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Natural ventilation in UK schools: design options for passive cooling

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Abstract

This paper presents an analysis of natural ventilation strategies in UK schools to reduce summertime overheating. Building simulation is used to predict internal air temperatures for three teaching spaces of a generic school building for three UK locations under current and future climates. The ventilation strategies investigated are single-sided ventilation, cross-ventilation with outlet stack and subterranean air ducts with lantern lights. Overheating potential is evaluated using two criteria, CIBSE guidelines and Building Bulletin 101. The findings demonstrate that, with careful optimisation of the design, natural ventilation can be used effectively to reduce the effects of overheating. Even in warm locations (such as London) or predicted warmer climates (such as the 2050 climate) summertime overheating can be reduced by cross-ventilation with stacks or ventilation using subterranean air ducts. However natural ventilation is predicted to be unable to meet all overheating criteria, in particular criteria relating to maximum internal air temperatures during summertime.

Keywords

Natural ventilation, passive cooling, schools, building simulation, overheating

1 Introduction

Building simulation tools are being increasing used in the design of new-build construction projects. These tools allow users to estimate the energy consumption, thermal conditions and indoor air quality of building designs, and enable investigation of design options to ensure optimum performance throughout the building's life. In the design of schools, building simulation has found a niche role in evaluating the thermal conditions of classroom spaces in order to ensure thermal comfort of students and a high quality learning environment.

Schools represent a particular challenge to building designers, particularly in terms of summertime thermal comfort due to potential overheating. Classrooms are densely occupied spaces with high levels of occupancy and increasingly contain large amounts of IT equipment with each student having access to a desktop or laptop PC and lessons delivered via projectors and electronic whiteboards. School buildings also differ from many non-domestic building types as their occupancy is based on the relatively short school day and the term times on which the school operates. As many school buildings are now being constructed under the Government's Schools for the Future programme, there exists great potential to optimise their design for summertime conditions using building simulation tools.

Overheating in buildings can be defined using a variety of thermal comfort metrics. Each individual's response to raised internal air temperature levels will vary but a number of standard criteria for overheating have been developed. The CIBSE Guide A suggests that, for schools, overheating occurs when internal operative temperatures are greater than 28°C for more than 1% of annual occupied hours (CIBSE, 2006). The operative temperature (sometimes referred to as the dry resultant temperature) of a space is a weighted average of the air temperature and mean radiant temperature. The CIBSE overheating guidelines do not account for the absolute temperatures that occur, so a building with very high maximum internal air temperatures (for example above 32°C) may meet this criteria even though the thermal conditions become unacceptable. The potential for occupants to adapt to higher temperatures is also not considered, for example during extended spells of hot external air temperature. An adaptive approach to thermal comfort has been developed by Humphreys and Nicol and this method uses the concept of a comfort temperature, calculated from a running mean of external air temperatures (Humphreys and Nicol, 1998). During periods of hot weather, or in warmer climates, this approach assumes that occupants will be become accustomed to higher temperatures and thus thermal discomfort is reached only when internal air temperatures are above the calculated thermal comfort temperature.

The adaptive approach is not currently adopted in the design guidelines for new school buildings and instead a specific set of thermal comfort metrics have been developed as part of the design guide for ventilation and are given in Building Bulletin 101 (BB101, 2006). There are three separate thermal comfort criteria and, in order to ensure a thermally comfortable environment, two out of three of the criteria should be met. The period to be evaluated is May to September inclusive, for times when the school building is occupied. The three thermal comfort criteria in Building Bulletin 101 are:

1. "There should be no more than 120 hours when the air temperature in the classroom rises above 28°C
2. The average internal to external temperature difference should not exceed 5°C (i.e. the internal air temperature should be no more than 5°C above the external air temperature on average)
3. The internal air temperature when the space is occupied should not exceed 32°C." (BB101, 2006)

The Building Bulletin 101 thermal comfort criteria take into account both the amount of time for which high internal temperatures occur (Criteria 1) and the maximum internal temperatures which are reached in the space (Criteria 3), an improvement on the standard CIBSE overheating criteria. In addition Criteria 2 ensures that the change in temperature for occupants moving from outside the building to inside remains within tolerable limits. Building simulation tools can predict hourly results for internal air temperatures for a specific building design and external climatic conditions, and so are ideally placed to evaluate various design options against these three criteria.

An example of the use of building simulation for evaluating school building performance is given by Jenkins et al (2009). Here the authors use the building simulation tool ESP-r to evaluate overheating in two proposed school designs for current and future (2030s) climates. Using the CIBSE Guide A schools overheating criteria of occupied hours above 28°C, the results imply that overheating will increase under future warmer climates, but the effects can be mitigated through a switch to low power electrical equipment (which reduces internal heat gains), increased shading and, of interest in this work, increased ventilation rates. CIBSE have provided their own analysis of building overheating in future climates in the publication Technical Memorandum 36 (TM36) ‘Climate change and the indoor environment: impacts and adaptation’ (CIBSE, 2005). TM36 assesses several built-form types for overheating in future climates using the simulation tool Energy2 developed by Arup Research and Development. The results for an advanced naturally ventilated school building suggest that such designs can cope well with current climates but under future climates, in particular the upper storeys, may require additional mechanical cooling to maintain thermal comfort requirements.

This paper investigates the overheating potential for three generic school spaces: two different classroom spaces and a landlocked core teaching space. The aim is to deliver results which can be used broadly in the current design of school buildings and not to focus on the design of a particular individual building. Secondary schools are considered, with pupils aged 11 to 16, and cooling is provided using advanced natural ventilation strategies; single-sided and cross-ventilation with outlet stack for the classroom spaces and subterranean air ducts with lantern lights for the landlocked core space. Building simulation is carried out using the IES software package and the thermal comfort metrics as defined in CIBSE Guide A and BB101 are used to evaluate summertime performance and overheating. The focus of the research is the ability of natural ventilation to provide sufficient cooling for teaching spaces both under current climatic conditions and under future warmer climates, as provided by the recently published CIBSE future weather data files. Design options, including ventilation opening size and exposed thermal mass, are evaluated in order to optimise summertime performance and to provide recommendations for natural ventilation strategies in current and future school building design.

