SIMULATION OF A COMPLEX WIND AND BUOYANCY DRIVEN BUILDING

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ABSTRACT

The majority of design studies on naturally ventilated or mechanically ventilated buildings do not take account of the close relationship between ventilation and thermal performance. That is it is common to assume that certain ventilation rates can be achieved and then used as input to a dynamic thermal model to assess temperatures within the building. In reality the two are closely linked and this paper seeks to demonstrate the feasibility of combining the two processes within a single analytical tool used within a leading UK consulting engineering practice. Furthermore it is recognised that controls cannot be ignored and so the modelling includes a representation of a rule based control system.

INTRODUCTION

This paper presents an investigation into the performance of a low energy building. The objective is to demonstrate the potential for natural ventilation to minimise the energy consumption of a building. The success of such a building is very dependent upon the ventilation strategy, in particular the application of night cooling. An important objective of the study was therefore to derive some rules for the control of the ventilation system and to demonstrate their application by means of simulation.

The quantity of air to be supplied for cooling is not the only issue, sufficient clean air must be supplied throughout the year to ensure a high standard of air quality within the building. In general it is to be expected that the higher the air intake above the ground the cleaner the air and the lower the ambient noise level, consequently the design adopted here makes use of roof mounted inlets and exhausts. The inlet and exhaust are adjacent to allow for the easy installation of an exhaust air heat recovery system. The general building concept is shown in Figure 1 where it is clear that wind power is expected to provide a significant component of the motive force for the ventilation system.

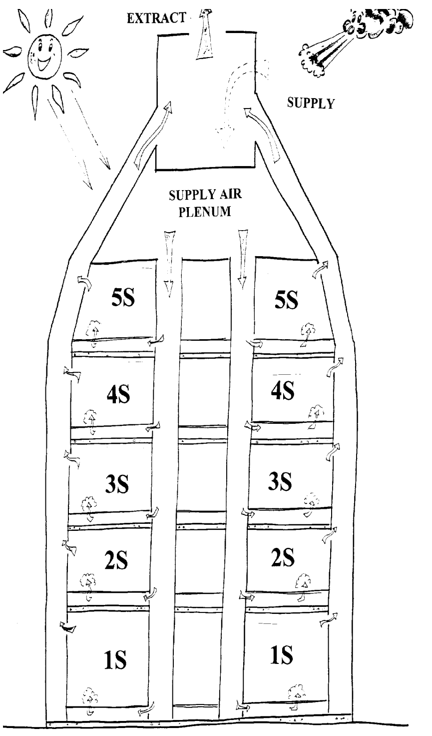

Figure 1 Concept

The performance of the building depends upon:
The design of the air inlet/exhaust system.
The control of ventilation.
The storage capability of the building fabric.

The simulation of a complete building should only be attempted after obtaining an understanding of performance of the various components, in this case that means the thermal performance of the fabric under both steady state and dynamic operation and the characteristics of the ventilation system. These studies are required to enable the specification of a ventilation control system. Simulation of the complete system, including controls requires an integrated thermal and airflow model. The development of the model, which is beyond the scope of this paper, was achieved by combining an explicit finite difference thermal model with a zonal ventilation model. The thermal model (ENERGY2) has been shown to give good temperature predictions in passive buildings[IEA, 1994] and the zonal model is described in a number of papers [Holmes, 1988].

In order to perform the building simulation, it was necessary to be able to calculate surface pressure coefficients. Computational fluid dynamics (CFD) is the only simulation tool available for this purpose. However, the validity of that technique has not been proven. An important aspect of the work was an assessment of the suitability of CFD for the prediction of surface pressure coefficients. This is done by comparing numerical predictions with wind tunnel measurements.

The paper is in four main sections:
Determination of wind pressure coefficients;
Assessment of ventilation characteristics;
Development of control rules;
Whole building performance assessment.

