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Simulation of a Naturally Ventilated Building at Different Locations

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ABSTRACT

This paper examines the proposed new method in the U.K.—linked to emerging European standards—for assessing by simulation whether a building will be comfortable with only natural ventilation or will need full air conditioning or mixed-mode air conditioning. The selection criteria are based on the ranking of 20 years' summers and the selection of the middle one in the upper quartile for the simulation. Criteria are then set for the number of hours the inside temperature is over 25°C (77°F) in the occupied time.

Selected summers for two sites in the U.K. are used and a simulation program is used with a building to compare results. Initial indications are that location significantly affects building performance and that it is far easier to design for natural ventilation in the north of the U.K. than in London and further south in Europe. It is suggested that experience be gained from the Europeans before such criteria are considered in North America and that an adaptive criteria may be a better solution, especially if energy and comfort are combined.

INTRODUCTION

New HVAC systems such as displacement ventilation, chilled ceilings, and mixed-mode air conditioning can save a considerable amount of energy and CO_2 and so reduce the atmospheric pollution associated with fossil fuels and greenhouse gases. In these buildings, there is usually the option for the occupants to use natural ventilation by opening windows. However, in some buildings, natural ventilation is the key element for ventilation, and summer cooling and detailed strategies including summer night ventilation are employed.

Most buildings employing natural ventilation are shallow plan buildings, as natural ventilation from an open window is generally considered to be effective in ventilating up to 6 m (19.7 ft) into a room. For a shallow plan building (shallow plan being effectively defined by the limits of natural ventilation), this means the width is up to 15 m (49.2 ft), 6 m (19.7 ft) from windows on each side of the building and a 3 m (9.8 ft) access corridor in between. The heuristic rules for natural ventilation are (CIBSE 1997):

- Single-sided single opening effective to a depth of 2 times the floor-to-ceiling height
- Single-sided, double opening effective to a depth of 2.5 times the floor-to-ceiling height
- Cross-ventilation (window openings on different, generally opposite, walls), effective up to 5 times the floor-to-ceiling height

To use natural ventilation in deeper plan buildings, a designer can utilize:

- Atria
- Streets
- Towers
- Funnels or chimneys
- Windcatchers

Where natural ventilation is the sole means of summer cooling, good control and careful design to reduce the heat gains, especially from solar radiation, are important. This is because natural ventilation can only provide about 20 Wm^{-2} (6.3 Btu ft^{-2} h^{-1}) of cooling. With a very high ventilation rate and an inside/outside temperature difference of 6 K (10.8°F),

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this can at best rise to 50 Wm^{-2} (15.9 Btu ft^{-2} h^{-1}), although this is an optimistic value (Brister 1994), especially as the ventilation is variable due to the wind and the variable inside/outside temperature difference for stack ventilation.

DIURNAL TEMPERATURE VARIATION

In naturally ventilated buildings, thermal fabric storage is a key element for absorbing internal gains during the day (especially high summer solar radiation that gets through the shading devices). At night during these hot summer periods, the fabric can be cooled with extra ventilation due to windows being automatically opened or occupants leaving them open. Security reasons often mean that only certain windows can be left open. The ventilation is stack driven (hot air rising, displaced by cooler entering air) and wind driven. The stack ventilation is enhanced by the diurnal variation in the dry-bulb temperature, with the nighttime dry-bulb temperature being much lower than the peak daytime and most probably lower than the fabric temperature. In northern Europe this diurnal variation can be about 12 K (21.6°F) (CIBSE 2000). For the U.K., a summer daytime peak of about 28°C (82.4°F) can be followed by a nighttime minimum of about 16°C (60.8°F) when the sky is cloud-free. However, natural ventilation cannot help comfort conditions when there are high levels of outside humidity.

NEAR-EXTREME WEATHER DATA FOR SIMULATION

Simulation, now that it is establishing itself as an accurate method, is better for natural ventilation design than short period manual design, as the thermal storage of the building fabric is an important aspect as well as the possibility of night ventilation. Fabric storage can have a time lag of hours, if not days, and so an extensive period of weather data is required.

U.K. NEAR-EXTREME DESIGN SUMMER PERIODS

The U.K. has a temperate and very variable climate, with large variations from year to year for each season. Southern areas experience significantly warmer summers than the rest of the country. Most offices in the U.K. are not mechanically cooled and are generally reasonably comfortable over the summer. However, in hot summer weather (when daytime temperatures exceed about 24°C [75.2°F]) many buildings become uncomfortably warm. Such conditions are common in the South and Midlands but are relatively infrequent further north.