2 Simulated school building design

2.1 Building overview and geometry

The simulated school building is a two-storey building consisting of classrooms surrounding a central core teaching space (Figure 1). The simulation is a simplified building representation designed to be widely applicable to the schools sector and does not include fine details such as entrance halls, WCs and staff rooms. Three spaces are considered for detailed analysis: two south-facing classroom spaces on the first storey; and the central land-locked teaching space. South-facing, first floor classrooms were chosen as these spaces has a higher likelihood of overheating (due to high solar gains and reduced potential for stack ventilation). The first floor classrooms on the west side of the building are single-sided ventilated, and those on the east are cross-ventilated with outlet stacks. Classroom sizes are based on recent school building designs and details of the three modelled spaces are given in Table 1.

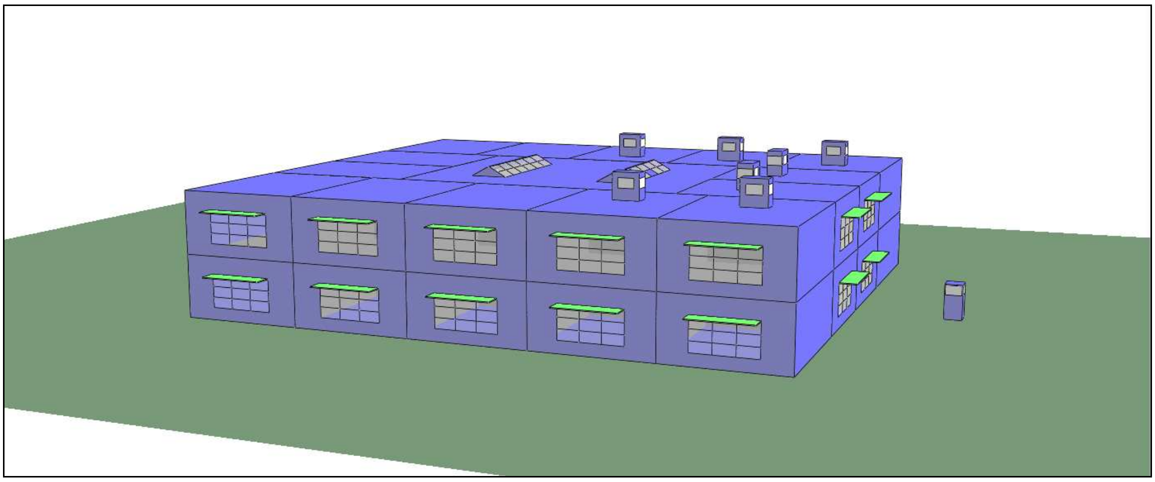

Figure 1: Model schematic of simulated school building

Table 1: Overview of simulated teaching spaces

	Classroom space (x2)	**Core teaching space**
Dimensions (m)	8.75 x 6.9 x 3.6	17.0 x 13.8 x 7.2
Maximum number of occupants	30	50
Area (m^2)	60.4	234.6
Volume (m^3)	217.4	1689.1
Level	First floor	Ground floor
Ventilation strategy	a) Single-sided ventilation b) Cross-ventilation with stacks	Subterranean ducts with lantern lights
Orientation	Window faces due south	-
Maximum internal sensible heat gains (W/m^2)	81.6	47.8
Occupancy times	09:00 – 15:30, Monday to Friday	09:00 – 15:30, Monday to Friday
Window/rooflight details	9 pane window (3 x 3) Each pane 1.2m x 0.6m	Lantern lights

2.2 Construction details

Construction materials for the simulated school buildings are given in Table 2. The materials are typical of recent school building design and represent current practice in meeting building regulations. Whilst the overall U-values for external components are reasonably low, the external walls are relatively lightweight in construction which will allow internal temperature swings and thus overheating. Some thermal mass in the form of cast concrete is included in the ground floor and internal ceiling/floor of the building, but the potential effects are offset through the use of insulation, carpet and ceiling tiles which will reduce the heat storage capacity.

Table 2: Main construction details for school building

Type	Material (outer layer to inner layer)	Overall U-value
External wall	Render (10mm), insulation (130mm), blockwork (100mm), plasterboard (13mm)	0.24
External window	Glass (6mm), cavity (12mm), glass (6mm)	1.97
Internal wall	Plasterboard (13mm), blockwork (72mm), plasterboard (13mm)	1.77
Ground floor	Clay (750mm), cast concrete (150mm), insulation (120mm), screed (50mm), carpet (10mm)	0.22
Internal ceiling / floor	Carpet (10mm), cast concrete (100mm), ceiling tiles (10mm)	1.62
Roof	Aluminium (10mm), insulation (100mm), cast concrete (100mm), ceiling tiles (10mm)	0.31

2.3 *Internal heat gains*

Internal heat gains are a key factor in overheating in buildings and, through minimising equipment power consumption, also provide one means of reducing overheating effects. These gains arise form the heat generated by people, lighting and electrical equipment in spaces. In schools these gains are typically high due to the high occupant density levels in classrooms and the increased use of IT in school lessons. For the simulations in this work the internal heat gains used are given in Table 3. The maximum heat gains for lighting ($12W/m^2$) and occupants (80W per person sensible gain and 60W per person latent gain) are based on the information provided in the CIBSE Guide A Table 6.2 for teaching spaces (CIBSE, 2006). However the number of occupants within the spaces is not based on the occupant density figure set out in the Guide but rather on recent school building designs. Similarly the Guide figure for equipment of $10W/m^2$ (15W per person) is considered too low for this study as recent experience suggests that many pupils will have individual access to laptops during lessons. In this work a maximum sensible gain of 60W per person was chosen for equipment gains which represents a much more challenging situation for controlling overheating. Radiant fractions for lighting and equipment internal gains were provided as default values by the building simulation tool.

