Performance Monitoring of a Naturally Ventilated City Centre Library

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ABSTRACT: In order to reduce carbon emissions to tackle climate change, it is becoming increasingly important to improve energy efficiency through more intelligent and sustainable building design. This paper describes the design and environmental performance of the Lanchester Library at Coventry University, which opened in September 2000 and incorporates natural ventilation, daylighting and passive cooling strategies.

Computer simulations used in the design phase demonstrated that comfortable indoor conditions could be maintained with a natural ventilation strategy which uses lightwells and perimeter stacks to supply and exhaust air, and careful control of solar gains and night time cooling, avoiding the use of air conditioning or mechanical ventilation.

This paper uses data from the Building Energy Management System (BEMS) to assess how well the building is performing 5 years on. Temperature, CO_2 and energy consumption data are used to give indications of building performance, and for comparison with the original design criteria and good practice guidelines. The data indicate that comfortable thermal conditions and a sufficient supply of fresh air are maintained in the library throughout the year and that it consumes 50% less energy than a standard air conditioned building.

Keywords: natural ventilation, energy, monitoring, performance, library

1. INTRODUCTION

With increasing concerns regarding climate change, the reduction of CO_2 emissions from buildings through improved energy efficiency and sustainable building design is receiving more attention. Significant energy savings can be achieved by incorporating natural ventilation and daylighting strategies into new buildings, rather than relying on energy intensive air conditioning systems and artificial lighting. This is a complex challenge, particularly for large, deep-plan buildings whose design brief is often strongly influenced by additional constraints such as noise, pollution, and daylight penetration issues.

To ensure that such sustainable design strategies can be implemented successfully and thus provide acceptable environments for the buildings' occupants, it is helpful to model a variety of parameters during the design phase, such as ventilation and thermal performance. However, it has been acknowledged that there is often little feedback between the design process and the actual performance of the buildings in use [1]. Post occupancy studies like PROBE aim to close this gap [1]. Such studies are often very comprehensive, covering the measurement of physical parameters as well as surveys of user satisfaction, and thus require high monitoring effort.

In the case of advanced naturally ventilated buildings, which typically rely on a sophisticated Building Energy Management System (BEMS) to control their ventilation and cooling strategies, it may be possible to derive basic performance parameters from the numerous BEMS sensors which are constantly monitoring internal thermal and air quality conditions. This could provide valuable long-term performance data without requiring the installation of a large amount of monitoring equipment. If required, additional short and medium term monitoring studies could then supplement the data set to cover a wider range of parameters.

This paper investigates the performance of the Lanchester Library at Coventry University, using data from BEMS sensors logged during a 12 month period. The design of the library has been described elsewhere by members of the design team [2-5] and by others [6,7]. This paper therefore gives only a brief overview of the building design. Opportunistic use is made of the data recorded by the BEMS to provide an insight into the internal thermal and air quality (CO_2) conditions. These measured values are compared with current design criteria for naturally ventilated buildings and with performance predictions from simulations during the design stage. Similarly, the building's energy use is compared with UK benchmarks for office buildings.

2. BUILDING DESIGN

2.1 Description of the Building

The brief for the Frederick Lanchester Library at Coventry University demanded a highly energy efficient building with a simple, legible, deep plan layout to be designed for an urban site. Additional constraints were security considerations as well as the close proximity of the site to main roads which results in high noise levels and pollution concentrations.

Based on design studies, a naturally ventilated building with a 50 m square footprint was conceived, which consists of four floors, providing 9103 m^2 open plan accommodation for the university's Library and Resources Centre. A basement houses a book archive and computer suite with 24 hour access which, due to the high and prolonged heat gains, requires air conditioning.

Figure 1 shows the basic layout of the library floors and the stack ventilation system. This basic layout was used as a template and has been modified for each floor to facilitate specific uses, e.g. offices, study rooms.

