 1. An additional mode of driving airflow to provide fresh air must be provided. If fans are excluded there are two possibilities in windless conditions:

•Air in the intake duct must be cooled until its temperature is below the internal air
•Air in the extract duct must be heated to induce airflow

These two possibilities can be combined by using a heat pump to cool the air in the intake duct and heat the air in the extract duct (see Figure 2). The strategy that has been developed is based on a modified form of gravity chiller. Gravity chillers are used in cold stores to provide a source of cool air and do not employ fans. They consist of coils containing chilled water / glycol with fins spaced at 8mm centres. Rectangular coils are available. These are double sided devices to be hung vertically from the ceiling with a minimum wall offset of 400mm Manufacturers literature[8] suggests that it is possible to achieve approximately 2.53Kw/m of cooling at a 10ºC difference between air and coolant temperature using this type of device. This type of heat exchanger is dependant on the airflow which is induced by it and does not restrict airflow while it is in operation.

The amount of cooling required to maintain a minimal airflow rate is small. In theory approximately 15 watts/m2 of cooling will provide intake air 15ºC cooler than the external air at 1.0 air changes/hour in a space 3.0 metres high. In effect, the morning

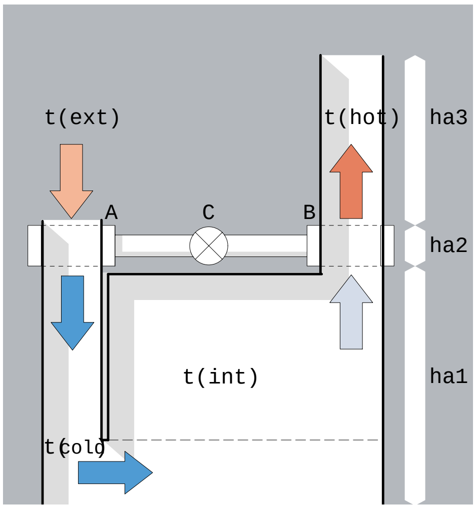

Fig 2. Using a heat pump to induce ventilation in hot weather

When the external air temperature t(ext) is above the internal air temperature t(int) ventilation can be induced by the heat pump C. The cold coil A reduces the temperature in the intake to below the internal air temperature t(int). Air is then heated by the hot coil B to a temperature above the external air temperature. Airflow is dependent on the temperature difference t(int) – t(cold) and the column height ha 1 plus the difference of the mean air temperature at A and B and the column height ha2 plus the temperature difference t(hot) – t(ext) and the column height ha3 and the total resistance of the system.

condition is extended into the day, gradually eroding as daytime fabric and occupancy gains warm the structure to a point where the internal air temperature is above the external air temperature. If this occurs when the external air temperature is unacceptably high then the air must be cooled further, and its volume flow rate increased so that all occupancy and fabric gains are absorbed into the airflow. Gravity heat exchangers are bulky. It is clearly more economic to provide an installation which maintains ventilation during summer days with an element of cooling than to provide an installation capable of significantly reducing occupancy heat gains. This can only be achieved by placing an increased value on night cooling.

Warm, dry conditions are much more acceptable than warm, humid conditions because perspiration can evaporate from the skin. The approach taken reduces humidity levels in two ways. Water vapour will condense on the gravity cooler at the top of the intake duct, where it can be easily discharged. Air is warmed when it enters occupied spaces therefore the relative humidity of the internal air before occupancy gains is lower than the relative humidity of the intake air.

Heat recovery

Placing the hot and cold coils of a heat pump in the supply and extract ducts of a top down gravity displacement ventilation system gives the possibility of heat recovery in winter. In this case cooling and heating water flows must be reversed. Convection currents run counter to the general ventilation airflow at intake and extract. A driving pressure difference from the wind is required to overcome these.

Method

Research at The Bartlett has concentrated in creating large test installations capable of operating in the open air or in indoor test environments. The question of wind induced pressure difference has been addressed because in moderate wind conditions these are greater than pressures induced by differences in air temperature. This aspect of the research has been separately reported[9]. The research is summarised in Bartlett Research Paper 11[10].