The work described here was carried out under the JOULE II Programme: **JOU2-CT94-0351 Office and public buildings incorporating wind/solar and buoyancy/photovoltaic powered ventilation systems.** The project was coordinated by Michael Hopkins & Partners (UK)

DETERMINATION OF PRESSURE COEFFICIENTS

The intention of the design of the inlet and exhaust stack is to optimise the power available from the wind. Maximum wind power would be achieved by maximising the difference in wind pressure coefficient across the stack or chimney. The first requirement to achieve this is a system that rotates to ensure that the inlet always faces into the wind and while it is possible to hypothesise about other desirable characteristics for the chimney the only certain way to obtain optimum performance is to construct models and test them. This was done by CSTB [CSTE, 1996] and is not reported here. The main conclusions were:

The performance of the chimney is dependent upon the slope of the roof.
The most effective supply is a plain opening facing into the wind.
The most effective exhaust is an upward facing vertical tube.

Tests on an isolated chimney however are unlikely to be representative of the performance when installed because surrounding buildings can have a significant effect upon the flow of air around the chimneys. Furthermore, where there are a number of chimneys on the same roof, the chimneys will interfere with one another. These effects were seen in both in the wind tunnel and CFD studies. The studies were carried out with the building in the urban environment shown in Figure 2 , where the roof and chimneys can be seen.

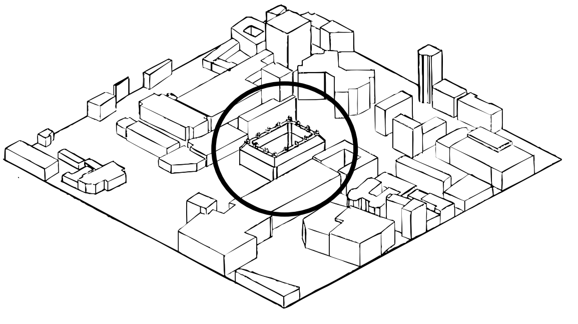

Figure 2 Building in Surroundings

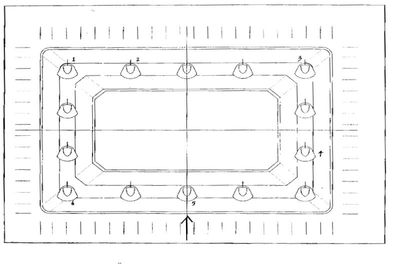

Figure 3

Figure 3 presents a plan view of the roof and reference chimney locations.

Both studies provided values of pressure coefficients at the inlet and outlet of each chimney which are compared in Table 1

Table 1 Comparison of numerical and wind tunnel predictions

Chimney Number	Without surroundings flow at 0°		With surrounding buildings flow at 0°		Without surroundings flow at 90°	
	CFD	CSTB	CFD	CSTB	CFD	CSTB
B1	-0.09	0.92	0.21	0.32	1.11	1.50
B2	-0.13	0.02	0.97	0.25	-0.05	0.60
B3	-0.09	0.45	0.41	0.20	0.10	0.75
B4	-0.06	0.40	0.47	0.30	-0.11	0.30
B5	0.57	1.60	0.91	0.45	0.10	0.40
B6	0.87	1.80	1.01	0.85	1.11	1.50

Notes: 1 The column headed CSTB is taken from measurements made by CSTB.

2 The pressure coefficients are the local pressure as measured (or predicted) at the chimney entrance (exit) divided by a reference dynamic pressure.

The differences between the results may be due to:
Differences in the wind velocity profiles.
Differences in turbulence structures.
Differences in Reynolds number. The numerical simulation was for the full size building. (It is of course, impossible to obtain Reynold's number similarity in a practical wind tunnel.
Practical limitations in the number of cells that could be used to describe the site and building (750,000).

The predictions made for the case with surroundings show a closer correlation between the two techniques than those without the surroundings. This latter observation would tend to support the premise that differences between the velocity profiles may be responsible for some discrepancies. The CFD simulations made use of a theoretical velocity profile the wind tunnel profile did not match that profile at heights below 20-30m.

Any comparison between two methods should also take into account ease of use, time taken and the detail that can be provided. Both techniques require skilled operators and model builders, although it is probable that at present a greater level of theoretical ability is required for CFD studies. In terms of time, the CFD model took about two man weeks to build. No information is available on how long it took to construct the wind tunnel model. In terms of test time, the wind tunnel is clearly very quick compared with numerical analysis which is of the order of one day per test. CFD however comes into its own in the area of flow visualisation.