In order to design low-energy naturally ventilated or mixed-mode buildings with simulation, it is necessary to have a comfort criterion, which will prevent excessive overheating during a "hot" summer. Using Dutch and Swiss standards (Cohen et al. 1993) as a starting point, an overheating criterion for dynamic simulation studies was developed for the Building Research Establishment's Office of the Future, a low-energy office building on the BRE site near Watford, which is now complete. The criterion is defined as follows:

"During the occupied hours of the year the dry resultant temperature should not exceed 25°C (77°F) for more than 5% of the occupied year and should not exceed 28°C (82.4°F) for more than 1% of the occupied year."

The occupied year was defined as being from 9 a.m. to 5 p.m. Monday to Friday for each week of the year, which corresponds to 2080 working hours (5% being 104 hours, 1% being 21 hours). The criterion is used in simulation with an appropriate weather year. The following procedure was chosen to select a (real) weather year:

- Obtain the last 20 years' climatic data for the site nearest the building under investigation.
- For each year, determine the daily mean temperature for June, July, and August.
- For each year, determine the average of these daily means.
- Rank the years in ascending order according to the average daily means.
- The sample year is the mid-year of the upper quartile.
- The 12 months of this year form the sample year; the climatic data are combined with radiative data to form a complete weather year.

The essential point of this selection process is that it is a simple method, relying on only daily average summer dry-bulb temperatures for all years except that year finally selected, so paper records, which are easily obtainable, could be used for earlier years if necessary.

No consideration seems to have been given to solar radiation or wind speed, both factors that will affect natural ventilation and comfort. It is also assumed that the humidity is at an acceptable level with natural ventilation, as is the case in a number of European locations. As discussed later, this summer-selection criterion was investigated with simulation and consequently changed slightly, although inclusion of solar and wind was not incorporated as the criterion was already being used and more feedback from practitioners is required before radical changes are made. The dry resultant temperature, t_{res}, is a measure of comfort used in the U.K. by CIBSE, given by

$$t_{res} = \frac{1}{2}t_{ai} + \frac{1}{2}t_{mst}$$

where t_{ai} is the inside air temperature and t_{mst} is the mean surface temperature.

It accounts for the convective and radiative heat transfer but does not consider humidity, which is invariably within the comfort band for most European countries, or the occupant's metabolic rate or clothing level.

A different number of years could, of course, be used, but in order to have a year in the middle of the upper quartile it is necessary to have an odd number in each quartile. This means the number of years has to be divisible by 4 but not by 8; the

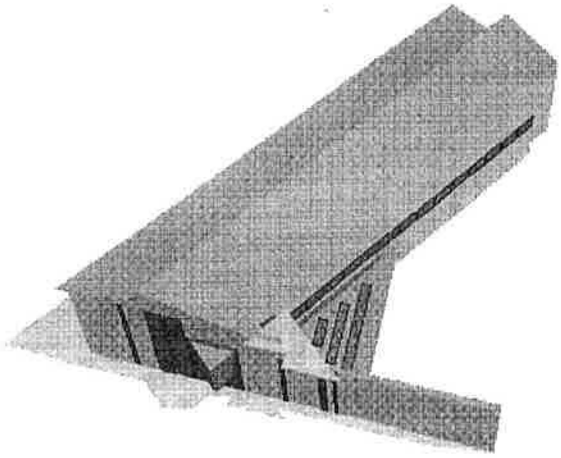

Figure 1 *The clinic building with solar shading viewed from the northwest.*

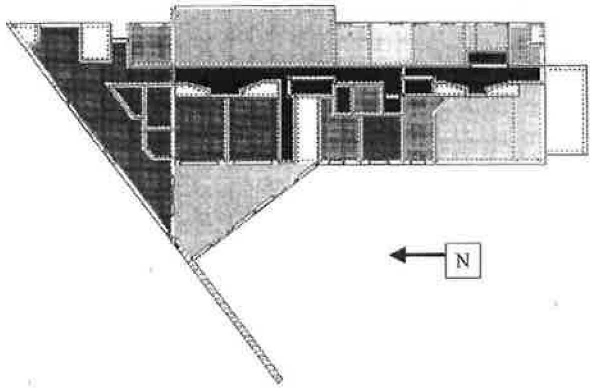

Figure 2 *Plan of clinic building, ground floor zones.*

nearest alternatives to 20 years would, therefore, be 12 (statistically rather short) or 28.