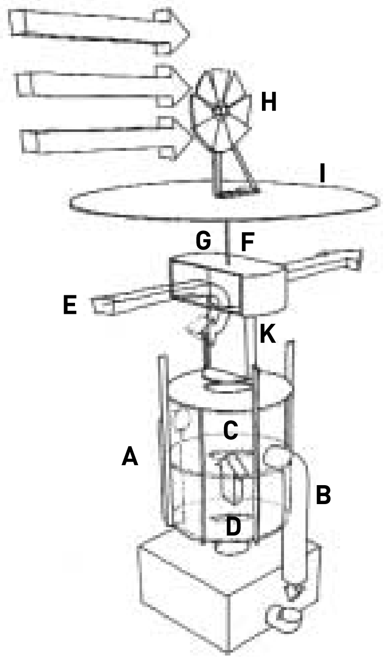

Fig 3. Rotary shaft duct combined intake and extract using shaft bearings

The wind-driven servo H turns the intake and extract hoods E and F on a central shaft so that they align with the direction of the wind. The central shaft G bears on the fixed shade roof I. Air enters through E into the intake plenum C which contains a finned chiller coil. Water is discharged and the air passes down ducts A and B to the test cell. Air rises from the test cell through duct J into the outlet plenum D which contains a finned heating coil. It then passes through the inlet plenum through pipe K and exits through extract hood F.

Gravity chillers work in free air. In top down gravity displacement ventilation, the temperature difference that they create must be enough to overcome system resistance and drive an airflow that will maximise the cooling effect of the chiller.

The installation shown in Figure 3 consists of a fixed shade roof with a central shaft. The shaft carries a rotating intake and extract hood with a circular split duct under this. One half of the split duct opens into an intake chamber or plenum that contains a finned chiller coil. The other half of the duct passes through the intake chamber into an extract chamber or plenum containing a finned heating coil. It should be noted that chiller and heater coils are placed around the circumference of the two chambers and do not impede airflow through them. Two separate ducts link the intake chamber to the test cell that then opens into the extract chamber above it. In order to ensure that wind pressures are always positive at the intake position and negative at the extract position the device is turned head to wind using a wind driven servo linked to a set of chain driven sun and planet gears. The heat pump used to drive this device is a Cornelius Classic 1000 Remote Cooler. This heat pump has a chilled water reservoir operating around 0ºC which is pumped through the chiller coiled and a variable temperature hot water output which is pumped through the heater coil. The heat pump operates intermittently, while maintaining a largely constant chilled water supply. In order to avoid peak load overheating in the hot circuit, a fan coil is fitted for experimental purposes. The hot coil temperature can rise to 45ºC before the fan coil cuts in.

The hypothesis that gravity chillers and heaters can be incorporated into gravity ventilation system and induce an airflow was tested in still air. It is possible to reduce supply air temperatures from 12ºC by up to 4ºC. Typical test results are shown in Figure 4.

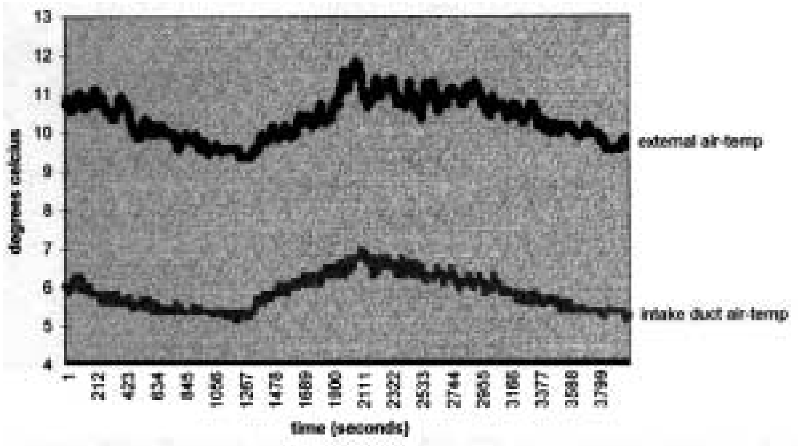

Fig 4. Graph showing temperature drop between external air temperature and intake air temperature using the equipment shown in figure 3.