VENTILATION CHARACTERISTICS

The objective of the work described in this section was to obtain an understanding of the main characteristics of the building ventilation system. In particular if it was possible for natural forces to provide free cooling and minimum fresh air needs. It is fairly well established that a target ventilation rate for free cooling is in the range 6-8 air changes per hour while the fresh air required is usually about one air change per hour. This study was carried out using a zonal ventilation model and although that model can predict temperatures and flow rates from either specified internal temperatures or convective gains, the effect of the building fabric upon the performance of the system is not included. The effect of building fabric is studied has in the following sections where first the characteristics of a single space are used to develop a ventilation control system and then the performance of a complete building module is examined.

Ventilation is provided by two (thermally massive) supply ducts dropping through the centre of the building, each serving one orientation of the facade. Air is supplied to the occupied areas, offices, by underfloor voids and a displacement ventilation system. The air is exhausted from the offices through the windows and ducts mounted above the windows. The exhaust ducts are located externally as shown in Figure 1. The use of externally mounted exhaust ducts offers the possibility to increase buoyancy driven ventilation by trapping solar gain within those ducts. For example, by cladding the ducts in transparent insulation. The analysis was carried out in two stages:

A simple ventilation model in which each supply and exhaust riser was considered to be a single zone in order to obtain an understanding of the general characteristics of the building and also to prove that minimum ventilation rates could be achieved. A complex ventilation model; in which each duct, was modelled as a separate zone.

In both cases a pressure co-efficient of 1 across the supply and exhaust points was used. This corresponds to an ideal chimney.

Simple ventilation model

The room terminals were initially based on 0.12m², a 1m x 120mm slot corresponding to a grille size of approximately 500 x 250mm within the offices. These sizes were determined from considerations similar to those given by [Holmes, 1985].

For most cases the simple ventilation model predicted air change rates greater than those required, (1 air change per hour for fresh air and 6 to 8 air changes per hour for free cooling). This model also indicated the need to reduce the area of the supply terminals, not only to balance the system but also to prevent reverse flow through Office 5 which occurred at wind speeds of less than 2m/s combined with solar gain to extract ducts on the South facade.

Reverse flow occurs when the pressure loss at the extract is so high that it is easier for air to short circuit through the top office than flow out through the extract. This means that the resistance to air flow through lower offices is too low. Thus it is necessary to reduce the flow area to the lower offices. A reduction in supply terminal area also balanced the system to produce a fairly uniform air change rate in each of the offices.

Complex ventilation model

The main difference between the two ventilation models was that in the complex model each duct was modelled as a separate zone. This allowed the resistance of the ducts to be incorporated within the model. All supply terminals had equal areas.

The predictions were carried out for summer conditions, 27°C external dry bulb, and at wind speeds from 0 to 10m/s under the following scenarios;

No solar gains to the exhaust ducts with all internal temperatures fixed at 27°C.
With internal gains only.
Internal gains and solar gains in south facing exhaust ducts.

No solar gains with all temperatures fixed:

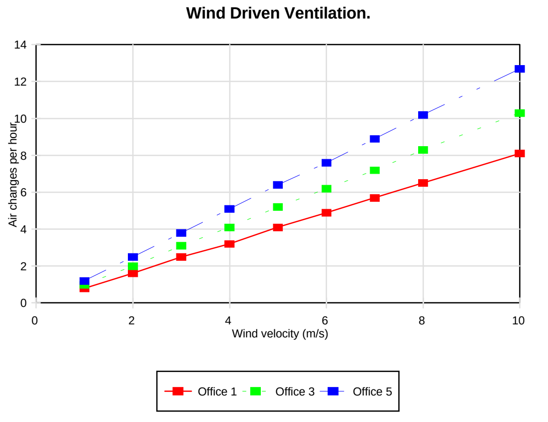

Figure 4

The results given in Figure 4 indicate the effect of increasing wind speed upon the building without solar or internal gains. It shows that the fresh air requirement for the offices is met at a wind speed of approximately 1m/s, with no contribution from buoyancy.

