COMFORT DRIVEN ADAPTIVE WINDOW OPENING BEHAVIOR AND THE INFLUENCE OF BUILDING DESIGN

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ABSTRACT

It is important to understand and model the behaviour of occupants in buildings and how this behaviour impacts energy use and comfort. It is similarly important to understand how a buildings design affects occupant comfort, occupant behaviour and ultimately the energy used in the operation of the building. In this work a behavioural algorithm for window opening developed from field survey data has been implemented in a dynamic simulation tool. The algorithm is in alignment with the proposed CEN standard for adaptive thermal comfort. The algorithm is first compared to the field study data then used to illustrate the impact of adaptive behaviour on summer indoor temperatures and heating energy. The simulation model is also used to illustrate the sensitivity of the occupant adaptive behaviour to building design parameters such as solar shading and thermal mass and the resulting impact on energy use and comfort. The results are compared to those from other approaches to model window opening behaviour. The adaptive algorithm is shown to provide insights not available using non adaptive simulation methods and can assist in achieving more comfortable and lower energy buildings.

KEYWORDS

Thermal comfort; Adaptation; Behaviour; Window; Overheating

INTRODUCTION

Naturally ventilated or hybrid ventilated buildings are common. The quantification of the comfort and energy use performance of these buildings is however an area under development. The importance of good understanding and good practice in this area is being heightened by increasing outdoor temperatures and the increased focus on reductions in building energy use across a number of countries.

In the UK building regulations, domestic dwellings now require a summer overheating calculation to be carried out using a standard methodology (BRE 2005) while the guidance for non domestic dwellings for summer overheating has recently been revised with the issue of CIBSE TM37 2006. The guidelines on how to achieve compliance are relatively simplistic, set static thresholds and take no explicit account of outside daily or hourly temperature variations or actual building ventilation paths and their interaction with the external climate. Other guidelines for building overheating performance do account for climatic variations and allow dynamic simulation but specify fixed values for the number or percentage of occupied hours allowed above a specified temperature (CIBSE 2006).

At the current time where dynamic simulation is used to investigate naturally ventilated building designs for summer overheating, it is common practice to use indoor temperature to trigger window opening at a threshold temperature value and to apply proportional control above that threshold. For annual heating energy calculations it is normal to represent the use of windows and other openings by imposing a ventilation rate based on diversity profiles or ventilation requirements given in appropriate building standards (CIBSE 2006). The values used in these pre-existing modelling strategies tend to be derived from an amalgamation of data from numerous surveys across many different buildings of similar type to define “typical” values which can be viewed as representing “typical behaviour”. While this typical behaviour may well represent behaviour in a notional “average” building it has no ability to accurately represent the range of behaviours seen in survey data and the use of these typical values does not provide insight into the behaviour that will actually prevail in any particular situation.

Adaptive comfort temperatures are now a well established concept (Nicol and Humphreys 2007] in which indoor comfortable temperatures vary with the running mean outdoor temperature, the adaptive behaviour applies to free running naturally ventilated buildings where the occupants have opportunities for adapting i.e. adjustment of clothing, posture, windows, blinds, fans etc. Adaptive comfort temperatures are now included in CIBSE (2006) and ASHRAE (2004) guidelines and most recently the CEN standard EN15251 (Olesen 2007). To make studies of occupant adaptive comfort possible using dynamic simulation at the building design stage the adaptive temperature algorithms must be implemented into the simulation code.

In an adaptive building the building performance is dependent how the building responds to climatic and internal variations and on how and when the occupants respond to their conditions (i.e. what adaptive actions they take and under what conditions will they take them) and in turn how the people's adaptive actions alter the buildings performance and so on. In order to model the performance of naturally ventilated buildings it is essential to be able to model the occupant's behaviour. Among the most common adaptive actions in a naturally ventilated building is to adjust the window position. The authors recent paper described how the Humphreys algorithm for window opening was derived from analysis of extensive survey data (Rijal et al. 2007) and its implementation in the ESP-r dynamic simulation software.

This paper reviews the implementation of the EN15251 adaptive comfort criteria and the Humphreys window opening behavioural algorithm in ESP-r and demonstrates their application to an analysis of summer overheating for an office in the UK. The effect of several building design options is then investigated and the use of the behavioural model is compared to the use of a static window opening threshold temperature. The use of the behavioural algorithm in modelling the window opening behaviour during the heating season is also demonstrated and compared to the use of a fixed ventilation rate approach.