Table 3: Internal heat gains for classroom space and core space

Space	Type	Description	Maximum sensible gain	Maximum latent gain	Radiant fraction	Total sensible gain for space (W)
Classroom space	Lighting	Fluorescent lighting	$12W/m^2$	-	0.45	725
	Equipment	IT equipment etc.	60W/person	-	0.22	1800
	People	30 occupants	80W/person	60W/person	-	2400
Core teaching space	Lighting	Fluorescent lighting	$12W/m^2$	-	0.45	2815
	Equipment	IT equipment etc.	60W/person	-	0.22	3000
	People	50 occupants	80W/person	60W/person	-	4000

2.4 *Occupancy*

School building have relatively short occupied hours compared to most other non-domestic buildings and occupancy will also be affected by the term times which the school operates under. For the simulated building it is assumed that the spaces are fully occupied between 09:00 to 15:30 for Monday to Friday of each week. During weekends and public holidays there are no occupants present in the building. In this work the performance of the building under future climates is assessed and it was decided to assume that the simulated building would be occupied throughout the year including school holidays. This accounts for any additional use of the building during holiday periods (either currently or in the future) and means that the thermal performance is evaluated irrespective of the term times of a particular school. This occupancy pattern is used to determine when occupants are present in the simulated teaching spaces and also when the lighting and IT equipment (as detailed in Table 3) is in use. Occupancy numbers of the two simulated teaching spaces are 30 people for the classroom space and 50 for the core teaching space.

2.5 Solar gains

Heat gains from solar radiation transmitted through glazing are a further key factor in overheating in buildings. Windows are used to fulfil both daylighting and ventilation requirements but will result in unwanted heat gains in the space, in particular during the summer months. For the simulated building in this study, these high solar gains in the summer period are offset through the use of a simple brise soleil shading device (Figure 1). This device is fitted above the classroom windows and extends for 1m out from the building. This blocks the direct solar radiation during the summer months when the sun's elevation is at its highest.

3 Natural ventilation strategies

3.1 Classroom space

Two ventilation strategies are considered for the simulated classroom spaces: single-sided ventilation and cross ventilation with an outlet stack. Air flow is generated by opening and closing individual panes of the classroom windows and these are controlled by motorised actuators. Single-sided ventilation makes use the heat gains in the space to draw cooler air in through openings at the bottom of the window and expel hotter air through an opening at the hot of the window. In the model both the bottom row and top row of window panes are set as controlled, openable windows. For cross-ventilation with an outlet stack, the buoyancy effect of the heated classroom air is used to draw in cool air from the window openings and to expel the hotter classroom air using an exhaust stack mounted on the roof of the school building. The exhaust stack is connected to the classroom space using a vertical air duct and here the bottom and top rows of window panes are also set as controlled, openable windows.

The window free areas and control strategies of the two ventilation strategies for the classroom space are summarised in Table 4. The window panes are hinged at the top and, at maximum opening, the bottom of the pane extends 0.155m from the window frame. Maximum free area (the area through which air can flow at the maximum window opening) are calculated for each row of three window panes as 0.65m^2, or 30% of the original closed window area. The window opening is automated and controlled using two control strategies. During occupied periods, window opening is proportional to the internal temperature of the space and the CO_2 level within the space. A ramp function is used based on a temperature range of 20°C to 24°C and a CO_2 range of 800ppm to 2000ppm. During unoccupied periods, night cooling is employed to purge the hot air from the space and replace it with cool night air. This is achieved by opening the windows to their maximum setting during unoccupied periods. For the outlet stack the free area is taken as 1m^2 and the stack is assumed to be constantly open.

Table 4: Classroom ventilation opening details

Space	Ventilation strategy	Window free area (m^2)	Window control strategy	Stack free area (m^2)	Stack control strategy
Classroom space	Single-sided ventilation	Top row: 0.65 Bottom row: 0.65	Ramp function based on internal temperature and CO_2 levels for occupied periods + night cooling	-	-
Classroom space	Cross-ventilation with outlet stack	Top row: 0.65 Bottom row: 0.65	Ramp function based on internal temperature and CO_2 levels for occupied periods + night cooling	1	Constantly open

3.2 Core teaching space

The core teaching space is ventilated using concrete ducts placed one meter below ground level. Air is drawn into the ducts via openings outside of the building and is cooled as it passes through the duct. An average summertime ground temperature of 19°C is assumed in this study, cooler than the majority of daytime summer air temperatures. The air enters the core teaching space in the centre of the building through floor vents and is exhausted from the space using openable lantern lights incorporated into the roof. In the simulated building two sets of subterranean air ducts are used and two sets of lantern lights. The free areas and control strategies of these openings are given in Table 5.

Table 5: Core teaching space ventilation opening details

Space	Ventilation strategy	Duct inlet free area (m^2)	Duct control strategy	Lantern light free area (m^2)	Lantern light control strategy
Core teaching space	Subterranean ducts with lantern lights	4 in total	Constantly open	10.4 in total (30% free area)	Ramp function based on internal temperature and CO_2 levels for occupied periods + night cooling

4 Location and climate scenarios

Three UK locations are simulated in this work: London, Nottingham and Edinburgh. Each location has a distinct climate and the CIBSE climate files are used to supply external weather conditions to the model (CIBSE, 2009). CIBSE produce two types of weather files for a location, both types generated from an amalgamation of climatic variables measured over the past decades. Test Reference Year (TRY) files represents an average year and are used for general simulations and calculating heating loads. Design Summer Year (DSY) files represent years with hot summers and are typically used to assess overheating in buildings. However in this work TRY data is used in the model simulations as this type of climate file is specified in the BB101 schools overheating criteria. Although the use of DSY climate data is recommended in CIBSE Guide A, the CIBSE overheating guidelines were also evaluated using TRY data in order to enable a more direct comparison between the CIBSE and BB101 overheating approaches. Similarly the time period analysis under investigation was chosen as May to September inclusive, to coincide with both the CIBSE guidelines and BB101 criteria.

The external air (dry-bulb) temperature from the TRY files for London, Nottingham and Edinburgh, for May to September inclusive, are described in Table 6. In all building design, and in particular naturally ventilated buildings, external air temperature is a key factor in potential overheating. London, as expected, has the highest external air temperatures due to being the most southerly location and being influenced heavily by the urban heat island effect. London is the only location which has external air temperatures greater than 28°C, which relates to BB101 Criteria 1 (a maximum of 120 hours of internal air temperatures greater than 28°C). London also has a maximum external air temperature of 31.8°C, only 0.2°C below the maximum permissible internal air temperature as given in BB101 Criteria 3 (a maximum internal air temperature of 32°C). Therefore meeting BB101 Criteria 3 for the London design appears almost unachievable, as internal air temperature will be higher than external air temperature due to the heat gains in the building (solar gains and internal heat gains). Only with active cooling (such as air-conditioning) or a very high thermal mass structure (to reduce the responsiveness of the building fabric) could this criteria be expected to be met.

