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Summary A simplified dynamic thermal response model has been used to study summertime overheating in temporary school buildings as a function of thermal insulation thickness, building orientation, external colour, shading, occupancy and ventilation rate. Practical advice on ameliorative strategies is given, and the provision of ventilation under buoyancy-driven flow discussed in some detail. It is suggested that dynamic thermal modelling could usefully be combined with the stack effect equation for the design of natural ventilation in buildings.

Thermal response of temporary school buildings: II Summertime overheating

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1 Introduction

This paper (Paper II) discusses a study of summertime overheating in temporary school buildings. It should be read as the second paper of a pair, the first of which (Paper I[1]) deals with the space heating requirements of such buildings. The work was initiated by Cornwall County Council who have a substantial stock of Elliott–Medway buildings (EMB), and so this is the type of temporary school building considered. The results may of course be relevant to other types.

The buildings are constructed from units of wooden frame construction, clad with plywood and lined with plasterboard, having thermal insulation within the roof, walls and floor between 25 mm and 60 mm thick, depending on the age of the building. The buildings are painted grey externally. The configuration considered here (designated CCC 693M) is 16×8 metres in plan, and has roughly 15 m^2 of single glazing distributed about equally between the two long walls. There is approximately 50 m^2 of internal partition. Type CCC 693 EMB can have 25, 50 or 60 mm of insulation.

Thermally lightweight construction has potentially significant advantages for space heating provision under the highly intermittent school occupation pattern. Paper I[1] quantified this potential advantage and gave practical indications of how to avoid losing it. Lightweight structures are however more susceptible than heavyweight to overheating in summer. This is because there is less thermal mass to absorb the solar gains. Paper II quantifies the likely degree of overheating and the benefits of possible ameliorative strategies.

2 Methodology and assumptions

Like Paper I, the present study is based on calculations made with the Exeter University Energy Studies Unit simplified building thermal response model EXCALIBUR[2], modified slightly to include allowance (based on the sol–air temperature approximation) for solar gains by conduction through the opaque fabric of a building.

Structural details and steady-state losses for the EMB are given in Paper I, Tables 1 and 2. Information particular to the overheating calculations is summarised in Table 1.

Table 1 Basic modelling assumption for overheating calculations

Item	Assumption/Relevance
Heating plant	OFF
Occupancy	5-day, 0900–1600 BST
Vacations	2 June–10 June (half-term)
Period of simulation	Summer term, 1 May–20 July (89 days).
Meteorological data	Hourly values of screen temperature, direct and diffuse radiation, measured at Kew Observatory in the summer of 1965–1966.
Lighting gains	Usually zero during the summer term, but 8.2 W m^{-2} of floor whenever estimated working plane illumination <250 lux.
Metabolic gains	Sensible heat gain, 90 W person^{-1} at inside temperature $T_{in} = 18$°C and 50 W person^{-1} at 27°C, continuing to decline linearly to zero for higher T_{in} (cf *CIBSE Guide*[3]).
Number of occupants	Maximum 60, working day average 47.
Colour of external walls	Grey (short-wave absorptivity 0.8), or white (short-term absorptivity 0.3).
Orientation	Long side east–west or north–south

It is necessary to have some criterion of what might be an acceptable degree of overheating. The *CIBSE Guide*[3,4] says that in designing a building it is '... important to ensure that it will not become uncomfortably hot during sunny periods, i.e. that the maximum peak temperature should not frequently exceed, say, 27°C. In statistical arguments 'not often' is usually taken to mean 'less than 5% of the time' and on this basis the criterion taken here for an unacceptable degree of overheating is a predicted temperature of more than 27°C for more than 5% of the occupied hours during the summer term.

EXCALIBUR provides an hour-by-hour simulation of building internal temperatures, taking into account meteorological data, heat storage effects and casual gains. Using results from the model we have tried to establish the degree to which summer term overheating in EMB depends on the thickness of thermal insulation, building orientation, colour of the external surface, shading of the glazing, number of occupants and ventilation rate. This we have attempted by changing one parameter for each model run, in the manner of a sensitivity analysis.