The combination of the adaptive comfort temperature together with the modelling of comfort driven occupant adaptive behaviour is shown to be important to allow correct modelling of the comfort and energy performance of a naturally ventilated building.

The objective of this work is to allow the behaviour of occupants to be predicted for a given situation and to incorporate this behaviour in the modelling of building performance in terms of energy and comfort. This will allow evaluation of different design options and will ultimately assist in the design of more comfortable and lower energy buildings.

ADAPTIVE COMFORT TEMPERATURE

Daily values for running mean outdoor temperature and the comfort temperature are calculated as described in CIBSE Guide A (CIBSE 2006) and the CEN standard EN15251 (Olesen 2007) from the climate data and the response factor α used to calculate the running mean outdoor temperature (the response factor can be user input, a default value of 0.8 is suggested).

The equations for comfort temperature are different when the building is being heated than when it is free-running because the indoor temperature is decoupled from the outdoor temperature by the heating control when the heating is on. It has been shown that heating systems are more likely to be on than off when the running mean outdoor temperature (T_{rm}) is less than 10°C. The equations linking comfort temperature to outdoor temperature are (CIBSE 2007):

For $T_{rm} > 10^oC$: $T_{comf} = 0.33T_{rm} + 18.8$ (1)

For $T_{rm} \leq 10^oC$: $T_{comf} = 0.09T_{rm} + 22.6$ (2)

These equations have been implemented in ESP-r. Fig. 1. shows the comfort temperature and the running mean temperature over the period from 1st Jun to 31st Aug for an east of Scotland climate. The comfort temperature varies from 22 to 25°C.

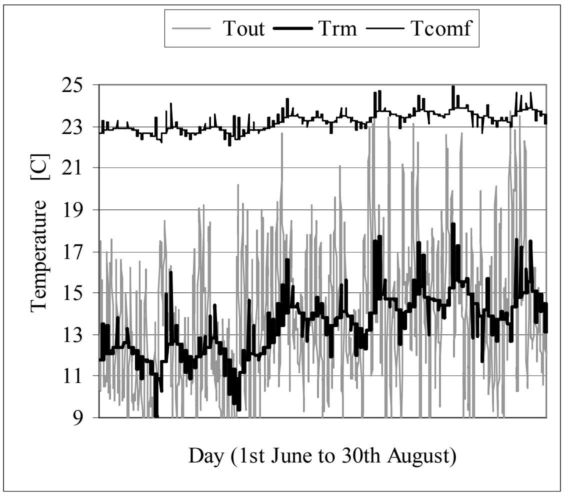

Figure1 Comfort temperature (T_{comf}), daily running mean outdoor temperature (T_{rm}) and outdoor temperature (T_{out}) from 1st June to 31st August.

This implementation of the adaptive comfort algorithm then allows the assessment of building comfort performance by comparing conditions agains the adaptive comfort criteria and forms the platform for the implementation of the adaptive behavioural algorithm.

THE WINDOW OPENING ALGORITHM

The analysis and assumptions made in the derivation of the behavioral window opening algorithm are given here in summary form.

The field surveys

The window opening algorithm was developed based on data collected in thermal comfort surveys conducted in 10 naturally ventilated office buildings in the UK. Two surveys were carried out, one longitudinal, the second transverse.

Window opening behavior

The window opening behaviour is assumed to be largely governed by the quest for comfort when in a situation of discomfort.

Temperature

As expected the proportion of windows open is found to be strongly related to temperature, people are most likely to open windows when both indoor and outdoor temperatures are high.

Behavioral prediction equations

Using multiple logistic regression analysis of windows open on both indoor globe temperature T_g and outdoor air temperature T_{ao_i} an equation was obtained (Rijal et al. 2007):

$$\log(p/1-p)=0.171T_g+0.166T_{ao\_i}-6.4 \quad (3)$$

Fig. 2 shows the predicted proportion open for each decile of T_g and T_{ao_i} compared to that which was observed for the longitudinal survey.