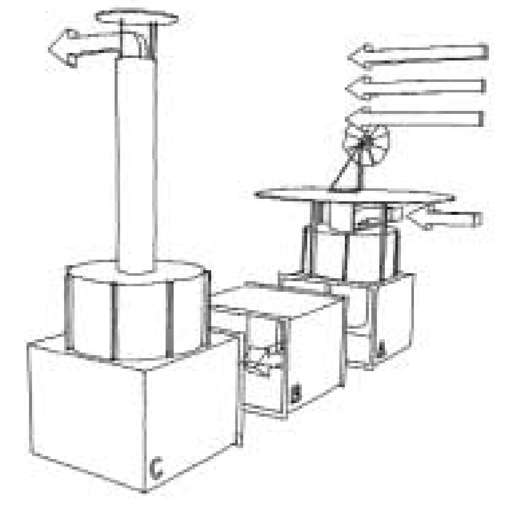

Fig 5. Separated intake and extract.

The components of this system are equivalent to those shown in figure 3 modified as follows: a single intake hood takes air into the inlet plenum which sits on test cell module A. A duct in this test cell module discharges the air at low level. Test cell module B contains a variable heat source. The outlet sits on test cell C and is terminated by a rising duct with a dished rain shield.

The installation shown in Figure 5 is in 3 sections. The intake section consists of a rotary intake cowl on a central drive shaft with a fixed shade roof. The intake cowl discharges air into an intake plenum lined with a finned chiller coil. The intake plenum contains a water discharge plate which shields the entry into the duct serving the bottom of a test cell. The central section of the installation contains a variable heater made from 9 no. 40 watt incandescent light bulbs. The outlet section contains an outlet plenum drum lined with a finned heating coil. Above this a vertical extract duct is terminated by a large flat dished cowl. A variable iris damper is placed at the base of the inlet duct in this system. It is possible to reduce volume airflow through the system in this way. The installation was tested in still air with the orifice diameter reduced from 300mm to 200mm. The same heat pump was used during these experiments; in order to maintain a more constant heat input the heating coil was disconnected and the heater battery was used to supply heat to the system. The gravity chamber will deliver air at 10ºc when the external air temperature is 26ºC at a rate of 0.8m/sec through the damper. This is equivalent to 0.4m/sec through the main 300mm inlet duct. This temperature drop is achieved in a chamber which is part of a system that prevents very little resistance to displacement airflow in other conditions. Typical results are shown in Figures 6 and 7.