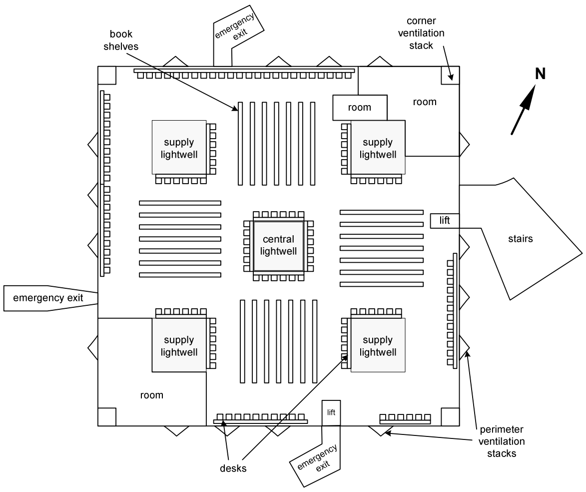

Figure 1: Typical floor plan, showing basic library layout and ventilation lightwells and stacks

Fresh air enters the building through a plenum between the ground floor and the basement, which serves four lightwells, one in each quadrant of the building. The air is warmed by the heat from occupants, computers, lighting, and heating (in winter). The buoyant air rises and accumulates in a layer below the 3.9 m high ceilings before flowing out through the 20 perimeter ventilation stacks and the central lightwell, due to the 'stack effect'. Four additional dedicated stacks were added for the ventilation of the top floor in order to avoid the problem of backflow of exhaust air from the central lightwell into the top floor which was identified during the design process [2].

Passive cooling, due to the building's thermal mass, is used to achieve comfortable indoor temperatures during the warm summer months. The exposed thermal mass of the building is cooled by night time venting so that it can absorb heat during the following day. Heating of the incoming air in winter is provided by pre-heating coils at the base of the supply lightwells and trench heating at the points where air enters onto each floor.

The lightwells are positioned so as to provide a good distribution of fresh air throughout the space as well as to ensure good daylight provision across the deep plan floors (Figure 1). In order to minimize solar gains, a number of shading strategies were incorporated in the design of the facades: self-shading due to stacks and stairwells; overhangs to windows; and metal shading fins. Moveable translucent blinds were fitted at the top of the supply lightwells. Together with careful window placement and sizing, these strategies are intended to reduce the risk of overheating and to improve the effectiveness of the natural cooling system.

A building energy management system (BEMS) monitors internal temperature and CO_2 levels as well as external weather conditions and adjusts the air supply and exhaust dampers accordingly in order to achieve comfortable conditions for the building's occupants. To control night time cooling the BEMS estimates the likely passive cooling requirement for the following day, using a self-learning algorithm, and optimizes the duration of the night venting accordingly.

2.2 Predicted Performance

During the design phase, alternative design propositions were considered from a variety of view points including cost, efficiency of space use, legibility of floor layouts and energy use. Since one of the main challenges in the design of naturally ventilated buildings is to maintain comfortable indoor temperatures during periods of high external temperatures, the design phase also included dynamic thermal simulations. These simulations indicated that comfortable indoor conditions could be provided with passive cooling and ventilation methods, even during the hottest periods, see for example Cook et al. [2].

It was predicted that "dry-resultant temperatures would always be below 28 °C and that 27 °C would be exceeded for only 11 hours of the year". Refined BEMS controls (not simulated) were expected to "be capable of reducing internal temperatures even further."

Based on these results, the building should be able to meet commonly used overheating criteria, which require that (1) dry resultant temperatures should not exceed 28 °C for more than 1 % of the occupied hours [8,9] and (2) dry resultant temperatures should not exceed 25 °C for more than 5 % of the occupied year [10].

The design process also included CFD simulations which were used to simulate conditions on the individual library floors and to determine suitable ventilation outlet opening sizes. Based on these simulations, it was predicted that, by appropriately sizing openings, uniform temperature distributions across each floor could be achieved [3].

The library's performance in terms of indoor air quality was not predicted during the design phase. However, CO_2 concentrations would be expected to remain within the levels recommended for educational buildings (1000 ppm [11]) since the BEMS constantly monitors CO_2 concentrations in the building and adjusts fresh air provision using a set point of 1000 ppm.

3. MONITORING OF TEMPERATURE AND CO_2 LEVELS

3.1 BEMS Sensors

Since the library is used for a variety of purposes, from book storage to study areas for PC users and group work, the basic square open plan floor layout has been adapted on each floor to provide a range of suitable spaces. All floors remain predominantly open plan, with a significant area taken up by book stacks (apart from the ground floor, which serves as an unofficial meeting place and provides access to the issue desks and main staff offices). Internal partitions create additional spaces. On each floor a number of zones with different occupancy and usage characteristics can therefore be identified. For example, on the second floor (Figure 2) these include:

- open plan area with book shelves
- a silent study room
- two differently sized group study rooms
- study desks with PCs (open plan)
- study desks without PCs (open plan)
- a print & photocopy room
- two offices.