3 Results

Table 2 and its footnotes summarise the results of twelve runs of EXCALIBUR. Each run represents a complete hour-by-hour summer term simulation of an EMB under a particular set of assumptions.

A number of observations may be made about overheating from the results given in Table 2. These include the following:

(*a*) In Case 1 (60 mm insulation; 5.7 ac h^{-1} during occupation; glazing facing north and south, no shading; grey colour; maximum occupancy 60 during working hours), 7.5% of school hours are estimated to have inside air temperature T_{in} at least equal to 27°C. This degree of overheating would not meet our acceptability criterion. As discussed in Paper I, the assumed ventilation rate of 5.7 ac h^{-1} is suggested by the DES recommendation that occupied school buildings should be capable of ventilation to 30 m^3 of fresh air per person per hour. The ventilation rate actually achievable in EMB under overheating design conditions is discussed below.

(*b*) Case 2 indicates that overheating is increased to an estimated 8.8% of occupied hours at $T_{in} \geq 27$°C if the insulation is only 25 mm thick.

(*c*) Case 3 shows that orientation of the building such that the windows face east and west rather than north and south increases the degree of overheating slightly. This may be found rather surprising. The reason is that whereas in Case 1 the south facing glazing receives direct radiation, the north facing receives very little. In Case 3, though the now east facing glazing receives less direct radiation than it did when facing south, the west facing glazing receives considerably more than it did when facing north, and the net effect of the changes is small. Of course this compensation will only occur for classrooms with the glazing about equally distributed between parallel sides.

(*d*) Painting the roof and walls of the building white, so that the short-wave absorptivity is reduced from 0.8 to 0.3, reduces the overheating to an estimated 2.9% of summer term occupied hours with $T_{in} \geq 27$°C, and therefore meets the acceptability criterion.

Table 2 Summary of overheating calculations

Case	Level of insulation (mm)	Ventilation rate (ac h^{-1})	Max. no. of occupants	Orientation	Shading	Colour	% of time above 27(°C)	ΔT_1 (°C)	ΔT_2 (°C)
a	b	c	d	e	f	g	h	i	j
1	60	5.7	60	SN	No	G	7.5	5.1	6.3
2	25	5.7	60	SN	No	G	8.8	5.1	7.1
3	25	5.7	60	EW	No	G	9.2	5.5	6.7
4	25	5.7	60	EW	No	W	2.9	4.6	4.3
5	60	5.7	60	EW	Glazing	G	5.7	4.8	5.7
6	60	5.7	60	EW	Glazing	W	2.3	3.9	3.6
7	60	5.7	0	EW	No	G	2.1	2.5	4.1
8	60	5.7	30	EW	No	G	4.3	4.1	5.4
9	60	3.0	60	EW	No	G	13.7	6.1	7.9
10	60	10.0	60	EW	No	G	5.4	4.8	*5.9*
11	60	15.0	60	EW	No	G	4.2	4.3	*5.4*
12	60	20.0	60	EW	No	G	3.7	3.9	*5.2*

Notes

Column

a —

b Thickness of insulation to the roof, walls and floor. Structural details given in Paper I, Table 1[1].

c 5.7 ac h^{-1} conforms to the Department of Education and Science recommendation of 30 m^3 per person per hour. Outside occupied hours the building is assumed to be shut and the ventilation rate to return to basal value of 1 ac h^{-1}.

d Maximum number of occupants assumed during the occupation period (see Table 1 of this paper). It is assumed that for about 1½ hours of a 7 h school day the classrooms will be empty, so the average occupancy assumed for calculating metabolic gains is reduced to about 80% of the maximum.

e EMB CCC 963M has 7.49 m^2 and 7.26 m^2 of single glazing on two parallel sides, and no glazing elsewhere. In this column, entry SN means that the 7.49 m^2 faced south (and the 7.26 m^2 faced north). Similaly EW means that the 7.49 m^2 faced east (and the 7.26 m^2 west).