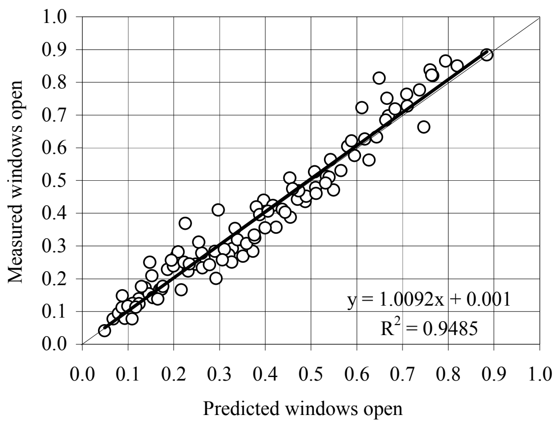

Figure 2 Predicted v. Observed window openings.

The “comfort zone”

A “comfort zone” of ±2 K about the comfort temperature is used to represent the range of internal conditions under which the occupant is likely to be comfortable. This ±2 K deadband is consistent with the analysis by Nicol and Humphreys using a wide range of data from the UK and Europe (CIBSE 2006 and CIBSE TM37 2006) and is incorporated in the CEN standard.

THE ALGORITHM IMPLEMENTATION IN DYNAMIC SIMULATION

The ESP-r dynamic simulation model

Many control modes are modelled within ESP-r. Most mimic standard building controls as would be executed by a building management system including proportional control, integral control, on/off control and optimum start control.

Some behavioural control models have been implemented. The Hunt model (Hunt 1979) for the switching on and off of office lighting has been implemented. The stochastic Lightswitch 2002 algorithm developed by Reinhart to predict dynamic personal response and control of lights and blinds from field study data and Newsham et al.’s (1995) original Lightswitch model is available. Bourgois et al. (2006) developed the SHOCC module to enable sub-hourly occupancy modelling and coupling of behavioural algorithms such as Lightswitch 2002 across many ESP-r domains. Prior to this work there was no behavioural model for window opening implemented in ESP-r.

The windows open algorithm in ESP-r

The windows open algorithm has been implemented in ESP-r to allow control of windows within the airflow network of a building model. The implementation of the algorithm in ESP-r is named the Humphreys adaptive algorithm (Rijal et al. 2007).

The frequency at which the Humphreys adaptive algorithm is run has been set to hourly but this could be varied in future. Each hour the operative temperature at a user defined point chosen to represent the occupant position within the zone of interest is calculated from the appropriate surface and air temperatures and a comparison made with the comfort temperature. If the operative temperature is more than 2 K above the comfort temperature then the state is “hot”, if the operative temperature is more than 2 K below the comfort temperature then the state is “cold”.

When the occupant is not comfortable (the occupant is “hot” or “cold”), then the probability of the window being open (p_w) is calculated from the operative temperature (T_{op}) and the outdoor temperature (T_{out}) using the logit function derived from the survey data (equation (3)). In this case the calculated operative temperature (T_{op}) and the climate file outdoor air temperature (T_{out}) are substituted for the measured globe temperature (T_g) and instantaneous outdoor temperature (T_{ao_i}) .

From this the probability that the window is open is calculated. To decide whether a window opening or closing action will occur, the calculated window open probability is compared to a random number between 0 and 1 to represent a single throw binomial function.

If the operative state is “hot” and the window is closed then the window will be opened if the random number is less than the probability of the window being open. If the operative state is “cold” and the window is open then the window will be closed if the random number is greater than the probability of the window being open. If the operative state is "hot" and the window is open then no action is taken, and if the operative state is "cold" and the window is closed then no action is taken. When the occupant is "comfortable" (neither "hot" nor "cold"), then no action is taken and the window remains as it was.

It can be specified that all windows will be closed and remain closed after a fixed time or prior to a fixed time (possibly to coincide with the start and end of occupancy) .

RESULTS USING THE ALGORITHM

An office model

To demonstrate the operation of the algorithm a simple naturally ventilated cellular office was chosen. The cellular office used is a "Type 1" office as defined in ECON19 (The Carbon Trust 2000) which is widely used for benchmarking of energy use in UK offices.

The cellular office is set within a larger open plan office space (Rijal et al. 2007). The cellular office faces south and is constructed to represent a typical 1990's office with a 22.5 m^2 floor area within a thermally lightweight building.

