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Low energy architecture for a severe US climate: Design and evaluation of a hybrid ventilation strategy

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Abstract

Natural ventilation, relying on openings in the façade, is applicable to a limited range of climates, sites and building types. Advanced naturally ventilated buildings, such as those using stacks to encourage buoyancy driven airflow, or hybrid buildings, which integrate both natural and mechanical systems, can extend the range of buildings and climate within which natural ventilation might be used.

This paper describes the design of a new library building for a college, located near Chicago, which uses a new hybrid ventilation concept despite the severe continental climate. The likely operation of the building is illustrated using dynamic thermal modelling and computational fluid dynamics analyses. The new building challenges ingrained preconceptions about building designs for severe climates and exposes barriers to low energy buildings posed by national standards and guidelines.

Keywords: Hybrid ventilation; Low energy buildings; Climate; Dynamic thermal model; Computational fluid dynamics

1. Introduction

Natural ventilation (NV) is widely recognised as a low energy approach to conditioning the interiors of buildings. The term 'natural ventilation' usually conjures up an image of a small scale building, with a shallow plan depth, operable perimeter windows and variable and unpredictable internal temperatures, air quality and air speeds. The manual operation of windows can be inconvenient, but on the other hand it has been shown that the provision of personal environmental control can, in part, enhance satisfaction with the building's internal conditions through adaptive opportunity [1] and the 'connectivity' with the outside world can be welcome. The simple NV strategy is therefore only well suited to temperate climates, sites with a benign micro-environment, buildings with modest internal heat gain and when occupant activities will tolerate variations of internal temperature.

Where such conditions do not prevail, or where deep plan buildings and sealed façades are required, designers generally presume that a mechanical ventilation strategy is necessary—and this usually means air conditioning. This presumption is, in fact, enshrined in some standards. For example, ASHRAE Standard 62.1 [2] states that NV systems are permitted 'in lieu of or in conjunction with mechanical ventilation systems' but goes on to list a number of pre-requisites which should be met. As the work of Bordass et al. [3] has shown, air-conditioned buildings invariably consume more energy to offer the same level of service to occupants than NV alternatives. The fans, pumps and control equipment being responsible for much of the additional electrical energy consumption (rather than the chillers).

Hybrid buildings can reduce energy consumption whilst offering the potential to combat tough climatic and site conditions and the prospect of meeting stringent internal environmental conditions. Such buildings are therefore becoming increasingly popular in Europe, however they tend to consume more energy than simple NV buildings, but less than those with air conditioning [3]. They also contain all the paraphernalia associated with mechanical air delivery systems (as well as the passive building elements) and can therefore be costly to build. If energy use is to be reduced significantly, and at an acceptable building cost, then more innovative thinking is needed.

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So called 'advanced natural ventilation' (ANV) [3] offers a way forward and in recent years there has been a resurgence of interest in stack-ventilated buildings. That is, buildings in which tall chimneys, lightwells or atria are used to draw fresh air through the building. Because the flow is buoyancy driven, if properly designed, the volume flows of air will increase or decrease in line with the increase or decrease in the inside to outside air temperature difference. Thus, if internal heat gains increase, causing a rise in space temperatures, air flows will naturally increase (i.e. without any intervention from fans and with no need to adjust control louvre or damper settings). Stack ventilated buildings are, therefore, tolerant of changes in occupancy and robust to imprecision in the operation of airflow controls (e.g. dampers and windows).