In order to ensure comfortable internal conditions for all occupants, the BEMS must be able to control ventilation and heating in each of these zones. Therefore, a large number of sensors are distributed throughout the space (Figure 2).

Based on readings from these sensors, individually controllable dampers are adjusted to provide ventilation for thermal comfort and air quality in each zone. In addition to their function as part of the building control system, the sensors can contribute to the assessment of the building's performance if their readings are continuously logged. For a comprehensive analysis, long term monitoring data are required for a variety of zones, ideally from all sensor locations. However, logged data is currently only available for a limited number of BEMS sensors. Temperature and CO_2 data, for example, are available for two locations on the ground and third floors, and four locations on the second floor. Logged data for the first floor includes temperature only for three locations.

This paper makes opportunistic use of these data. However, since the sensors from which data have been logged were not chosen with thermal performance analysis in mind, the data available do not allow a thorough statistical analysis. This paper will thus use time series plots and summary statistics to evaluate the building's performance. It is worth noting, however, that additional BEMS sensors have recently been selected for data logging to aid future performance analyses and to provide further explanations of the initial results presented in this paper.

Temperature data

The temperature sensors are designed to monitor air temperature. However, due to the close proximity of the sensors to the wall surface, the logged temperature values may not be equivalent to the air temperature in the space and can thus only be used as indicators for the conditions experienced by the occupants. In order to quantify the relationship between the sensor readings and parameters typically used to assess thermal comfort, short-term monitoring studies are currently being carried out. These include the measurement of operative temperature, PPD, PMV, air velocity and humidity. Once available, these data can be used to determine whether, and how accurately, the BEMS temperature readings relate to the air temperature levels experienced by the occupants.

It is further worth noting that the CIBSE overheating criteria, used here for performance assessment, are based on dry resultant temperature (DRT) as their target parameter. It is probable that, during the summer days, the DRT is lower than the air temperature because the thermal mass will have been cooled during the night. Therefore, it is likely that the frequency of occurrence of high temperatures as measured by the BEMS sensors is an overestimate of the actual frequency of occurrence of high dry resultant temperatures, i.e. the building may actually perform better than the results presented in this paper indicate. Further work is underway to clarify this matter.

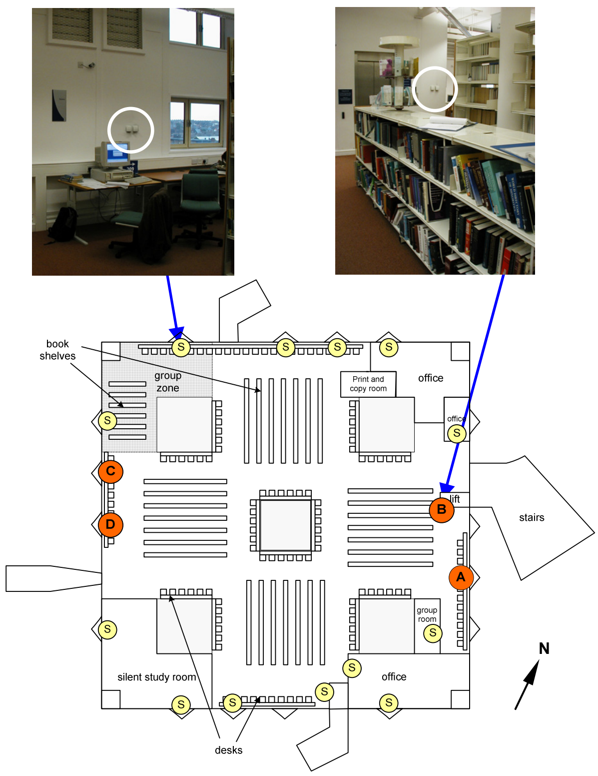

Figure 2: Floor plan of the second floor showing the location of BEMS temperature and air quality sensors (each circle represents a sensor pair: one temperature and one CO_2 sensor). Data from sensor pairs A-D are currently logged while data from the other sensors (S) are currently not logged but may be included in further monitoring phases.