f Entry No means that the building was unshaded. Entry Glazing means that the glazing was assumed to be completely shaded from the direct (beam) radiation.

g Entry G means that the roof and walls of the building were assumed grey (short-wave absorptivity 0.8). Entry W means that they were assumed painted white (short-wave absorptivity 0.3). These figures were taken from the *CIBSE Guide*[4].

h This is the percentage of time during occupation that the estimated inside temperature equalled or exceeded 27°C.

i & j ΔT_1 is the average inside–outside temperature difference during occupation. ΔT_2 is the same quantity, but averaged only over the hours during which the inside temperature equalled or exceeded 27°C. Values set in italic are used subsequently in the discussion of buoyancy-driven flow.

(*e*) Reverting to a grey building, but shading the glazing from direct radiation, reduces the overheating to 5.7% of the occupied hours with $T_{in} \geq 27°C$ (Case 5).

(*f*) shading the glazing *and* painting the walls and roof white reduces the overheating to 2.3% (Case 6).

(*g*) Reducing occupancy to very low levels cuts overheating for a grey unshaded building to about 2% of occupied hours with $T_{in} \geq 27°C$ (Case 7).

(*h*) Half full occupancy also produces an acceptable degree of overheating with $T_{in} \geq 27°C$ for 4.3% of occupied hours (Case 8).

(*i*) Returning to full occupancy and reducing the ventilation rate to 4 ac h^{-1} increases the overheating to an estimated 13.7% of occupied hours with $T_{in} \geq 27°C$ (Case 9).

(*j*) Cases 10, 11, 12 examine the effect of increasing ventilation to 10, 15 and 20 ac h^{-1} respectively, all at full occupancy. These cases produce respectively an estimated 5.4%, 4.2% and 3.7% of occupied hours with $T_{in} \geq 27°C$.

Five main indications emerge from the above:

- The better insulated EMB are as liable to overheat as the more poorly insulated.
- Orientation has little effect on overheating for classrooms with equal areas of glazing on two parallel sides. (This would not be true for classrooms when the glazing was not evenly distributed between parallel sides; e.g. where one side only is glazed, the orientation effect would of course be stronger).
- Painting the walls and roof white is sufficient to reduce overheating to acceptable levels at the ventilation rate assumed.
- Shading the windows from direct radiation also reduces overheating, but under the conditions modelled is found to be not quite sufficient to meet the acceptability criterion. Note however that shading will also have the advantage of increasing the thermal comfort of people sitting close to the windows, on whom the sun otherwise shines directly.
- Increased ventilation and reduced occupancy are also effective ways to cut overheating.

4 Overheating and ventilation

Ventilation will in practice be critical in determining the degree of overheating. So far our analysis has relied mainly on the ventilation rate of 5.7 ac h^{-1} during occupied periods. This is the value corresponding to the DES recommendation that occupied spaces in schools should be capable of ventilation to a first air supply rate of 30 m^3 $person^{-1}$ h^{-1}. We now use the thermal model to determine the ventilation rate likely to be achieved under what amount to overheating design conditions.

It will be assumed that overheating is most likely on anticyclonic days in summer. Such days, which occur about 30% of the time in summer[5] usually combine sunshine, high outside temperatures and low windspeed, which suggests that buoyancy-driven flow (the stack effect) will tend to determine the ventilation rate.

It is therefore relevant to decide whether buoyancy-driven flow in an EMB is likely to produce ventilation rates sufficient to reduce overheating to an acceptable level, as defined above. However buoyancy-driven flow depends on inside–outside temperature difference and so is effectively a function of the degree of overheating. It will therefore be necessary to use the results of the thermal respone model together with the stack effect equation to determine the operating point for the building under overheating conditions.