External walls have a brick outer layer, an air gap, mineral wool insulation between studs, plasterboard and a thin plaster skim. The floor is of suspended timber on joists with underlay and carpet. The ceiling is of plasterboard with a thin plaster skim on wooden joist. Glazing is of a standard double glazing type as used in the 1990's. The internal walls are of plasterboard partition type. Normal office heating, lighting, occupancy and equipment gains and schedules were applied and the office was set in an east of Scotland climate. The heating setpoint used was 22 ^{o}C and a start up period used to achieve this by the beginning of occupancy. An airflow network was established to represent background infiltration openings as well as the openable windows.

The office has south facing window, occupant gains are set at 90 W during occupied hours, lighting gains at 90 W during occupied hours and equipment gains of a constant 50 W. The combination of the solar, occupant and equipment gains give an adjusted for climate value of 36.6 W/m^2 using the TM37 calculation method. This is within the 30 to 40 W/m^2 range where natural ventilation is thought to be effective and just above the 2007 regulation threshold of 35 W/m^2 .

Simulated window open behaviour

The model was run through annual simulations with the Humphreys adaptive algorithm controlling the window opening. The simulations showed that the proportion of occupied days when the window was opened at some time during the day varied from 0.05 in the winter to 0.59 in the summer. The results are shown in Fig. 3 and show a trend consistent with survey data which is shown for comparison.

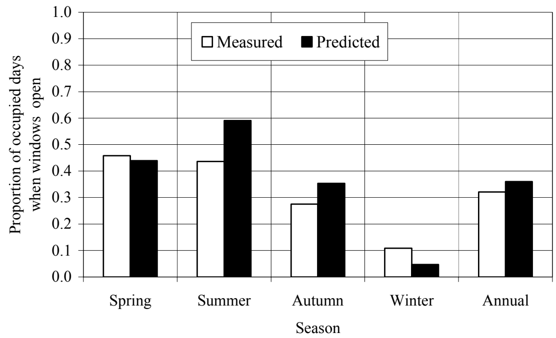

Figure 3 Predicted window opening for the simple office compared to the longitudinal survey data.

A more detailed analysis of time, temperature and energy flow for a summer's day is shown in Fig. 4. In this case the window is opened at noon when the operative temperature is close to 26 ^{o}C. The outdoor temperature peaks at 23 ^{o}C at 14:00 while the indoor operative temperature peaks at 27 ^{o}C around 16:00.

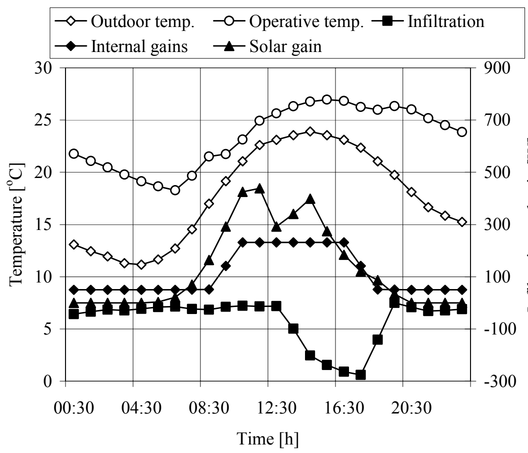

Figure 4 Temperature, heat gains and ventilation losses for a summer day modeled using the Humphreys algorithm.

The incoming air energy flow (infiltration) represents the cooling available to the office from inflow of outside air after the window is opened. Initially there is less than 200 W of cooling due to the relatively high outdoor temperature but the cooling increases to around 300 W by 17:30 as the outside temperature drops relative to the indoor operative temperature. The operative temperature continues to rise until 16:00 even after the window is opened as the cooling effect is not sufficient to offset the heating due to solar gains, casual gains and increasing outdoor temperature.

Fig. 5 shows the same time period but with the windows remaining closed. In this case the operative temperature rises to a peak of 30 °C around 17:00, window opening behaviour appears to reduce the peak temperature by around 2.5 K on that day.

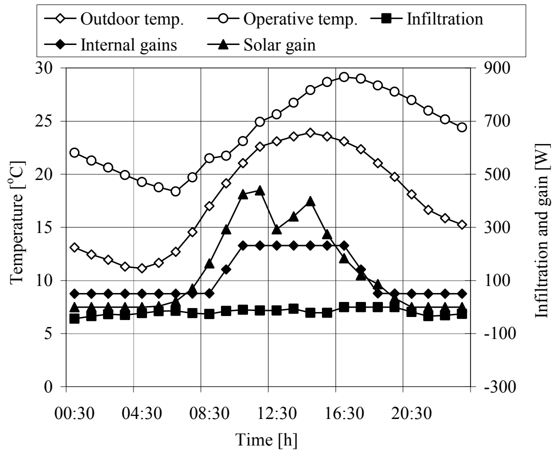

Figure 5 Temperatures, gains and losses for a summer day with windows closed.