With internal gains:

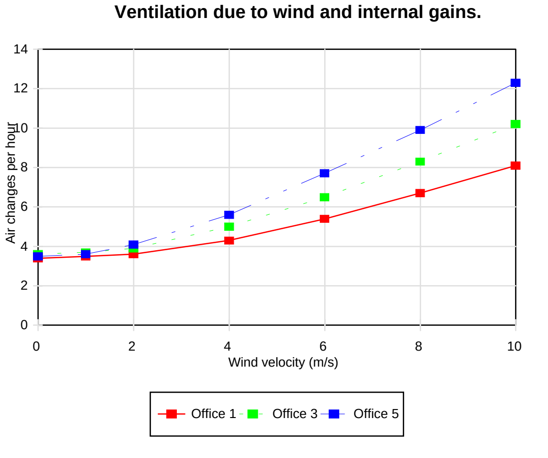

Figure 5

Figure 5 shows that the assumed internal gains provide enough buoyancy to more than achieve the minimum fresh air requirement at still air conditions. Wind effects are not very significant at speeds below 4m/s. It is also seen that 6 to 8 as changes will only be achieved at fairly high arial speeds.

Internal gains with solar gains in south facing exhaust ducts:
This simulation was run to investigate the effect of inducing extra buoyancy in the exhaust ducts. The result was an increase of 1 air change rate per hour on the south facade and a minimal increase on the north facade at still air conditions. As the wind velocity increases the benefit from this solar gain reduces, at 8m/s the effect is negligible.

The simulations have shown that it is possible to ventilate the building using a combination of wind, internal heat gains and solar power. It would also seem that the system is relatively insensitive to wind speeds below the annual average of 4m/s. Also It would appear that the two sides of the building do not interact so there may not be a need for physical separation of the air paths. However, these observations are based upon an analysis that does not include the effect of heat transfer to the building fabric. The effect of internal gain is therefore to increase the internal temperature to above that outside. The conclusions are probably more appropriate to mid season than mid summer.

DETERMINATION OF BASIC CONTROL RULES

The objective of the study was to develop a set of control rules that could be used to minimise overheating whilst ensuring that minimum ventilation rates were maintained. To do this it is necessary to assess the combined effect of ventilation and thermal storage A complete building simulation was considered to be uneccesary and so the performance of a typical space was studied using the Oasys Ltd ROOM program [Holmes, 1991], from which internal dry bulb and dry resultant air temperatures can be obtained. The office model used in the analysis has a high mass structure with a well insulated external construction, high performance glazing, internal concrete block walls and concrete floor slab. A single cell, south facing, one person office (3.6m x 4.8m) was analysed, with internal loads taken to be 12W/m² for lighting and 15W/m² for IT. Part of this air is extracted through the window which has mid-pane blinds. The blinds are assumed to raised by the occupants when the sun is 'off' the facade. As shown in Figure 1 the air supply is via the floor slab.

It was anticipated that different control strategies would be required at different times of the year therefore the analysis was split into three parts Summer, Mid Season and Winter.

The meteorological data used in the study was for South East England and determined by the following process [HMSO, 1995]:

The last 20 years are ranked according to average mean daily temperature using June, July and August only. The sample year is then chosen from the upper quartile of this in order to assess the effect of high external temperatures and the possibility of overheating.