CO_2 data

The BEMS air quality sensors log CO_2 concentrations at hourly intervals. It was found that some CO_2 sensors read consistently higher than others. However, comparison of the time series traces showed that the overall shapes of the profiles of all the sensors matched well and that the values for individual sensors decreased to a consistent minimum value over night. Considering that internal CO_2 concentrations during unoccupied periods (e.g. over night) are likely to be equivalent to the ambient CO_2 concentration, it was assumed that minimum values which exceeded the ambient concentration were in error due to calibration drift. The data from these sensors were therefore adjusted by an offset value so that the baseline values of all sensors matched that of the sensor with the lowest baseline readings, i.e. night time values of approx. 360 - 370 ppm, which is equivalent to typical background CO_2 concentrations [12].

3.2 Measured Values for the Second Floor

Data for temperature and CO_2 levels is available for a six week period in summer 2005 (10 May – 22 June 2005) from four sensor pairs at locations A-D, as shown in Figure 2. Sensors at A, C and D are located above study desks (without PCs) around the side walls of the building, aligned with perimeter ventilation stacks. The sensors at location B are located on an internal wall near the lift adjacent to the entrance door. All sensors are installed at a height of 1.5 m.

Time series plots, such as the two week plot in Figure 3, clearly illustrate the different variability of the temperatures and CO_2 concentrations. Although both parameters are influenced by ventilation settings and occupancy levels, the CO_2 curves show distinct peaks, usually in the early afternoon, while the temperature curves rise throughout the day before decreasing sharply at night due to the night time venting strategy.

The plots showed that there were slight temperature differences across the floor during the period investigated. Temperatures seem to be typically higher at locations A and B than at locations C and D, the average difference between A and D being 0.52 K. This could be due to movement of people through the doors leading to the main staircase causing an exchange of air into the adjacent zones where sensors A and B are located. It is interesting to note however that this pattern sometimes changes, with temperatures at location D rising to similar levels as A while temperatures at the adjacent location C remain lower. A likely cause is that there is a rather localised effect of desk users on temperature levels in the close proximity of sensor D. The presence of people at the desks below the sensor will warm the air and cause it to rise up towards the ventilation openings of the perimeter stack, i.e. vertically past the sensor location, while sensor C on the adjacent stack (7 m away) is likely to register little change in temperatures if the desks directly below it are unoccupied.

A similar observation can be made for the CO_2 concentrations. While the profiles of the data from the three sensors seem to match in general, concentrations at one location occasionally increase significantly above the levels measured at the other locations. This often coincides with elevated air temperature at the same location. Again, increased occupancy density at the desks near the sensors is thought to be a likely reason for these peaks.

The CO_2 concentrations for occupied periods during the six weeks investigated typically were between 400 and 500 ppm, with occasional peaks of up to around 700 ppm. The maximum CO_2 concentration recorded was 720 ppm, which is below the recommended limit of 1000 ppm [11].

These preliminary investigations suggest that the natural ventilation strategy is working well, ensuring a sufficient supply of fresh air and providing relatively uniform conditions across the second floor.