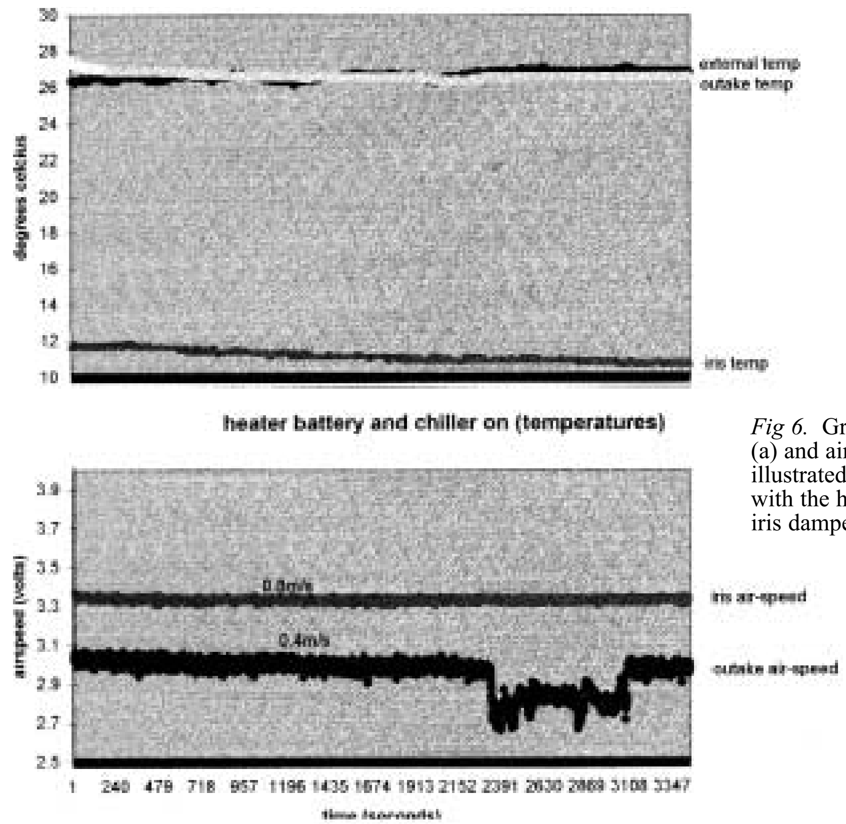

Fig 6. Graphs showing air temperature differences (a) and air speeds (b) measured in the equipment illustrated in figure 5. The readings were taken with the heater battery and the chiller on and the iris damper closed to a diameter of 200 mm.

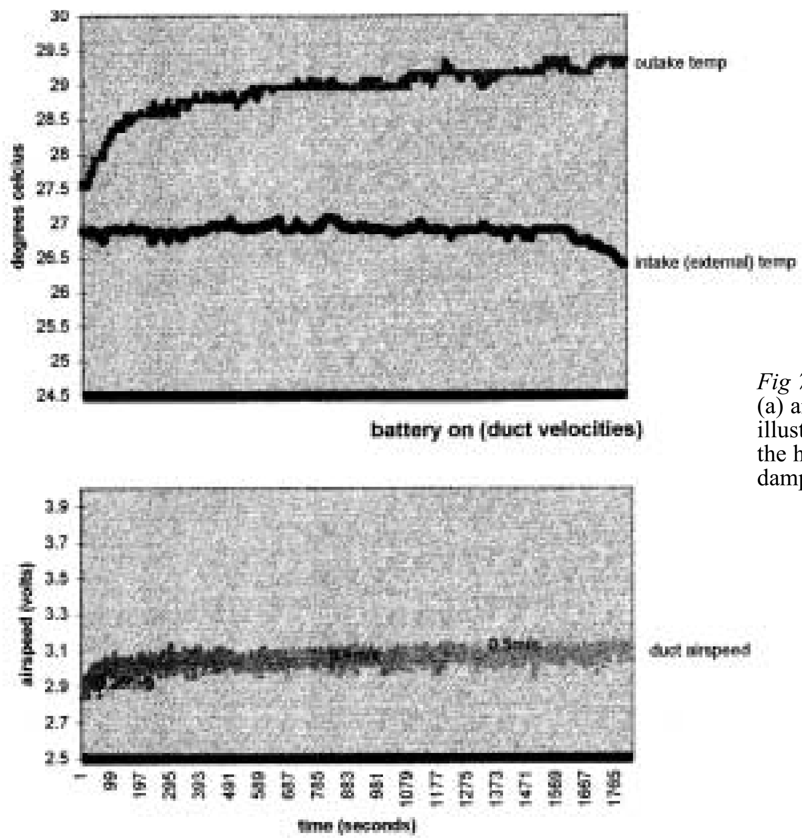

Fig 7. Graphs showing air temperature differences (a) and air speeds (b) measured in the equipment illustrated in figure 5. The readings were taken with the heater battery on, the chiller off and the iris damper fully opened to a diameter of 300 mm.