Table 6: Statistics for external air (dry-bulb) temperature for 2005 CIBSE Test Reference Year data at three locations. These results are for the period May to September inclusive.

Location	Average air temperature (°C)	Maximum air temperature (°C)	Number of hours above 28°C	Average air temperature during occupied hours (°C)
London	16.2	31.8	28	18.4
Nottingham	14.3	27.5	0	16.7
Edinburgh	12.8	26.6	0	15.0

However the very high external air temperatures in London occur for relatively short periods. The maximum external air temperature for each day (daily maximum) is shown for the three locations in Figure 2. There are only two occasions when external air temperatures in London rise above 30°C, 26th June and 19th August. Aside from these two peaks, London maximum external air temperatures are similar in magnitude to those of Nottingham. If the London design does fail on the BB101 maximum temperature criteria (Criteria 3), it will be caused by these two brief hot weather periods.

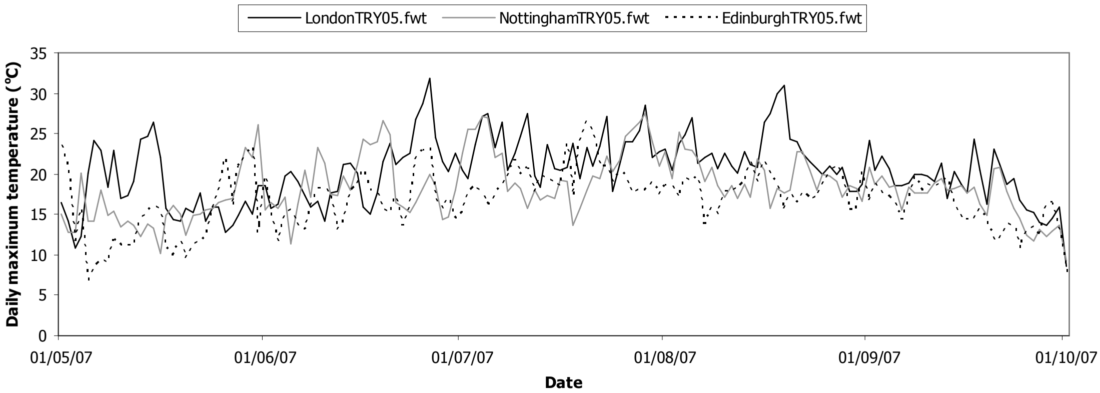

Figure 2: Daily maximum external air (dry-bulb) temperature for 2005 (current) CIBSE Test Reference Year data for London, Nottingham and Edinburgh

CIBSE have recently published future climate data for three future time periods (2020s, 2050s and 2080s) and, for each time period, four different future carbon dioxide emission scenarios (low, medium, medium-high and high). The future climate data is provided for both TRY and DSY files which means that each location has in total 26 weather files associated with it (including the files already available for the 2005 climate). In this work two future time periods, the 2020s and 2050s, are chosen for the simulations based on the expected lifetime of recently constructed school building (at least 50 years). A single future carbon dioxide emission scenario is chosen, the medium-high (MH) scenario, which gives the second highest rise in temperatures for 2020 and 2050 climate. Table 7 describes the predicted increases, compared to the 2005 climate data, for a number of external air temperature statistics for the 2020 and 2050 medium-high climate data. Increases in average external air temperatures range compared to the 2005 data range from 0.5°C (Edinburgh 2020) to 1.3°C (London 2050). For particular importance for meeting the BB101 criteria are the increase in maximum air temperature, the highest being a 1.7°C increase for London in 2050. Achieving BB101 Criteria 3 will become very difficult under such high maximum temperatures. The temperature increases are greatest for London which, given that the London 2005 climate data is already the warmest climate of the three locations, makes designing for London future climates even more challenging. Figure 3 shows, for the London climate data, the predicted increase in daily maximum temperatures for the three time periods. The overall pattern of the temperature values remain similar, but their magnitude is increased in the 2020 and 2050 predictions.

Table 7: Increase in external air (dry-bulb) temperature statistics for 2020 medium-high and 2050 medium-high CIBSE Test Reference Year data at three locations compared to 2005 data. These results are for the period May to September inclusive.

	Increase compared to 2005 TRY data for:							
	Average air temperature (°C)		**Maximum air temperature (°C)**		**Number of hours above 28°C**		**Average air temperature during occupied hours (°C)**	
Climate year	2020	2050	2020	2050	2020	2050	2020	2050
London	+0.7	+1.3	+1.0	+1.7	+14	+52	+0.8	+1.4
Nottingham	+0.6	+1.2	+0.9	+1.8	+2	+25	+0.7	+1.3
Edinburgh	+0.5	+1.0	+0.7	+1.3	0	+3	+0.5	+1.0

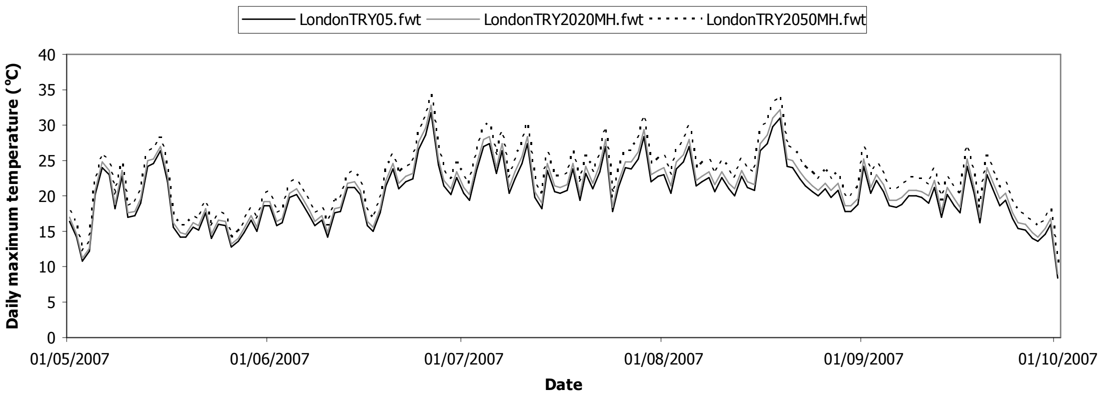

Figure 3: Daily maximum external air (dry-bulb) temperature for 2005, 2020 medium-high and 2050 medium-high CIBSE Test Reference Year data for London