A taxonomy of stack ventilated buildings has been proposed [4,5]. Of the four stack ventilated building forms identified, two utilise fresh air supplied directly from the outside through perimeter openings: edge-in centre-out (E–C), for example, as in the Queens Building at De Montfort University [6]; and edge-in edge-out (E–E), as used in the Building Research Establishment (BRE) energy efficient office of the future [7]. The other forms: centre-in edge-out (C–E), and centre-in centre out (C–C), are of particular interest if a hybrid building, especially one in a severe climate, is planned. By using discrete air delivery shafts suitably positioned across a floor plate, essentially deep plan buildings are possible. Likewise, air exhaust stacks can be located either within the floor footprint (C–C) or around the perimeter (C–E). Air can be delivered at low level and exhausted at high level, i.e. a displacement ventilation strategy, which can yield improved air quality and more effective ventilation cooling than mixing ventilation [8]. Airflow rates are invariably controlled by dampers at the inlets and outlets by using a building management system (BMS). This makes the strategy eminently suitable for buildings with large, possibly open plan, spaces when no single occupant is exercising control over the internal environment, e.g. libraries, theatres and conference halls. However, the strategy does not entirely preclude operable windows, should this be deemed desirable, although some caution is required to avoid unwelcome draughts and the preferential supply of air from the windows rather than from the air delivery shaft when in mechanical cooling mode. Most importantly, it is possible for a NV building to have a sealed façade, thus opening up this low energy strategy as a real design possibility on noisy and polluted sites, in areas where security is of particular concern, to buildings which house valuable or easily stolen objects or where the façade must offer maximum design flexibility, for example to adopt the vernacular of the surrounding buildings in areas of historic importance.

The authors of this paper have previously taken a lead role in devising the ventilation concept, undertaking the simulation analyses and proposing the control strategy for two UK buildings which utilise a central air supply shaft: the Frederick Lanchester Library, located in central Coventry [4,9,10,11], which uses both the C–E and C–C strategy; and the School of Slavonic and East European Studies (SSEES) [4,12], which uses the C–E approach. It is beyond the scope of this paper to describe these buildings in detail, the interested reader is directed to the references cited. They are mentioned here as they represent design precedents for the Harm A Webber Library at Judson College in Elgin, near Chicago, Illinois, which is the subject of this paper.

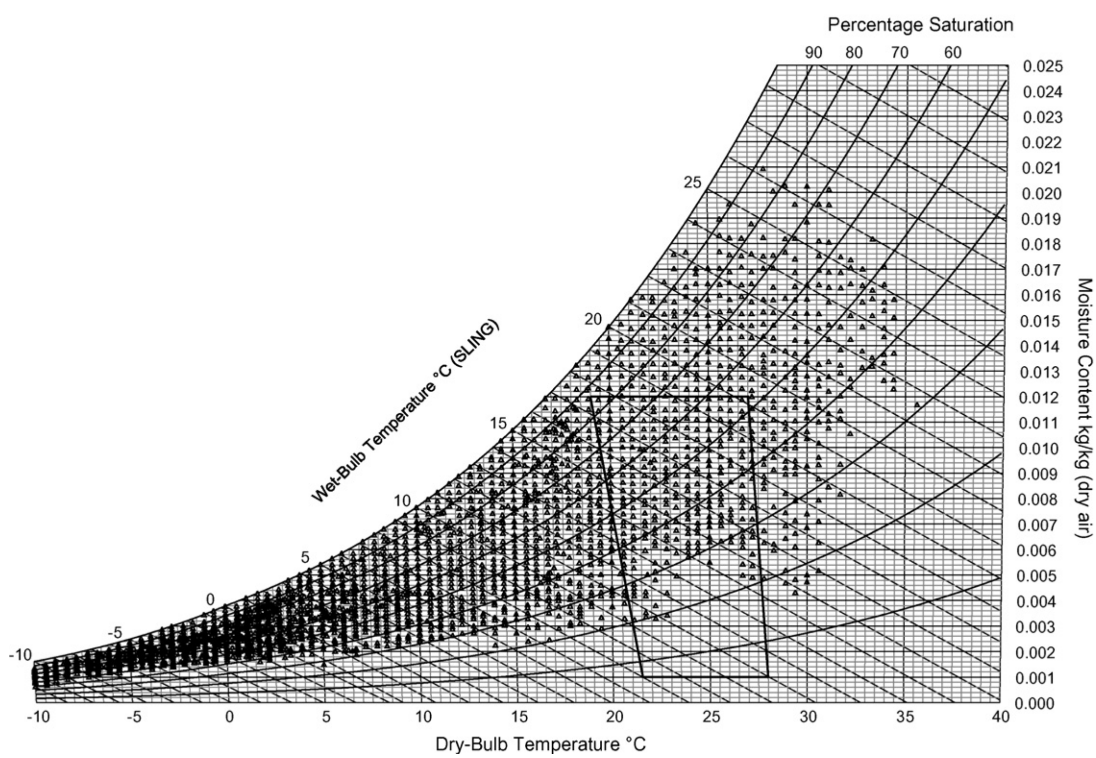

Fig. 1. Temperatures and moisture content in the Chicago TMY2 weather data set and the ANSI/ASHRAE Standard 55 [14] thermal comfort envelope.