Summer

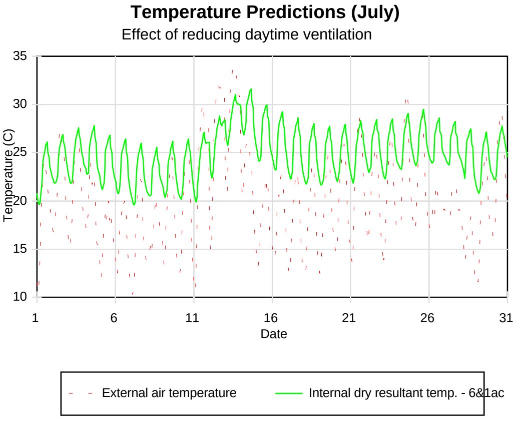

Figure 6

The climatic data includes a stretch of particularly high temperatures in the middle of July. Therefore the summer analysis concentrated on the performance of the office during this month. Various ventilation strategies were analysed in order to determine the most effective control for the system. Initially the ventilation rate was set to a constant 10 air changes per hour (ac/hr). This was gradually reduced to 6ac/hr with very little effect on the peak internal temperatures being observed. When external temperatures are very high, it is undesirable to supply this air to the space as this may cause over heating, therefore the ventilation rate during the day was reduced to 1ac/hr (which equates to the minimum fresh air requirements for the space) while keeping the ventilation rate at night at 6ac/hr. This resulted in improved conditions within the space over the course of the month Figure 6.

This ventilation strategy has the effect of reducing fluctuations in internal temperatures eg. conditions are slightly warmer on the cooler days and slightly cooler on the very hot days. On very hot days the slab has the effect of reducing the temperature of the supply air to the room sufficiently so that the internal temperature in the space is below outside, whereas on the slightly cooler days, the effect of the slab is not as great, therefore the temperature of the supply air is not reduced by as much.

The effect of an extended period of hot weather can be seen in the middle of the month. Due to the high mass in the model, the office gradually becomes hotter as the period of hot weather continues and even when the external temperatures reduce the internal temperatures remain high for a few days.

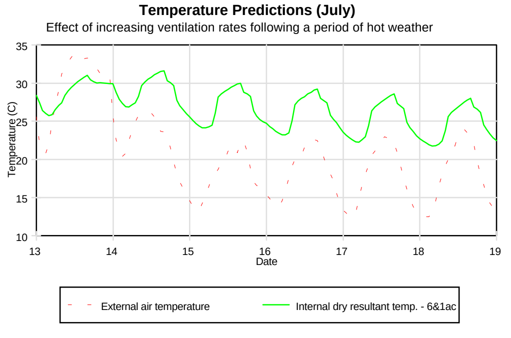

Figure 7

With increased ventilation rates the internal temperatures stabilise more rapidly as external temperatures decrease. So in this case it may be advisable to increase the ventilation rate to further cool the structure and reduce this build up of heat in the office (Figure7). Therefore a strategy must be developed to decide when it will be

effective to increase the ventilation rate to the space, taking into account the previous internal conditions and the external conditions.

Mid Season

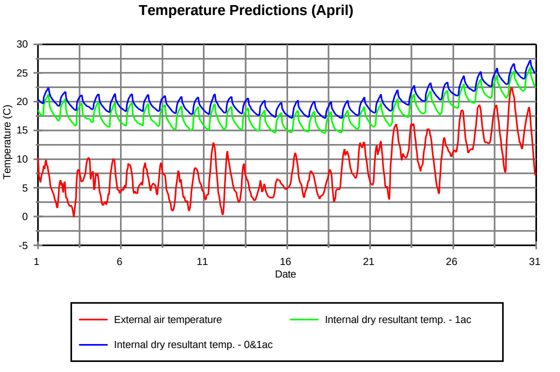

Figure 8

The analysis to determine the mid season strategy concentrated on April. As can be seen from the results, the external temperatures at the beginning of April are consistently below 10°C, and if this air is allowed into the building at night the internal temperatures during the occupied period are unacceptable (Figure 8). Therefore, the vents should be closed down at night to avoid over cooling the building fabric. In general the internal temperature can be maintained within the comfort range during the occupied period by a strategy of supplying minimum fresh air during the day and closing the vents at night, with supplementary heating being supplied when required.

Winter

In winter it is reasonable to expect external temperatures to be consistently too low to allow into the building in any greater quantity than the minimum fresh air requirement during the occupied period with the vents being closed at all other times. Supplementary heating will be required through much of the winter to maintain comfortable conditions in the space during occupancy.

Specifications of control system

Unoccupied:

If the external temperature is below 10°C then close the vents

If the external temperature is above 10°C then control internal temperature to 18°C (to prevent overcooling) by opening the vents.