The same office was analysed for a run of high temperature days covering a Friday, Saturday, Sunday and Monday period in July. It can be seen (Fig. 6) that the window opening on the weekdays allows the temperatures to be lower despite the increased internal gains (Rijal et al. 2007 (IBPSA)).

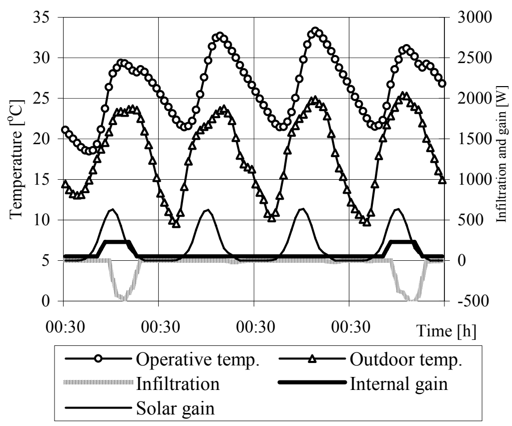

Figure 6 Temperatures and gains for a warm Friday to Monday period in July

IMPACT OF OFFICE DESIGN ON COMFORT AND ENERGY USE

To illustrate the impact of office design parameters a second and third version of the office model were created (Rijal et al. 2007). The second office is identical to the original except a fixed opaque external shade is added above the office window. The third variant has the same external shade but also an exposed concrete ceiling to provide some thermal mass to the room (Rennie and Parand 1998).

SUMMER OVERHEATING

It is common in the study of the summer performance of naturally ventilated buildings to assume that windows will begin to open in the summer when the indoor operative temperature reaches some threshold and will be fully open when some higher threshold is reached. Between the two thresholds it is normal to assume proportional opening. This behaviour is illustrated in Fig. 7 which shows windows begin to open at 20°C and to be fully open at 21°C for the same baseline office. The windows are open earlier for this assumption than for the Humphreys algorithm (Fig. 4). The thresholds chosen here are towards the low end but within the range commonly used to demonstrate the capability of a building to achieve an overheating specification.

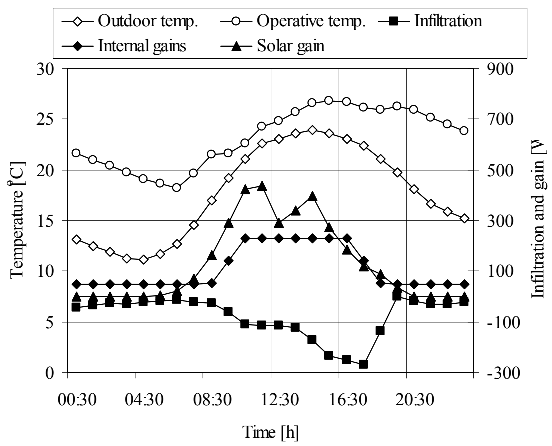

Figure 7 Temperatures, gains and losses for a summer day with window opening behavior modeled using a temperature threshold with proportional opening.

Comparing the window open threshold approach to the Humphreys adaptive behavioural algorithm over the summer period shows significant differences as illustrated in Fig. 8 and Fig. 9. The threshold (and proportional) method gives lower peak temperatures and much lower temperature exceedances.

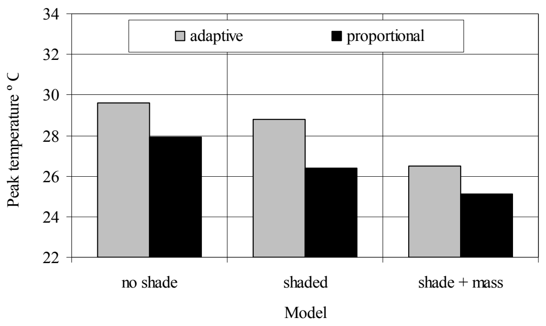

Figure 8 Peak operative temperatures modeled using the Humphreys algorithm (adaptive) and the threshold method (proportional).