5 Simulation results and discussion

5.1 Results for 2005 TRY climate data, 30% window free area and low thermal mass

Initial results were generated for a base-case scenario of 2005 TRY climate data, 30% free area for window openings and low (non-exposed) thermal mass. Using the London climate data the main heat gains and losses for the three teaching spaces, for the entire simulation period of May to September inclusive, are shown in Figure 4. Both classroom spaces have the same solar gains (0.75MWh) and internal heat gains (3.49MWh); this is as expected as the dimensions, location and internal conditions of these spaces are identical. Ventilation heat loss is only marginally higher for the cross-ventilated classroom (4.08MWh) than the single-sided classroom (3.48MWh), even though a separate outlet stack is utilised for the cross-ventilated classroom. However for reducing overheating an important factor is the time of day that ventilation heat loss is provided, as well as the total heat loss throughout the overall time period. As the overheating metrics (in this work the three BB101 criteria) consider only time when the building is occupied, ventilation heat losses that are greatest during occupied times will have the greatest effect at reducing overheating.

The core teaching space has much higher solar gains (7.44MWh) and internal heat gains (6.92MWh) than the classroom spaces. The high solar gains result from the two large lantern lights used in the core space which have no shading in place. Internal heat gains are higher than the classroom spaces due to the higher number of occupants and IT equipment in the core teaching space. The high solar and internal heat gains are balanced by higher heat losses from the ventilation strategy used in the core teaching space. The combination of subterranean air ducts and lantern lights provide a total ventilation heat loss of 18.85MWh.

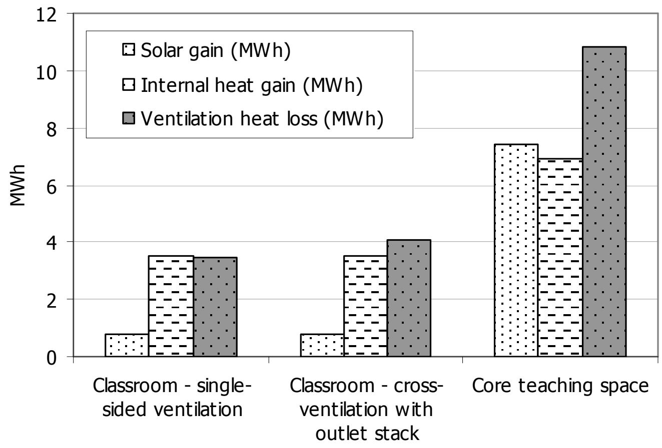

Figure 4: Total solar gain, internal heat gain and ventilation heat loss (May to September inclusive) for the three simulated teaching spaces using the base-case scenario (2005 climate data, 30% window opening free area and low thermal mass) and London location

Simulation results for internal air temperatures using the base-case scenario for the three UK locations are shown in Table 8. For each of the three teaching spaces, statistical results on the simulated internal temperature results are given to demonstrate their compliance with the CIBSE guidelines and three BB101 criteria. Instances where individual criteria are not met are marked as ‘FAIL’ in the table and, for BB101, two or three fails indicates that the teaching space will not pass the BB101 overheating standard. The threshold number of hours for the CIBSE guidelines was calculated as 17 hours, based on 1% of annual occupied hours for a Monday to Friday 09:00 to 15:30 schedule. The evaluation against the CIBSE guidelines is partially incomplete as the simulation results were only for May to September inclusive rather than a complete year, to enable comparison with the BB1010 results. However, as the majority of high outdoor temperatures occur during the summer months, the evaluation was assumed sufficiently robust for this investigation. Operative temperatures are, as expected, generally slightly lower than air temperatures, due to daytime mean radiant temperatures being lower than daytime air temperatures.

Clearly the classroom with single-sided ventilation is overheating, with the London location failing the CIBSE criteria and all three BB101 criteria and the Nottingham location failing the CIBSE criteria and two BB101 criteria. The single-sided and cross-ventilated classroom spaces in all locations have average internal and external temperature differences of greater than 5°C and therefore fail to meet BB101 Criteria 2. In the lower external air temperatures of more northerly climates, it is less likely that this criteria will be met. This can be seen in the average internal and external temperature difference for the cross-ventilated classroom in Edinburgh (6.2°C) compared to that of London (5.2°C). This is in contrast to the other overheating criteria where lower external air temperature means that the criteria are more likely to be met.

The cross-ventilation strategy clearly performs better than the single-sided ventilation strategy for the classroom space, due to the increased ventilation rates possible. Only the cross-ventilated classroom for London location fails to pass the BB101 overheating standard, with a fail on two of the BB101 criteria. The failure to meet the maximum air temperature criteria (BB101 criteria 3) was anticipated due to the maximum external air temperature in the London 2005 climate data of 31.8°C on 26th June. It is impractical to reduce the internal air temperature to below 32°C during these external climate conditions without employing active cooling or large amounts of thermal mass, and a more practical solution may be to attempt to reduce the average internal and external temperature difference by 0.2°C to meet BB101 Criteria 2. The Nottingham cross-ventilated classroom, although it passes BB101 with a single criteria failure, does not meet the CIBSE guidelines as operative temperatures are above 28°C for 31 hours. This is the only case where the CIBSE guidelines and BB101 overheating standard have a conflicting result in their evaluation of overheating.

Table 8: Simulated internal air temperature results for occupied periods using the base-case scenario (2005 climate data, 30% window opening free area and low thermal mass). Results which do not meet the CIBSE or BB101 criteria are marked as 'FAIL'.