Occupied:
If the internal temperature is below 23°C then control on minimum fresh air
If the internal temperature is above 23°C and the external temperature is below the internal temperature, then control to 23°C (a good target) by modulating the vents

Heating to 21°C will be provided during the occupied period when required.

This is recognised to be a very simple control strategy, however research into the control of naturally ventilated buildings is in its infancy and more sophisticated strategies cannot yet be justified.

WHOLE BUILDING SIMULATION

The single office study demonstrated that, provided a satisfactory ventilation strategy could be developed, it should be possible to prevent serious overheating within the offices. This section presents the results of an analysis of the performance of the whole building with the objective to assess the performance of the ventilation control system. It was also considered useful to look at the effect of different chimney designs and because the ventilation studies suggested that internal gains might provide an adequate driving force a special, wind shielded, chimney is therefore included here. The climatic data used were for July, the hottest month on the weather tape [HMSO, 1995].

Early studies showed that there could be short circuiting around the upper North and South officies which was not revealed by the ventilation analysis. A possible reason for this is the varying temperatures within the building produced by the thermal analysis. All anlysis here therefore assumes separate North and South air supply systems.

This type of analysis produces a vast amount of data and there is the serious issue of how to make proper use of the information. It was therefore decided to concentrate on the performance of a centrally located south facing office (3S), if acceptable conditions could be achieved there then conditions in the others could be looked at in detail.

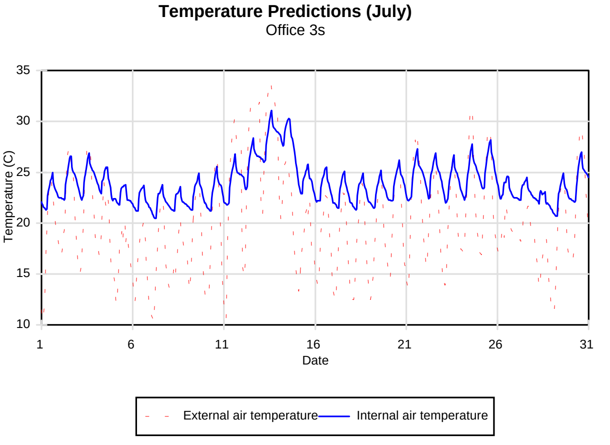

Figure 9

Figure 9 presents a comparisson between predicted internal and the external temperature for office 3S. These can be compared directly with the values given in Figure 6 in the single office study. While there is little difference in the peak internal temperature the complete building model generally shows lower temperatures, possibly because of the effect of storage of 'coolth' within the supply air ducts. The most significant feature is that internal temperatures lag significantly behind the external temperature during the period when the external temperatures rises steeply. It would appear that reasonable comfort can be achieved in this office space.

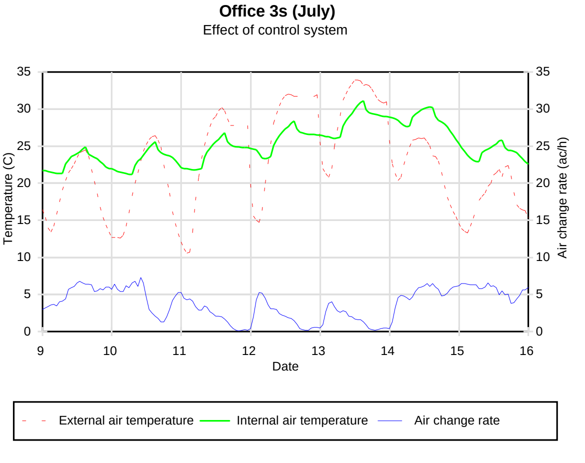

Figure 10

The performance of the control system under these conditions is also of great interest. Figure 10 contains predictions for a few days in July showing both predicted space temperatures within office 3S together with the corresponding airchange rate. The control would appear to be working operating correctly in that high airchanges occur during the night with a significant reduction as the internal temperature increases. In particular low airchanges occur when the external air temperature is above the internal temperature. This confirms the performance of the ventilation control system on hot days.