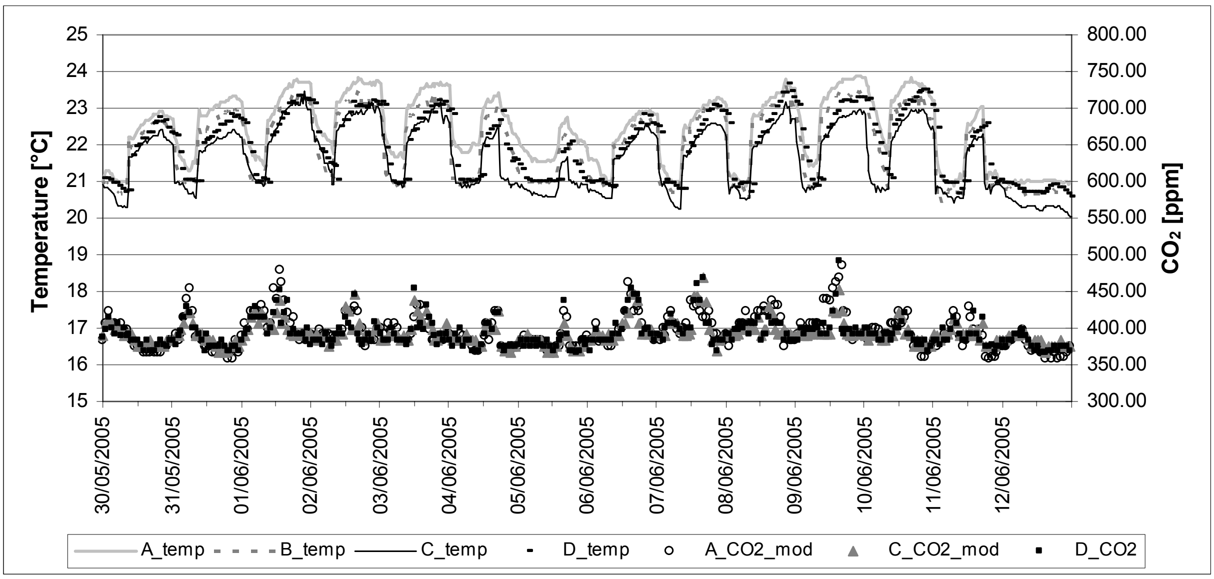

Figure 3: Temperature and CO_2 levels measured at locations A - D on the second floor of Lanchester Library during the period 30/05/2005 – 12/06/2005

4. COMPARISON OF MEASURED PERFORMANCE WITH GUIDELINES AND PREDICTIONS

4.1 Internal Temperatures

Average internal temperatures, derived from BEMS data from all floors, were found to be relatively stable throughout the year (Figure 4). They were generally between 21 °C (night) and 24 °C (day). Temperatures below 21 °C, i.e. the set point for occupied periods, can be observed at weekends and holiday times (e.g. Christmas and Easter breaks).

Results presented elsewhere [13] showed that the exposed thermal mass of the building, together with the night time ventilation strategy, ensure that even during prolonged hot spells, internal temperatures remained within comfortable limits. It was found that the temperatures on the third floor are higher than on floors 1 and 2, which is thought to be the result of the stack height being smaller on the top floor. This indicates that meeting overheating criteria in stack ventilated buildings is likely to be most difficult for the top floor.

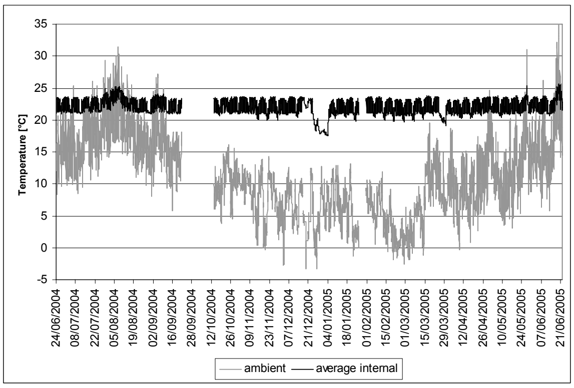

Figure 4: Internal and external temperature during the monitoring period June 2004 – June 2005 (Three weeks are missing in autumn 2004 and one week in Feb. 2005.)

Overheating statistics showed that the temperature most frequently exceeded 25 °C on the third floor and the ground floor, whilst on the first floor temperatures remained below 25 °C throughout the entire monitoring period. However, even on the third floor the CIBSE 2002 overheating criterion (less than 5 % of occupied hours over 25 °C [10]) was met, with temperatures greater than 25 °C only occurring during 3.8 % of the hours of use. The internal temperatures never exceeded 27 °C, i.e. less than the number predicted at the design stage (11 hours), which confirms the expectations stated by Cook et al. [2] - that with intelligent BEMS control a better building performance can be achieved than the simulation results suggested.

Clearly the building meets the current CIBSE 2005/2006 criterion that there should be less than 1 % of occupied hours over 28 °C [8,9]. Thus, the library should give confidence to designers that, in the UK midlands, natural ventilation can meet prevailing overheating criteria, even in a challenging urban environment.