Space	Location	Number of hours of operative temperature above 28°C [1]	Number of hours of air temperature above 28°C [2]	Average internal and external air temperature difference (°C) [3]	Maximum air temperature (°C) [4]
Classroom space with single-sided ventilation	London	135 (FAIL)	172 (FAIL)	7.4 (FAIL)	34.9 (FAIL)
	Nottingham	79 (FAIL)	100	7.6 (FAIL)	33.3 (FAIL)
	Edinburgh	7	12	7.7 (FAIL)	31.5
Classroom space with cross-ventilation and outlet stack	London	41 (FAIL)	46	5.2 (FAIL)	34.0 (FAIL)
	Nottingham	31 (FAIL)	40	5.8 (FAIL)	31.2
	Edinburgh	3	4	6.2 (FAIL)	30.6
Core teaching space	London	15	15	3.5	31.8
	Nottingham	5	5	4.0	29.0
	Edinburgh	0	0	4.3	26.6

[1] CIBSE guidelines: There should be less than 1% annual occupied hours over operative temperature of 28°C. For the building under study 1% of annual occupied hours is defined as 17 hours.

[2] BB101 Criteria 1: There should be no more than 120 hours when the air temperature in the classroom rises above 28°C (for occupied hours)

[3] BB101 Criteria 2: Average internal to external temperature difference should not exceed 5°C (for occupied hours)

[4] BB101 Criteria 3: The internal air temperature when the space is occupied should not exceed 32°C (for occupied hours)

The core teaching space meets the three BB101 criteria for all locations. The lower internal heat gains per unit area compared to the classroom spaces, combined with high ventilation rates, provide sufficient cooling to keep internal air temperatures low. Ventilation heat loss is improved by the incoming air coming into contact with the walls of the subterranean air ducts, which remain cool due their contact with the soil. This technique is so effective that even the maximum internal air temperature of the London location is kept below 32°C. There is only a single instance when a space has internal air temperatures greater than 28°C for more than 120 hours, the single-sided ventilated classroom space in the London location. Interestingly, although this overheating metric is the standard one used for overheating criteria (either using hours above 25°C or 28°C), many of the cases described in Table 8 pass this overheating criteria but fail significantly on the others.

These results demonstrate that external air temperatures has a significant influence on the potential of the spaces to overheat, and locations with hotter climates (such as London) will be more prone to overheating. In addition this may become more pronounced in the hotter climatic conditions expected in future years. To investigate this further, the relationships between external and internal air temperatures is explored for a single case, the single-sided ventilated classroom, using the London 2005 TRY climate data in Figure 5. The daily maximum external air temperature (the maximum recorded air temperature for each 24 hour period) is plotted against the daily maximum internal air temperature (for comparison with BB101 Criteria 3) and the daily average internal and external temperature difference (for comparison with BB101 Criteria 2). There is a clear positive linear relationship between maximum external and internal air temperatures. A clear negative linear relationship exists between maximum external air temperature and the average internal to external temperature difference. This suggest that in future warmer climates it might be expected that the space will have a higher maximum internal air temperature and a lower average internal and external temperature difference. Thus the space would be more likely to fail BB101 Criteria 3 and to pass BB101 criteria 2.

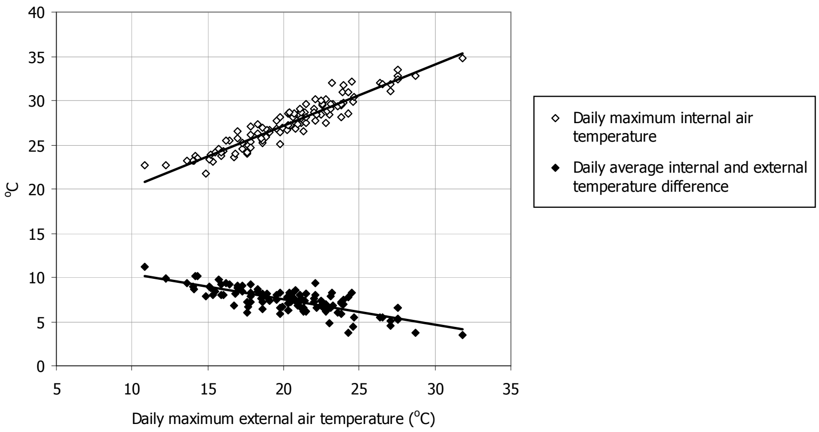

Figure 5: Simulated internal air temperature results plotted against daily maximum external air temperature using the base-case scenario (2005 climate data, 30% window opening free area and low thermal mass) for the single-sided ventilated classroom in London

5.2 Results for variable window free area and thermal mass

The potential to reduce overheating is investigated through varying two parameters: the free area of window openings (the proportion of the window area which can be opened for ventilation); and level of exposed thermal mass. These are investigated for the cross-ventilated classroom space in London and the results are given in Table 9. In the base-case scenario window free area was set at 30%; here the free area is varied from 10% to 50%. A low thermal mass case was considered in the base-case and here the effectiveness of the thermal mass to moderate temperature swings is increased by removing the ceiling tiles from the roof construction and exposing the cast concrete above (see Table 2 for original construction details). This is defined as the 'high thermal mass' case.

All of the overheating indicators are reduced through increasing the window opening free area but the space continues to fail the CIBSE overheating guidelines. However, although this space initially failed two of the three BB101 criteria in the base-case scenario, increasing the window opening free area to 40% or 50% results in the space now failing only BB101 Criteria 3. For a window opening free area of 40% the average internal and external temperature difference falls to 4.9°C, which just passes BB101 Criteria 2. Increasing the exposed thermal mass results in a similar decrease in average internal and external temperature difference to 4.8°C, and this case also meets BB101 Criteria 2. The high exposed thermal mass case does not sufficiently reduce the number of hours with operative temperatures greater than 28°C so the modified space still fails the CIBSE guidelines. Even at a window opening free area of 50%, or in the high thermal mass case, the maximum internal air temperature remains high (both at 33.3°C). It appears unlikely that either of these factors could easily reduce this to below 32°C and thus meet BB101 Criteria 3. This illustrates that careful choice of design parameters can be effective in reducing overheating for naturally-ventilated buildings and that different design options are available to meet overheating criteria. It is also clear that the BB101 overheating standard is achieved with relatively minor modifications to this space, whereas the CIBSE guidelines are not met using the same modifications.