Heat recovery using the wind

A preliminary experiment was undertaken using the equipment shown in Figure 3 by reversing a wind driven airflow so that air entered across the hot coil and left across the cold coil. The performance of the experiment was erratic at all wind-speeds and especially erratic at wind-speeds below 1m/sec. At 1m/sec average duct speeds were 0.4m/sec. Intake air was heated by 9ºC when the hot coil was at 43.5ºC and the cold coil was 2.5ºC. The external air temperature averaged 5ºC. Typical test results are shown in Figure 8.

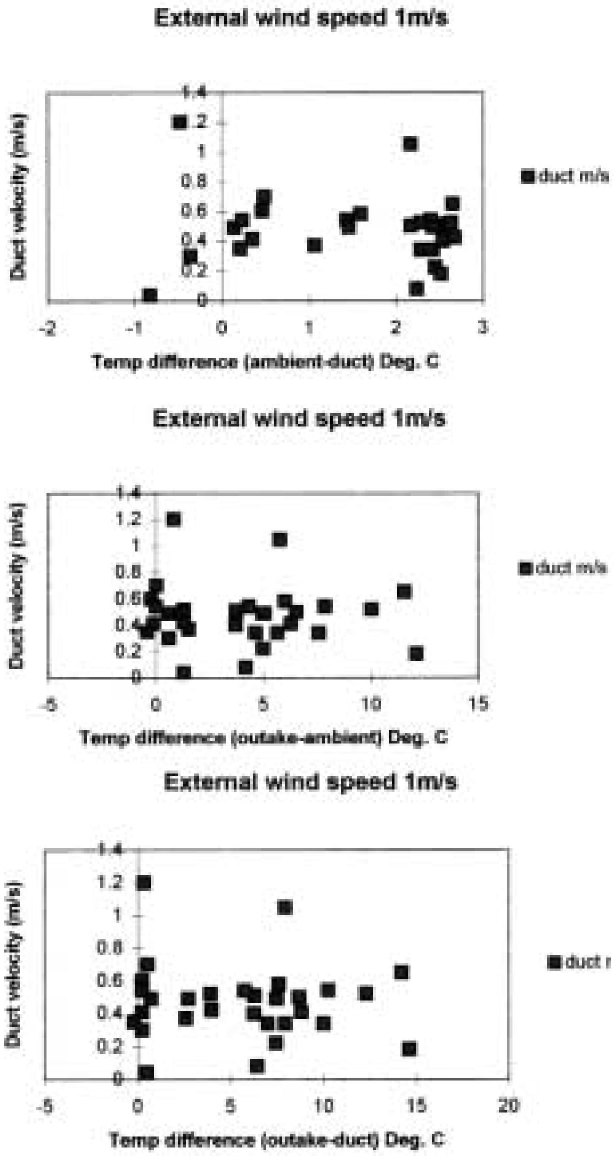

Fig 8. Scatter graphs showing the effect on air temperature of reversing the heat pump water flows in the equipment shown in figure 3, when exposed to a wind speed of 1m s^{-1}. This experiment was performed outdoors and the wind speed reading was that measured at the time of the experiment. a The rise in temperature in the intake shaft. b The temperature difference between the extract duct and the external temperature. c The temperature difference between the intake and extract ducts.

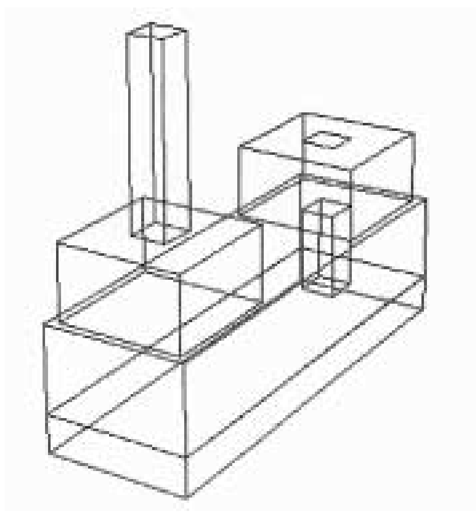

Fig 9. Wireline of simplified Tas model of figure 5.