A research project was carried out by Cooper (1998), using a U.K. finite difference simulation program, to compare the summertime comfort and energy use of naturally ventilated and mixed-mode (limited cooling) U.K. office buildings. A large number of simulations were run to investigate the effects of different design factors on four facades. This adopted the BRECSU comfort criterion and applied the selection process for a "hot" summer to the weather data available. Initially this was from Gatwick Airport south of London, 1976-1994. Over this period, 1983 was the selected year. However, during the project, data for 1995 (a very hot summer in the U.K.) became available, which changed the selected year to 1989. Radiation data, which were not available for Gatwick, were taken from Bracknell to the west of London and added to the synoptic data for simulations.

This work used the percentage of working hours above 25°C (77°F), given the symbol Ω, as the main output from simulations of many different designs (Wright et al. 1999). It was found that if a building passed the 5% > 25°C (77°F) criterion, it invariably passed the 1% > 28°C (82.4°F) criterion, making the latter redundant. One way of testing the robustness of the former criterion was to see how Ω varied with different threshold temperatures. There was an almost linear response, which was similar on all four facades. For example, for a design without passive features to limit heat gain and 60% glazing, the value of Ω on the west facade varied from 34 (percent of hours) for a threshold of 23°C (73.4°F) to 20 (percent of hours) for a threshold of 26°C (78.8°F). Clearly, this building failed; Ω at 25°C (77°F) was about 25 (percent of hours).

Another test was to investigate the effect of varying the percentage of hours at a given threshold temperature. The proportions of designs "passing" the 25°C (77°F) test for varying percentages were plotted for each facade. This is a less scientific test since the proportion of designs passing is not a physical measurement and depends on design options, but with a very large number of designs based on incremental changes to glazing, air change rates, etc., it is qualitatively useful. Again, the response was fairly linear. These results suggest that this type of criterion will be a reliable test that can be extrapolated without sudden changes in behavior for different values.

Previous studies have often used peak internal temperature over the year as a measure of the ability of a design to maintain summer comfort. This takes no account of the length of time that the building is uncomfortable, usually just depends on the hottest few days of weather, and can be affected by when weekends occur. In fact, Cooper found that one design could have a higher peak temperature but a lower Ω than another design.

The new CIBSE weather guide (CIBSE 2000) adopted a similar criterion but extended the months used to calculate average summer temperature to April to September. It was felt that this was useful because overheating had often been observed by Cooper outside the months of June, July, and August. Lower solar angles can cause high solar gains in spring and autumn although outside temperatures tend to be lower.

Figures 1 and 2 show the years 1976-1995 ranked on average summer temperature (April-September) for two U.K. sites. These are Heathrow Airport (London), and Ringway Airport (Manchester) representing the southern and northern regions of England. The graphs show that while the average summer temperature falls the further north the site is, from a maximum over 16°C (60.8°F) at Heathrow to just over 14.4°C (57.9°F) at Ringway, the ranges are very similar.

Rankings vary considerably between sites, but 1976 and 1995 are the two hottest. Significantly, the third hottest year, which is the one selected under the BRECSU criterion with 20 years of data, is different for the two sites. While the differences between the ranked years for Heathrow are all small, there is a significant step change for the other site from

TABLE 1
Climatic Design Information from *ASHRAE Fundamentals* (ASHRAE 1997)

Latitude	City	99% Exceedence Dry-Bulb Temperature °C (°F)	Annual Extreme Daily Maximum Dry-Bulb Temperature °C (°F)	Annual Extreme Daily Minimum Dry-Bulb Temperature °C (°F)	1% Exceedence Dry-Bulb Temperature °C (°F)	1% Exceedence Mean Wet-Bulb Temperature °C (°F)
53.35N	Manchester (U.K.)	–2.7 (27.1)	28.3 (82.9)	–6.4 (20.5)	23.1 (73.6)	16.4 (61.5)
51.48N	London (U.K.)	–2.3 (27.9)	30.5 (86.9)	–6.3 (20.7)	25.7 (78.3)	17.7 (63.9)
47.45N	Seattle	–2.2 (28)	33.4 (92.1)	–7.4 (18.7)	27 (80.6)	18 (64.4)
49.18N	Vancouver	–5 (23)	28 (82.4)	–10 (14)	23.2 (73.8)	17.6 (63.7)

the coldest to the next coldest and from the third hottest to the second and first ranked years. Although these step changes are almost certainly statistical artefacts rather than climatic features of the sites, they do indicate the sensitivity of datasets to the set of years chosen and, hence, the values of Ω. Therefore, it is necessary to compare values of Ω only in relation to a given site and weather dataset for "hot summer" selection.