Table 9: Simulated internal air temperature results for occupied periods using a modified base-case scenario (2005 climate data, variable window opening free area and variable thermal mass) for the cross-ventilated classroom space in London. Results which do not meet the BB101 criteria are marked as 'FAIL'.

Space	Thermal mass	Window opening free area	Number of hours of operative temperature above 28°C [1]	Number of hours of air temperature above 28°C [2]	Average internal and external air temperature difference (°C) [3]	Maximum air temperature (°C) [4]
Classroom space with cross-ventilation and outlet stack, London location	Low thermal mass	10%	142 (FAIL)	154 (FAIL)	7.2 (FAIL)	35.9 (FAIL)
		20%	66 (FAIL)	77	5.8 (FAIL)	34.7 (FAIL)
		30%	41 (FAIL)	46	5.2 (FAIL)	34.0 (FAIL)
		40%	35 (FAIL)	36	4.9	33.6 (FAIL)
		50%	27 (FAIL)	33	4.6	33.3 (FAIL)
	Low thermal mass	30%	41 (FAIL)	46	5.2 (FAIL)	34.0 (FAIL)
	High thermal mass		29 (FAIL)	36	4.8	33.3 (FAIL)

[1] CIBSE guidelines: There should be less than 1% annual occupied hours over operative temperature of 28°C. For the building under study 1% of annual occupied hours is defined as 17 hours.

[2] BB101 Criteria 1: There should be no more than 120 hours when the air temperature in the classroom rises above 28°C (for occupied hours)

[3] BB101 Criteria 2: Average internal to external temperature difference should not exceed 5°C (for occupied hours)

[4] BB101 Criteria 3: The internal air temperature when the space is occupied should not exceed 32°C (for occupied hours)

5.3 *Results for 2020 and 2050 climate*

Simulation results using the 2020 medium-high and 2050 medium-high CIBSE TRY climate data are shown in Table 10 for the three teaching spaces with 30% window opening free area and low (unexposed) thermal mass. Here only the statistics directly relevant to BB101 are shown. The number of hours of air temperature greater than 28°C (used for BB101 Criteria 1) can be taken as an approximate indicator of the same statistic for operative temperature (used in the CIBSE guidelines), as observed in Table 8. The results show that the classroom with single-sided ventilation cannot cope with the increased external air temperatures in the 2020 and 2050 climates. In all three locations, the single-sided ventilated classroom fails on two out of the three BB101 criteria and for London and Nottingham the space fails all three criteria. The classroom with cross-ventilation does not perform much better with only the Edinburgh classroom in 2020 meeting the BB101 standard (a single failure of 6.1°C for the average internal and external temperature difference). Notably the London cross-ventilated classroom passes BB101 Criteria 2 in the 2050 climate (with average internal and external temperature difference of 4.9°C); however under these conditions it fails BB101 Criteria 1 (with 153 hours above 28°C). This is the effect of the average internal and external temperature difference decreasing with increasing external temperatures, making it more likely for a space to pass BB101 Criteria 2 in future, warmer climates. Interestingly there may be a point between 2020 and 2050 where the London cross-ventilated classroom actually passes two of the three BB101 criteria, even though it fails two of the criteria under the 2005 climate. The core teaching space passes the BB101 standard for all locations and climates, although the maximum internal air temperatures do rise above 32°C for the London space in the 2020 and 2050 climates. For all teaching spaces, the number of hours with internal air temperatures greater than 28°C proves to be the least problematic, in terms of meeting the BB101 criteria, compared to the other two overheating metrics. Given the rate of failures for the average internal and external temperature difference and the maximum air temperature, this questions whether these metrics are suitable for evaluating overheating in future climates or if revised, possibly adaptive, overheating criteria are required.

Table 10: Simulated internal air temperature results for occupied periods using 2005, 2020 and 2050 climate data, 30% window opening free area and low thermal mass. Results which do not meet the BB101 criteria are marked as 'FAIL'.

Space	Location	Number of hours of air temperature above 28°C [1]			Average internal and external air temperature difference (°C) [2]			Maximum air temperature (°C) [3]		
Climate file year		2005	2020	2050	2005	2020	2050	2005	2020	2050
Classroom space with single-sided ventilation	London	172 (FAIL)	244 (FAIL)	369 (FAIL)	7.4 (FAIL)	7.3 (FAIL)	7.1 (FAIL)	34.9 (FAIL)	35.7 (FAIL)	37.3 (FAIL)
	Nottingham	100	127 (FAIL)	179 (FAIL)	7.6 (FAIL)	7.4 (FAIL)	7.2 (FAIL)	33.3 (FAIL)	34.1 (FAIL)	35.6 (FAIL)
	Edinburgh	12	22	52	7.7 (FAIL)	7.6 (FAIL)	7.3 (FAIL)	31.5	32.1 (FAIL)	33.2 (FAIL)
Classroom space with cross-ventilation and outlet stack	London	46	79	153 (FAIL)	5.2 (FAIL)	5.1 (FAIL)	4.9	34.0 (FAIL)	34.9 (FAIL)	36.5 (FAIL)
	Nottingham	40	65	100	5.8 (FAIL)	5.6 (FAIL)	5.3 (FAIL)	31.2	32.0 (FAIL)	33.6 (FAIL)
	Edinburgh	4	5	14	6.2 (FAIL)	6.1 (FAIL)	5.9 (FAIL)	30.6	31.3	32.4 (FAIL)
Core teaching space	London	15	22	42	3.5	3.2	2.8	31.8	32.7 (FAIL)	34.3 (FAIL)
	Nottingham	5	9	28	4.0	3.8	3.4	29.0	29.9	31.4
	Edinburgh	0	0	2	4.3	4.2	3.8	26.6	27.2	28.2

[1] BB101 Criteria 1: There should be no more than 120 hours when the air temperature in the classroom rises above 28°C (for occupied hours)

[2] BB101 Criteria 2: Average internal to external temperature difference should not exceed 5°C (for occupied hours)