For this example the threshold method gives a more optimistic prediction than the Humphreys algorithm. The difference appears to be that in the threshold case the window opening occurs before a discomfort triggered window opening event would occur. The Humphreys algorithm which is survey based and building and climate specific is more likely to represent actual behaviour than an arbitrary threshold which in the absence of established criteria would be likely to be set at the most advantageous value.

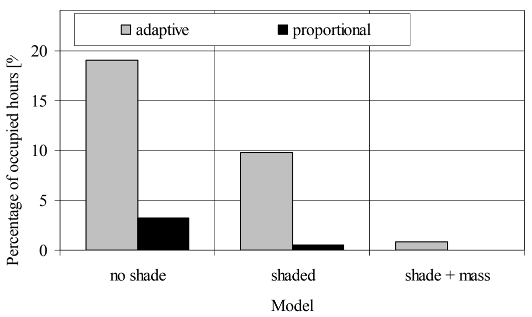

Figure 9 Percentage of occupied hours with operative temperatures over26°C for adaptive and the threshold (proportional) window open algorithms.

Using the threshold method in this way could lead to the assumption that the lightweight unshaded office performance would prove acceptable. However the Humphreys algorithm identifies that the risk of overheating in the no shade or shaded office would be significant. Moving ahead with a design based on the threshold method there would be a risk that occupants would experience discomfort leading to the seeking of remedial measures such as fans, air conditioning or glazing replacement.

The integration of the algorithm and the adaptive comfort criteria within the dynamic simulation tool allows the comfort and behaviour in a given situation to be modelled but also the effect of the behaviour for any given situation. In this case the window opening behaviour is integrated with the dynamic thermal model and the model of the designed ventilation paths and the dynamic models of the climate so that the window opening dimensions and the effect on airflows of wind speed and direction can be modelled together so that interactions can be fully comprehended at the "virtual prototype" stage in the design and adjustments made to address issues found.

HEATING SEASON ENERGY USE

Heating energy demands for baseline office

The cellular office model was also used for analysis of the annual energy demand for space heating. The model was run with and without the Humphreys adaptive algorithm. Where the window open algorithm was not used it was assumed that occupants adjust the window openings or trickle vents to achieve a ventilation rate of 8 litres per second per person during occupied hours and a background infiltration rate of 0.25 air changes per hour outside occupied times. This assumption is of a type commonly used in annual energy demand calculations for naturally ventilated offices [CIBSE 2006, The Carbon Trust 2000].

The results extracted from the simulations are shown in Fig. 10. Normalised heating energy demands were 105 kWh/m^2 per annum for the Humphreys algorithm and 109 kWh/m^2 per annum for the averaged ventilation rate which is within the normal range for an office of this kind (The Carbon Trust 2000).

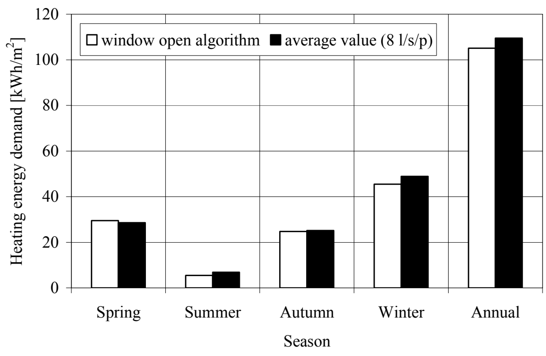

Figure 10 Heating energy demand by season using the Humphreys algorithm (window open algorithm) and a fixed ventilation rate during occupancy assumption (average value (8l/s/p)).

Impact of office design on heating energy

The three office models were first simulated using the averaged ventilation rate assumption. Using this model the effect of the shade is to increase heating demand from 109 to 112 kWh/m^2 p.a., thermal mass added to the shaded office gives a demand of 108 kWh/m^2 p.a.

Next the effect of the shade and the thermal mass were evaluated using the Humphreys adaptive algorithm. Fig. 11 shows how the window opening varies by season and design type.