It is worth noting that a WYEC or Test Reference Year would only give an average year suitable for average energy calculations. However, for design conditions a year nearer to the hot extreme is required. The third ranked summer will only be exceeded by two summers in 20 years, a probability of occurrence of 10%. This seems a low value compared to the hourly annual exceedence in the current *ASHRAE Fundamentals* (ASHRAE 1997) of 1%, 2%, and 0.4%, but the greatest exceedence for the 20 summers is 5%, i.e., the occurrence of the hottest summer.

BUILDING SIMULATED

The building simulated is a three-floor clinic with offices, patient lounges, consulting rooms, and seminar rooms (Figures 1 and 2). A particular room has been used to illustrate in detail the overall performance of the naturally ventilated spaces in the building. The sample office is on the east side of the building with a single opening window. The external wall has a very good U-factor; internal walls are plastered blockwork and the ceiling is exposed. Occupation is standard 9 a.m. to 5 p.m. with typical heat gains from PCs, lights, and occupants.

SIMULATION RESULTS

The simulation program used here is a response factor or transfer function program used extensively in the U.K. It is different to the program from which the results above were derived, which was a U.K. finite difference program. The starting specification was clear double glazing and windows that opened only during occupation to provide about 5 air changes per hour of outside air.

Two U.K. locations have been used in the simulations, London and Manchester, and the same building examined in

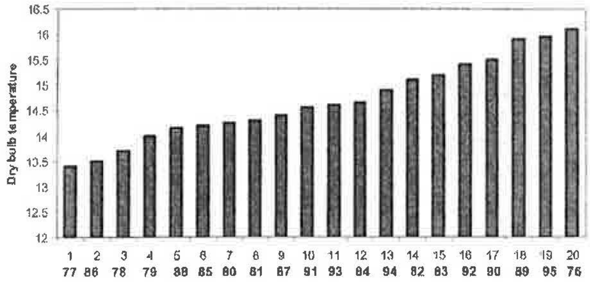

Figure 3 *London ranked summer average dry-bulb temperature.*

each location. Examining the dry- and wet-bulb data in the *ASHRAE Fundamentals*, chapter 26, "Climatic Design Information," suggests that Seattle and Vancouver have similar design temperatures, as Table 1 shows.

London Location

Two sets of simulations have been run. The first is based on the design summer, 1989 (see Figure 3), and also a cooler summer for comparison, chosen here to be 1985, which is the sixth coldest summer from Figure 3. Table 2 shows that the design 1989 summer external temperature had 283 hours over 25°C (77°F), whereas the cooler 1985 had only 114 hours exceeding 25°C (77°F).

Simulation showed that the basic design over the design 1989 summer produced 393 hours over 25°C (77°F), the internal resultant temperature, 110 hours over the outside temperature, and 289 hours over the 5% limit. By allowing the windows to be open for both day and night ventilation, the number of hours over 25°C (77°F) dropped to 312. Putting in external solar shading reduced the hours substantially to 222 hours and changing the glass to an antisun version reduced it further to 164 hours. But this is still above the 104-hour limit. Effectively this building has to be air conditioned, either conventionally or by a mixed-mode system. In a cooler summer, such as 1985, it just passes the limit without resorting to antisun glass. Design solutions are relatively easy to see for the cooler 1985 year, where adding night ventilation and solar shading meets the standard with 104 hours over 25°C (77°F).