Table 2, column h, gives the percentages of occupied summer term hours with inside temperature estimated by EXCALIBUR equal to or exceeding 27°C. Of the entries, cases 3, 9, 10, 11, 12 all refer to EMB with maximum occupancy and the same level of insulation, orientation, shading assumption and colour. They are therefore a homogeneous set and can be used to study the dependence of overheating on ventilation rate. This is done in Figure 1, which shows that under these conditions about 11 ac h^{-1} would be necessary to meet our criterion of acceptability, that for no more than 5% of occupied hours should the internal temperature be above 27°C. The requirement is therefore that buoyancy-driven flow should produce 11 ac h^{-1}.

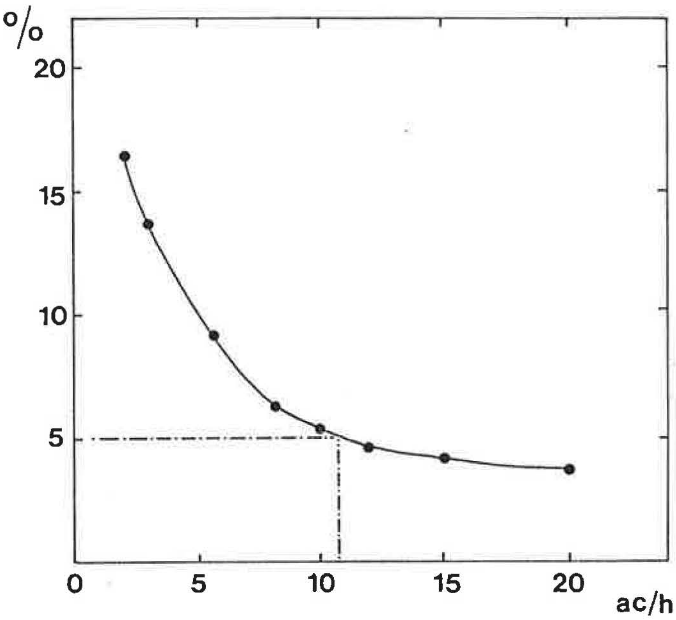

Figure 1 Overheating as a function of ventilation rate. The horizontal axis shows the ventilation rate during occupation. The vertical axis shows the percentage of occupied hours with the inside temperature T_{in} equal or in excess of 27°C. About 11 ac h^{-1} is required for $T_{in} \geq 27°C$ for less than 5% of occupied hours.

Under buoyancy-driven flow the rate of ventilation of an enclosed space depends on the size and disposition of the openings to the outside air, and the temperature difference between the inside and the outside.

With EMB CCC 693M a common type of glazing is aluminium sash windows giving a maximum total openable area of about 7.7 m^2 about equally distributed between two parallel sides of the building. If all the lower sashes were raised, this would be equivalent to two rectangular openings each measuring 7.0 × 0.55 m. Alternatively half the lower sashes and half the upper sashes were opened, when the equivalent two areas would be about the same, but each measure 3.5 × 1.1 m^2.

These geometries may be modelled using the stack effect relationship given in case b, Table A4.4 of the 1986 *CIBSE*

Guide[6]. This suggests that with a mean air temperature about 300 K (27°C) and a coefficient of discharge taken to be 0.61, the ventilation rates V (ac h^{-1}) in the EMB CCC 693 M under buoyancy-driven flow are given by:

$$V = 2.55\,\Delta T^{1/2} \tag{1}$$

(all bottom sashes open) *or*

$$V = 3.60\,\Delta T^{1/2} \tag{2}$$

(half bottom sashes open, half top)

where ΔT is the inside–outside temperature difference.

The ventilation rate is thus about 40% higher (for given ΔT) if the opening is split equally between the upper and lower sashes. This is because with this geometry a greater pressure head is available to drive the flow.

Table 2, columns i and j show that the inside–outside temperature difference in the EMB is itself a function of ventilation rate. We are therefore in the situation where the ventilation rate determines the inside–outside temperature difference, but (under buoyancy-driven flow) the inside–outside temperature difference determines the ventilation rate. Under these conditions the building will operate so that the ventilation rate and the inside–outside temperature differences are in balance. The operating point can be determined graphically by plotting the buoyancy-driven flow equation 1 or 2 and the ventilation rate–ΔT relationship from Table 2 on the same axes and noting where they cross. This will tell us the ventilation rate under operating conditions, which can then be used on Figure 1 to estimate the degree of overheating assuming that the ventilation rate on overheating days is predominantly buoyancy-driven.