4.2 Energy Consumption

The measured annual consumption of electricity and gas for 2004, as determined from meter readings, was 198 kWh/m^2. This includes the heating, lighting and power consumption of the basement and the four levels of the library; the two cannot be disaggregated. The basement is a computer suite, accessible 24 hours each day, and so is mechanically cooled due to power and lighting loads. The library itself is accessible for approximately 4000 hours each year.

With this data it is difficult to make comparisons between the energy consumption of the library and benchmark figures for purely naturally ventilated buildings, or with energy use predictions for the library made at the design stage. However, a comparison for the whole building is possible, by presenting the library and benchmark data normalised by both floor area and period of occupancy (Table 1).

Table 1: Energy consumption of the Lanchester Library in 2004

	End Use		
	Heating	Electricity	Cooling
Total annual consumption [MWh]	1117	1012	205
Consumption per m^2 [kWh/m^2]	95	86	17
Consumption per m^2 and per occupied hour [kWh/m^2/h]	0.024	0.021	0.004

With an annual energy consumption of 0.049 kWh/m^2/h, the building performs better than the ECON19 guidelines [14] (Figure 5). The building uses 51 % less energy than the typical air conditioned building and 35 % less than the typical naturally ventilated open plan building. In fact, the Lanchester Library also performs better than an office building built to the good practice standard for naturally ventilated open plan offices, equivalent to an energy saving of around 4 %. It is worth noting that these figures are conservative estimates since they include the 24 hour computer suite in the basement but are based on the lower occupancy hours for the other three floors (4000 h/a).

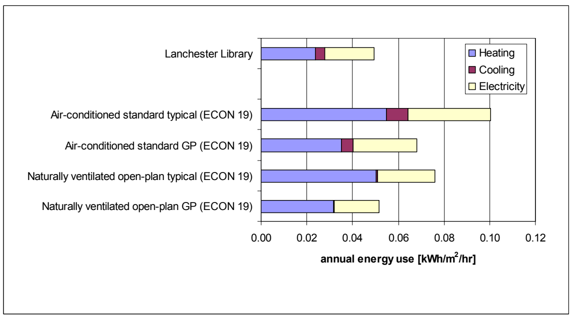

Figure 5: Comparison of the library's annual energy consumption (2004) with ECON19 benchmarks [14]

5. CONCLUSIONS

The Lanchester Library at Coventry University is a deep plan urban building which relies on natural ventilation and passive cooling to maintain comfortable conditions for library users and staff.

Data from the Building Energy Management System (BEMS), which controls the building's indoor environment, was used to investigate the conditions within the library. Analyses included: short-term variations of temperature and CO_2 across floors; long-term performance differences between floors; and the calculation of annual overheating statistics.

Temperature and CO_2 data from four sensor locations on the second floor indicate that the natural ventilation strategy is working well. It provides relatively uniform conditions across the floor and ensures a sufficient supply of fresh air; CO_2 concentrations rarely exceeded 700 ppm, which is below the recommended maximum value of 1000 ppm [11].

The temperature data show that the exposed thermal mass and the BEMS controlled night time ventilation strategy ensured that internal temperatures remained within comfortable limits even during prolonged hot spells. In the period June 2004 – June 2005, the building met the CIBSE Guide A thermal comfort criterion that there should be no more than 1 % of occupied hours with a dry-resultant temperature above 28 °C [9]. In fact, the building also met the more stringent criterion, outlined in CIBSE Guide J, that there should be no more than 5 % of occupied hours over 25 °C [10].

The library's annual energy consumption in 2004 was 0.049 kWh/m^2/hour of occupancy, which means that it used 51 % less energy than a typical air conditioned office and 35 % less than a typical naturally ventilated open plan office [14].

The building is thus an example of how natural ventilation can be successfully incorporated into large urban buildings with complex user requirements and challenging environmental constraints.

6. FURTHER WORK

This analysis has made opportunistic use of temperature and air quality data logged by the building's BEMS system. However, in order to assess the building's performance more rigorously and to diagnose the reasons for the performance features observed in this paper, detailed medium-term measurements of indoor thermal comfort, occupancy density and occupant satisfaction are planned.

It would be interesting to see how the observed variability of the temperatures and CO_2 concentrations relates to changes in occupancy density as well as ventilation settings and damper control. Further monitoring campaigns should therefore include user counts, ideally separately for zones with different occupancy patterns.

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