TABLE 2
Simulation Results for Clinic Building in London

Room Specification East Side Office	Number of hours > 25°C (77°F) 1989 design year	Number of hours > 25°C (77°F) 1985 typical year
External Weather Data		
London design summer 1989 and typical year 1985	283	114
Clear double glazing, single-sided vent during occupation only (~5 ach), no shade	393	180
Clear double glazing, single sided vent day and night (~5 ach), no shade	312	133
Clear double glazing, single-sided vent and night (~5 ach), external solar shade	222	104
Anti-sun double glazing, single-sided vent day and night (~5 ach), external solar shade	184	76
Anti-sun double glazing, single-sided vent day and night (~10 ach), external solar shade	164	63

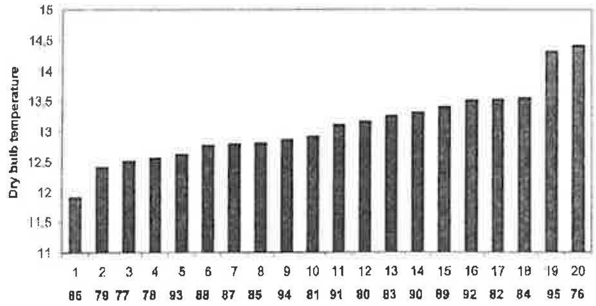

Figure 4 *Manchester ranked summer average dry-bulb temperature.*

TABLE 3
Simulation Results for Clinic Building in Manchester

Room Specification East Side Office	Number of hours > 25°C (77°F)
External Weather Data	
Manchester design summer 1984	62
Clear double glazing, single-sided vent during occupation only (~5 ach), no external shade	255
Clear double glazing, single-sided vent during occupation only (~5 ach), external solar shade	188
Clear double glazing, single-sided vent day and night (~5 ach), no external shade	81
Clear double glazing, single-sided vent day and night (~5 ach), external solar shade	57

Manchester Location

Manchester is situated 170 miles northwest of London. Figure 4 shows it has a slightly lower summer dry-bulb temperature than London, but Table 3 shows that the dry-bulb temperature for the design summer, 1984, exceeds the 25°C (77°F) limit for only 62 hours compared to London's 283 hours. Consequently, natural ventilation will be more successful in Manchester.

The simulation results in Table 3 show this. The base case (with clear double glazing and no external shading and about 5 air changes an hour) exceeds the limit by 255 hours compared to London's 393 hours. By allowing the windows to be open for night ventilation, the number of hours over 25°C (77°F) dropped to 81. Replacing the option to open windows at night with a fixed external solar shade reduced the number of hours from 255 to 188. By introducing both night ventilation and the external solar shade, the number of hours over 25°C (77°F) fell to 57.

These two measures, but particularly the nighttime ventilation, put this space well within the comfort criterion of being no more than 104 hours above 25°C (77°F) resultant temperature. Other spaces on the west facade, where more glazing was specified, showed a further benefit from the addition of solar control glazing.

CONCLUSION

The task of achieving the comfort standard with the London weather data is more challenging than with the Manchester data. This suggests that natural ventilation will not be very successful for buildings such as this clinic building for locations around London in the U.K. or further south in Europe. It also suggests that natural ventilation, judged by the 25°C (77°F), 5% criterion, may not be very successful in many parts of North America.

However, before condemning natural ventilation, mixed-mode air conditioning, rather than full air conditioning, could reduce the hours above 25°C (77°F) with relatively little intervention of the air-conditioning system. In effect it could "peak lop" the high heat gains by switching in at high temperatures or run at a lower rate than full air conditioning. Also, in a mixed-mode strategy, natural ventilation, especially night ventilation, plays an important role. It should also be noted that simulation still has to account for wind-driven ventilation and that stack ventilation only is often considered. However, there is an increasing realization that wind-driven ventilation is a significant, if not dominant, natural ventilation driver and that common wind measurements with traditional cup anemometers overestimate the zero and lower wind speeds.

Single-sided ventilation was considered for the clinic building, but double-sided ventilation, more appropriate for open-plan offices, would increase the quantity of outside air and, consequently, increase the cooling effect when the outside dry-bulb temperature air is below the inside temperature.

The 25°C (77°F) 5% criterion is also a crude criterion and a first attempt at a simple rule for successful natural ventilation. Adaptive comfort theory could well be used to relate the criterion to the outside conditions. A rule of thumb used by some designers is that a low-energy naturally ventilated building is well designed if it can maintain the summer inside temperature below the outside temperature. There is some support for this in this paper in that the clinic building passed in Manchester, U.K., whereas it could not in London, even with extra low energy design features. Perhaps a compromise could be to relate the hours above 25°C (77°F) to the hours that the outside air is above 25°C (77°F).

However, before North America adopts a simple 25°C (77°F), 5% type criterion for natural ventilation, experience from Europe should be examined. It should also consider combining energy and comfort into a criterion, as a building may end up thermally comfortable but with very small windows and high lighting costs.

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