The operating point is determined on Figure 2 which shows equations 1 and 2 as broken curves A and B, together with a solid curve representing the ventilation rate–ΔT relationship taken from the five cases in column j of Table 2 which form the homogeneous set. Column j has been used rather than column i because column j gives the ΔT likely to apply on overheating days.

From the crossing points on Figure 2 it seems that with maximum opening the existing windows in the EMB will produce ventilation rates between about 6 and 9 ac h^{-1} under buoyancy-driven flow. The higher end of the range will be achieved by dividing the window opening equally between top and bottom sashes.

Referring back to Figure 1 we see that 6 ac h^{-1} corresponds to about 9% of occupied hours above 27°C, and for 9 ac h^{-1} the figure is 6%.

We conclude that at full occupancy the existing openable windows are probably not adequate to meet the overheating acceptability criterion. However if the occupants choose to divide window opening equally between top and bottom sashes, the degree of overheating under the conditions modelled is not likely to be far in excess of what we have chosen to regard as acceptable.

Were one redesigning the building, the criterion could be satisfied fully by specifying somewhat larger openable windows. All buoyancy-driven flow through rectangular openings in vertical partitions will be described by an equation of the form

$$V = k\Delta T^{1/2} \tag{3}$$

where k (ac h^{-1} K$^{-1/2}$) depends on the areas, shapes and

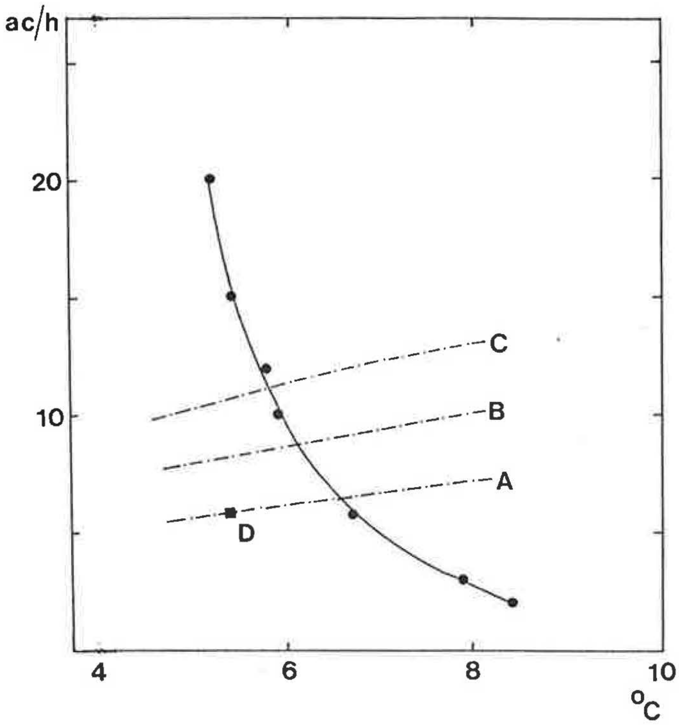

Figure 2 Graphical solution of equations determining ventilation rate under buoyancy driven flow. The horizontal axis shows the inside–outside temperature difference in degrees Celsius. The vertical axis shows the ventilation rate in air changes per hour. The full curve is the relationship from the entries underlined in column j of Table 2 (EXCALIBUR results). Dotted lines A, B and C are buoyancy driven flow relationships given by equations 1, 2 and 4 in the text. These correspond respectively to all the bottom sashes open, half bottom and half top sashes open, and the vertical dimension of the openable area enlarged by about 20% so that the building is estimated just to meet the overheating acceptability criterion described in the text.