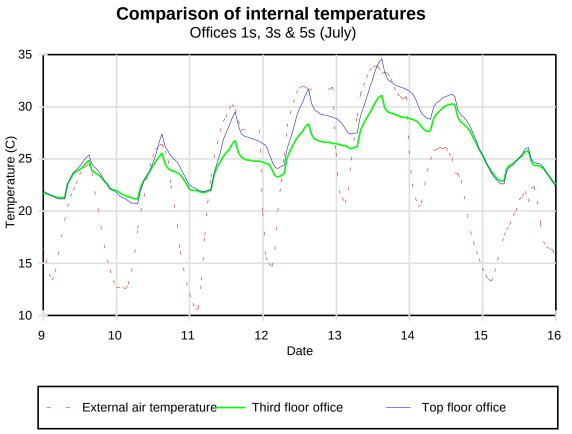

Figure 11

Conditions within a single office space are not sufficient to confirm proper functioning of the whole building. Figure 11 compairs predictions made for office 3S with those for the top floor (5S). Overheating occurs in the upper office. The reason is a problem with the airflow balance under dynamic conditions. There also remains the question as to what happens on cold and cool days. Figure 12 contains predictions for April.

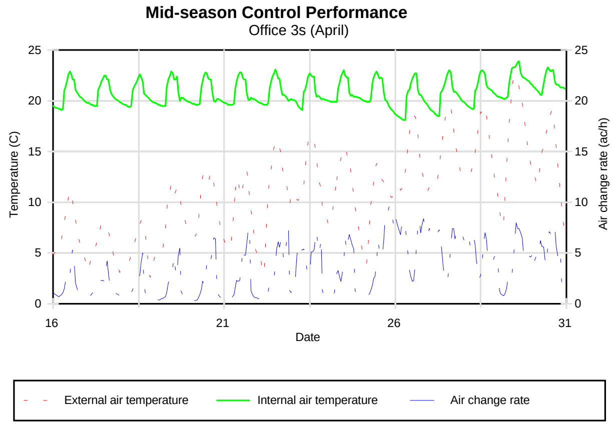

Figure 12

It is clear that ventilation rates are lowest at lower outside air temperatures, (when buoyancy might be expected to increase ventilation) and increase to limit rises in space temeprature as the external air temperature rises. This confirms correct performance of the numerical implementation of the ventilation control model.

The performance of the ventilation system is also related to the characteristics of the chimney.

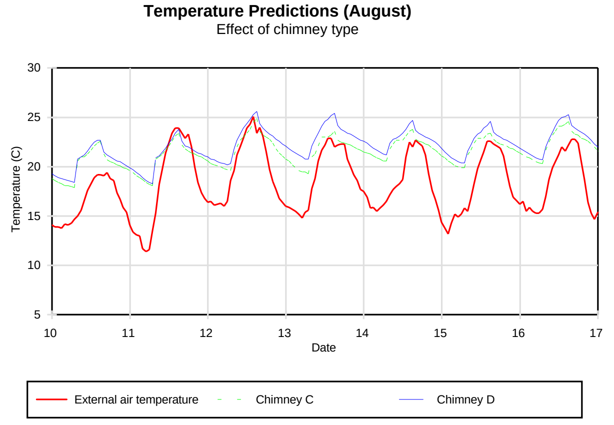

Figure 13

In order to compare the performance of chimney types a typical hot month was simulated (August, Kew, Holmes, 1978). The predictions are contained in Figure 13 where the wind shielded chimney (type D) is compared with the ideal chimney (Type C). The contribution of wind driven ventilation is seen to be useful.

CONCLUSIONS

The simulations show how modelling can be used in the development of a design. It is very often assumed that detailed simulation models are not appropriate at the concept stage. It would not have been possible to assess the proposed design by any other method. The study presented here is incomplete in that there remains the fine tuning of the control system to achieve balanced flows within the building. Hopefully, that study will follow. There also remains the question of occupant satisfaction with a building that has many characteristics of an air conditioned building without the benefit of cooling. Furthermore the performance predicted has been obtained with a very well insulated facade with shaded windows, and significant internal thermal storage. Lightweight, steel frame buildings with poor solar shading combined with this approach would probably be a disaster.

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