Zonal Models
A simplified zonal model of the installation shown in figure 4 was created using Tas software supplied by Environmental Design Solutions Limited. Ducts and plena are shown square, changes in airflow direction at intake hood and rainshield plates are omitted, and no attempt has been made to model wind effects. The model is shown in wire frame in Figure 9. The chiller coil in the intake plenum is modelled by including a negative equipment gain of 475 watts. This is based on a calculation of the heat transfer from the intake to the coil derived from the volume airflow and temperature drop shown in Figure 6. Heat gains in the test cell are taken from the heater battery which was running at 360 watts.

The Tas model is contained in a virtual climate chamber at 26˚C. Results are shown in Figure 10. These results demonstrate that the outtake duct temperature closely corresponds to the test cell temperature indicating that the overall heat flows in the virtual model correspond to the reality. The intake duct temperature is substantially below reality at 7.9˚C and the velocity through the outlet duct is shown at 0.2m/sec. This is one half of the observed duct velocity. We can assume that the Tas simulation errs on the side of caution when representing slow moving gravity driven airflows in vertical ducts.

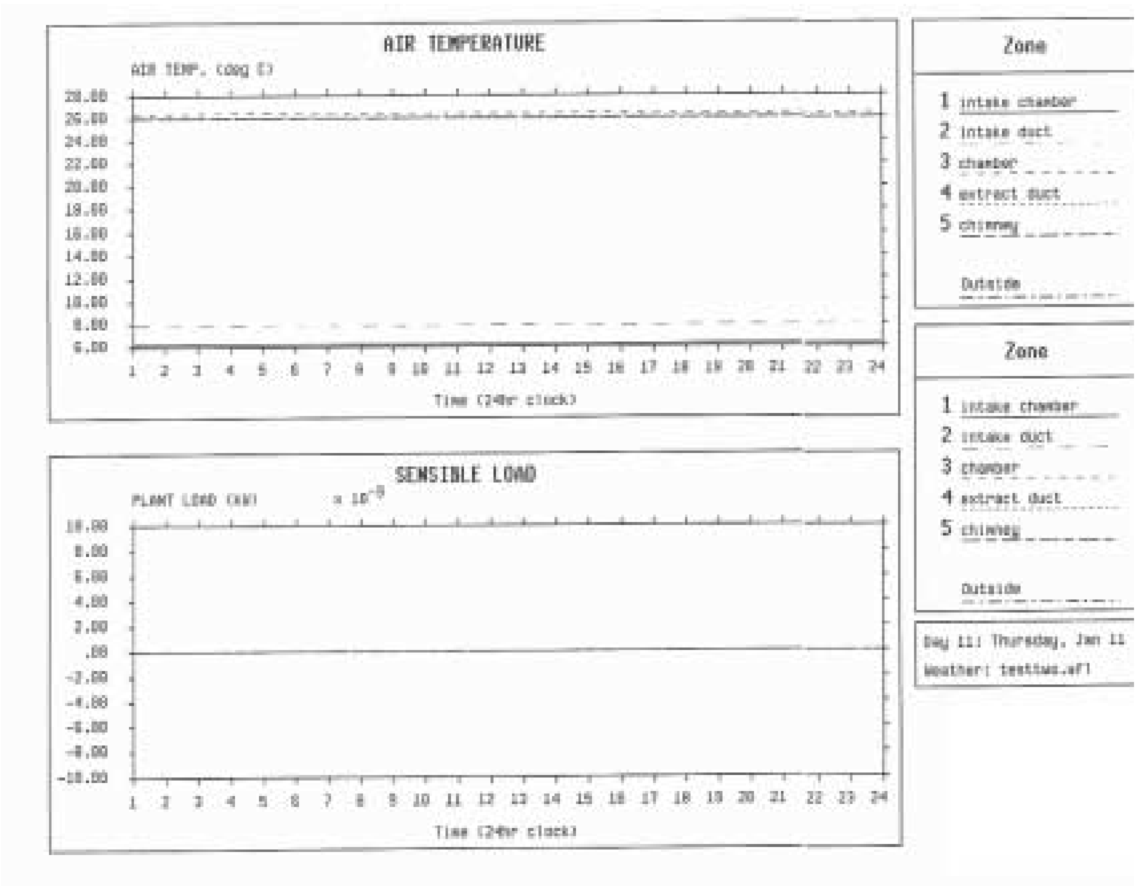

Fig 10. The model shown in figure 5 running in a virtual climate chamber at 260C.

Duct Resistance
We have demonstrated that the physical test cell that we constructed, illustrated in figure 4 has a much higher duct velocity than is shown by its virtual Tas representation.

Our physical experiments cause us to view existing data on slow speed gravity flows and ducts with caution.

The driving gravity pressure in the system shown in Figure 2 is dependant on the temperature differences in the columns of hot, warm and cold air in the system. The driving pressures can be approximately expressed as follows:

$$\Delta p = \frac{\rho g}{300} (ha1(t(int) - t(cold)) + ha2(t(mean\ hot\ chamber) - t\ (mean\ cold\ chamber))$$

$$+ha3(t(hot) - t(ext)))$$

This is equivalent to

$$\Delta p = 0.043((ha1(t(int) - t(cold)) + ha2(t(mean\ hot\ chamber) - t\ (mean\ cold\ chamber))$$

$$+ ha3(t(hot) - t(ext)))$$

The system as a whole will have a resistance (R) that gives a maximum residual gravity pressure. This is the dynamic velocity pressure at the point of greatest constriction, that is the point where air is moving at its greatest velocity

$$\Delta p\ (RG) = \frac{\Delta p}{R}$$

This relationship can also be expressed as

$$\Delta p\ (RG) = K(RG)\ \Delta p$$