[3] BB101 Criteria 3: The internal air temperature when the space is occupied should not exceed 32°C (for occupied hours)

Of interest is the ability to mitigate the increased overheating risk in future climates through altering the design of natural ventilation strategies. Here this is tested by increasing the window opening free area for the cross-ventilated classroom situated in London. For the three climate years (2005, 2020 and 2050) the effect on internal air temperatures for three window opening free area (30%, 40% and 50%) are shown in Figure 6. For all three overheating metrics, the reductions due to increasing window opening free area are similar or greater under the 2020 and 2050 climates. A window opening free area of 40% reduces the average internal and external temperature difference to 4.7°C in the 2020 climate, allowing this space to meet BB101 Criteria 2 and to pass two out of three of the BB101 criteria overall. Increasing the window opening free area to 50% results in the number of hours with temperature greater than 28°C falling below 120 hours, so in this case the space passes two out of the three BB101 criteria. However, under the high external air temperatures which occur in the London climate, the maximum internal air temperature remain above 32°C for all window opening free area and climate year combinations. These results clearly demonstrate that design options exist to reduce overheating in natural ventilated building even under the hotter climates expected in future years.

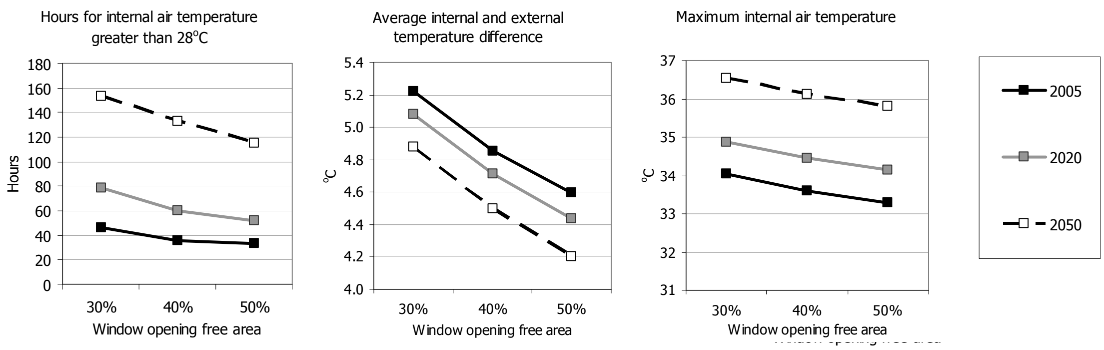

Figure 6: Simulated internal air temperature results against window free area opening for the cross-ventilated classroom in London using 2005, 2020 and 2050 climate data.

6 Conclusions

This work describes the use of building simulation tools to predict the internal air temperatures of a generic school building which utilises natural ventilation strategies to minimise summertime overheating. Overheating is evaluated using the criteria set out in CIBSE Guide A and Building Bulletin 101 (the current guidelines in place for new school buildings in the UK). Three types of naturally ventilated teaching spaces are tested: a classroom with single-sided ventilation; a classroom with cross-ventilation and an outlet stack; and a core teaching space ventilated by subterranean air ducts and lantern lights. The teaching spaces have a high density of occupants and IT equipment, making it challenging to avoid overheating. Key conclusions from this work are:

- Distinct differences arose in assessing the potential overheating of the simulated teaching spaces depending on which criteria were used. The CIBSE overheating guidelines tended to be harder to meet and, in these cases, the criteria could not easily be met by making minor modifications such as increasing the window opening free areas. The BB101 overheating standard requires a space to meet two out of three overheating criteria and this flexibility meant that the teaching spaces were able to meet this standard more often than the CIBSE guidelines. In addition when using BB101 it was more likely that design modifications could be tailored to ensure the space would pass the overheating criteria.

- The more advanced natural ventilation strategies, the cross-ventilation with outlet stack and subterranean air ducts with lantern lights, provide sufficient cooling to meet the BB101 overheating standard in the majority of cases for the current climate. Under future climates, the cross-ventilation strategy fails to meet BB101 unless modifications are made (in this work by increasing the window opening free area). Single-sided ventilation proves inadequate under current and future climates for all three locations (except for the Edinburgh 2005 scenario).

- BB101 Criteria 2, which states that the average internal and external temperature difference should be no more than 5°C, is more likely to be passed by the naturally-ventilated spaces under warmer temperatures, such as the London climate or 2020 and

2050 climates. This result appears counter-intuitive for an overheating metric as higher internal air temperatures will almost certainly be present under warmer climates.

- The high maximum external air temperatures in the London current and future climates (such as a 31.8°C maximum for London 2005) means that meeting BB101 Criteria 3, a maximum internal air temperature of no greater than 32°C, becomes almost unachievable using naturally-ventilation design. However in Edinburgh, and in some cases Nottingham, BB101 Criteria 3 is more easily achieved which suggests that design options which may fail in some locations will be better suited to others.

- There is potential to optimise the natural ventilation strategies to reduce overheating in the teaching spaces. In this work increasing window opening free area and increasing the exposed thermal mass are both shown to enable a previously failing space to pass the BB101 overheating standard. Under the 2020 and 2050 warmer climates, by increasing window opening free area it is still possible for the London cross-ventilated classroom to meet two of the three BB101 criteria.

References

BB101, 2006. *Building Bulletin 101, Ventilation of School Buildings*, Version 1.4, ISBN 011-2711642

CIBSE, 2005. *Climate change and the indoor environment: impacts and adaptation*, Technical Memorandum 36, Chartered Institute of Building Services Engineers, London

CIBSE, 2006. *Environmental Design, CIBSE Guide A*, Chartered Institute of Building Services Engineers, London

CIBSE, 2009. *Use of climate change scenarios for building simulation: the COBSE future weather years*, Technical Memorandum 48, Chartered Institute of Building Services Engineers, London

Humphreys MA and Nicol JF, 1998. *Understanding the adaptive approach to thermal comfort*, ASHRAE Transactions, 104(Part 1B), 991-1004.

Jenkins DP, Peacock AD and Banfill PFG, 2009. *Will future low-carbon schools in the UK have an overheating problem*, Building and Environment 44 (2009) 490–501