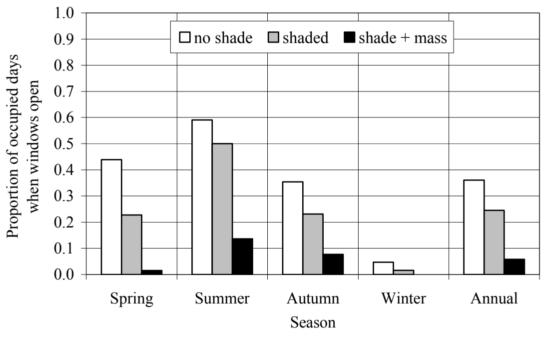

Figure 11 Predicted window opening v. building design option.

The effect of the shade is to reduce the number of occupied days when the window is opened, this effect is biggest in the spring and the autumn when the unshaded low mass office window would be open on up to 45% of days. The thermal mass slows response to gains and for this particular building and climate temperatures only occasionally cause discomfort.

The combined effect of the shade with the thermal mass modelled using the Humphreys algorithm is to reduce heating energy demand from 105 to 98 kWh/m^2 per annum.

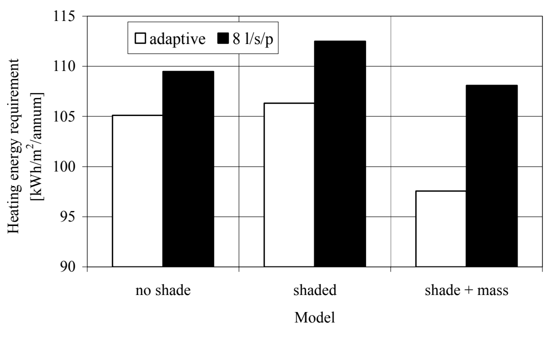

Figure 12 Annual heating energy demand for each design option modeled using the Humphreys algorithm (adaptive) and the fixed ventilation rate method (8l/s/p).

The Humphreys algorithm predicts that a shaded office with thermal mass will be more comfortable and have lower heating demands (Fig. 12) in part due to fewer window openings during heating periods. The averaged ventilation rate assumption makes no link between occupant comfort and energy use and predicts a much smaller effect on energy consumption.

The average ventilation rate approach is less sensitive to building design than the Humphreys adaptive algorithm. In the case of the shaded office with the exposed concrete ceiling the average ventilation approach gives a 10% higher estimate of annual heating energy requirement than the Humphreys adaptive algorithm (108 kWh/m^2 for 8 l/s/p v. 98 kWh/m^2 for the Humphreys adaptive algorithm) and does not show the effect of improved thermal comfort on the natural ventilation rate.

DISCUSSION

The adaptive algorithm approach can be used to provide similar insights in all applications where occupant controlled natural or hybrid ventilation is being considered including assessment of summer and winter performance for current or future climates.

Future studies will allow the Humphreys adaptive algorithm to be developed and validated further. Anecdotally a driver of window opening is air freshness which could be modelled using ESP-r's embedded contaminant modelling and CFD capabilities.

The adaptive algorithm is particularly relevant to the performance of naturally ventilated buildings, the algorithm has implications for ventilation design and also other building parameters such as heating controls, thermal mass and solar shading.

It has often been experienced that operational energy used is higher than the design prediction, the comfort driven adaptive behaviour of occupants is one potential source of this discrepancy. It is a commonly observed phenomenon to see windows open in a building while the heating is on, this algorithm lets us begin to comprehend the drivers for this behaviour in our models.

The use of the Humphreys adaptive algorithm in the dynamic building simulation software will assist in identification of buildings which may perform poorly and assist in the development of robust solutions.

There is a risk that buildings built today as naturally ventilated may in fact prove to be uncomfortable and require the retrofit of air conditioning, the use of the Humphreys adaptive algorithm within simulation software would assist in avoidance of this scenario.

The main advantage of this method compared to other methods is that it comprehends the impact of adaptive comfort driven window opening behaviour specific to the building and climate rather than making more generalised assumptions.

CONCLUSIONS

An algorithm (the Humphreys adaptive algorithm) has been implemented in ESP-r which uses adaptive theory to predict the probability that windows will be open. The algorithm gives similar results to those extracted from survey data. The window open behaviour as represented by the algorithm is shown to be more sensitive to changes in building design parameters than a non adaptive approach. It is suggested that an adaptive algorithm will better represent human control of windows and allow a more accurate assessment of human thermal comfort conditions and building performance including summer overheating and annual energy use. The algorithm embedded in simulation software will assist in the design of more comfortable and energy efficient buildings.

ACKNOWLEDGEMENTS

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