dispositions of the openings involved. It will be seen that equation 3 is a generalisation of equations 1 and 2. By choosing reasonable values of k, equation 3 can be used to generate a family of ventilation rate–ΔT curves to plot on Figure 2. To meet the overheating criterion we are interested in the value of k which produces a curve that crosses at a ventilation rate of 11 ac h^{-1} the ΔT–ventilation rate plot displayed in Figure 2. Since the operating point is then such that $\Delta T = 5.8$°C, we deduce by substitution in equation 3 that the appropriate k is 4.6 ac h^{-1} K$^{-1/2}$. Thus a system of openings which will produce a buoyancy-driven flow equation

$$V = 4.6\Delta T^{1/2} \tag{4}$$

will, on these calculations, produce a ventilation rate of 11 ac h^{-1} on the critical overheating days. The curve corresponding to equation 4 is also shown on Figure 2 (broken curve C). Using once again the stack effect relationship given in case (b), Table A 4.4 of the 1986 *Guide*, it can be shown that a value of 4.6 for k would follow if the EMB considered (internal volume 314.9 m^3) were ventilated by an openable area the equivalent of 7 m horizontally by 1.3 m vertically. The present windows, under alternate opening of top and bottom sashes, provide an openable area equivalent to 7 m horizontally by 1.1 m vertically, so on the basis of the present calculations one would regard the openable area of the present windows as undersized by something like 20% from the overheating point of view.

The stack effect relationships can also be used in conjunction with the results of thermal modelling summarised in Table 2 to examine the consequences of operating the buildings at less than maximum occupancy. Thus at half maximum occupancy and 5.7 ac h^{-1} the inside–outside temperature difference characteristic of overheating conditions is found to be 5.4°C, (Table 2, Case 8, column j). Plotted at D on Figure 2 this point lies close to the $k = 2.55$ stack effect line, indicating that these operating conditions could be obtained by just opening top (or bottom) sashes. Since from Table 2 we see that this case meets the criterion for overheating acceptability we conclude that when operating at half maximum occupancy, the existing openable window area is likely to be sufficient to control any overheating problem.

5 Conclusions

Using a simplified thermal response model in conjunction with the stack-effect equation we judge summertime overheating to be a potential problem in lightweight school buildings of the type considered. This conclusion does not seem critically dependent on the level of insulation. However the strategy of alternate opening of upper and lower sashes is found to reduce overheating at full occupancy to close to the tolerable level as defined here. This problem is therefore not likely to be very serious.

In practice therefore, where overheating does arise, staggered window opening may be suggested as an ameliorative strategy. Of the other possibilities, building orientation is found to have little effect for classrooms where the glazing is about evenly distributed between parallel sides. Shading of windows from direct sun does have an effect, although perhaps not sufficient to contain the problem at maximum occupancy with ventilation at the DES recommended level. Painting the walls and roof white does seem to suffice in this respect, and shading the building as a whole would presumably also be effective and not so dependent as maintaining the quality of the paintwork. Restriction of occupancy to less than half maximum is also likely to be effective in controlling overheating to levels acceptable on our definition.

We have suggested that enlarging the openable window area by about 20% vertically would be sufficient to control overheating at full occupancy. This is unlikely to be a cost-effective retrofit strategy but it does indicate that using thermal models together with the stack effect relationship in the manner described here may be a useful technique in designing natural ventilation in new buildings.

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References

1 Penman J M and Murdoch N Thermal response of temporary school buildings: I Heating *Building Serv. Eng. Res. Technol.* **10**(2) 61–68 (1989)

2 Crabb J A, Murdoch N and Penman J M A simplified thermal response model *Building Serv. Eng. Res. Technol.* 8(1) (1987) 13–19

3 *CIBSE Guide* Section A7: Internal heat gains (London: Chartered Institution of Building Services Engineers) (1986)

4 *CIBSE Guide* Section A8: Summertime temperatures in buildings (London: Chartered Institution of Building Services Engineers) (1986)

5 Chandler T J and Gregory S *The climate of the British Isles* (London: Longmans) (1976)

6 *CIBSE Guide* Section A4: *Air Infiltration* (London: Chartered Institution of Building Services Engineers) (1986)