K(RG) is the residual gravity velocity pressure factor. It is a measure of the pressure loss of a complete gravity system expressed as the maximum velocity pressure in the system.

Calculations based on the experimental results demonstrate that the test installation shown in Figure 3 has a value of K(RG) at 0.3. The test installation shown in Figure 4 has a value of 0.4. Calculations based on CIBSE data[11] suggest that the installation shown in Figure 3 should have a value of K(RG) at 0.1 and the installation shown in Figure 4 should have a value of K(RG) at 0.17, excluding duct resistance. This poses a considerable problem which must be the subject of further research if this type of technology is to be realised. It is clearly unacceptable to initiate a large scale programme of physical testing or CFD modelling on a built project by project basis.

The use of the TAS model described above suggests that it may be possible to create a generic description of this type of system and modify an existing zonal model so that it can be easily applied to a range of largely similar installations.

Further Work

The authors have undertaken a further study where the TAS zonal model is used to represent the performance of a large test cell in top down ventilation throughout the year[12]. This paper addresses the issue of the comparative effectiveness of fans and refrigeration both to induce airflow and to provide comfortable conditions on hot days. The paper also examines the problems of winter heat recovery in more detail.

Conclusions

A gravity ventilation system which takes air in from the roof of a building without the use of fans will fail in conditions when the external air temperature is above the internal air temperature, and when there is no wind. It is, however, possible to reduce the temperature of the incoming air and raise the temperature of the outgoing air by using a heat–pump. A ventilation airflow can be successfully induced in this way.

The resulting systems are passively operated for most of the year and provide a form of gravity driven variable air volume air cooling on summer days which can also operate in overcast humid, windless conditions and maintain cooling during periods when temperatures are high at night. It is suggested that the peak daytime cooling load energy demand could be met by utilising solar power.

The major conclusion of this paper is to question the assumptions about resistance in low velocity gravity induced airflows which are contained in guidance from CIBSE and built into existing zonal models. It would appear that resistances are too high. As a result gravity ducts are probably being oversized, and standby fans are being fitted unnecessarily.

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