2. Pre-design analysis

The climate of Elgin was studied using data in the typical meteorological year (TMY2) database, produced by the National Renewable Energy Laboratory [13], and alternative criteria for defining acceptable indoor thermal comfort conditions were considered. This led to the adoption of the Chicago climate data and the standard ANSI/ASHRAE 55 [14] comfort envelope as the basis for the environmental design (see [15]).

Plotting the hourly Chicago temperature and moisture content on a psychrometric chart (Fig. 1), it is evident, as expected, that the ambient conditions frequently lie above the upper bands of acceptable temperature (27–28 °C) and humidity (12 g/kg): during the working day (08.00–18.00) there are about 250 h of the year when the ambient temperature exceeds the upper temperature band and a further 150 h, or so, when the temperature is below 27 °C but above a moisture content of 12 g/kg. Even with a well designed, naturally ventilated building, utilising night time ventilation, it is highly unlikely that an acceptable internal temperature could be achieved and, of course, simple comfort cooling, as adopted in the SSEES building [12], could not produce an acceptable internal moisture content.

To overcome these problems a new development of the C–E ventilation form was conceived, in which a central lightwell, which is sealed at the top was supplied with mechanically cooled air in summer. The plant would also be utilised in the depths of winter to heat and, if necessary, to humidify the air. This led to a building with four distinct modes of operation: passive ventilation (PV); passive ventilation with pre-heating of fresh air (PVH); mechanical ventilation and cooling (MVC); and mechanical ventilation and heating (MVH).

In the interests of energy efficiency, the exhaust air could not simply be allowed to escape from the building in either summer or winter. Therefore a mechanism for re-circulating the air back to the air handling plant was necessary. A passive ventilation strategy was devised which utilised the following: a low level plenum (as in the Coventry and SSEES buildings) to deliver fresh pre-heated ambient air; exposed thermal mass; and a deep façade to shade the interior from the summer sun (Figs. 2 and 3). The client was interested in maintaining connectivity between the inside and outside of the library building, thus good views out were important, as was the ability of the occupants of cellular offices to open windows.

The introduction of a full HVAC system, air recirculation routes and openable perimeter windows, whilst retaining all the benefits of a C–E advanced natural ventilation system, represents a significant design advance. Initial calculations suggested that energy savings through such a design could be around 50%, compared to a standard US HVAC building, due to a reduction in both the duration and intensity of mechanical cooling. This estimate was confirmed by subsequent modelling studies, which were based on a realistic environmental control strategy [15].

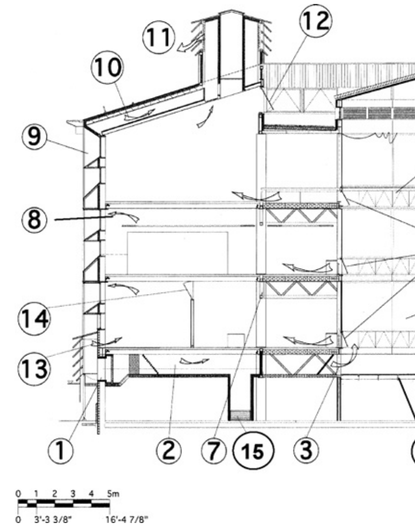

Fig. 2. Half section illustrating key features of the Judson Library design (adapted from [15]). (1) Secure air inlet to plenum; (2) smooth, unobstructed accessible plenum; (3) opening into lightwell on all four sides; (4) lightwell acts as air supply stack; (5) inlets to floor with fine control and preheat device; (6) transparent lens, tight sealing to avoid air leakage; (7) open truss enabling airflow across ceiling soffit; (8) highest outlet into stack; (9) well insulated stack; (10) gently rising plenum allowing free movement of warm buoyant air; (11) terminations protected from wind and rain; (12) operable clerestory windows; (13) dedicated supply to perimeter cellular spaces (out of plane of figure); (14) operable window provides an alternative, occupant controlled air inlet; (15) down-feed from plenum to level one; (16) glazed floor enables daylighting of bottom level.

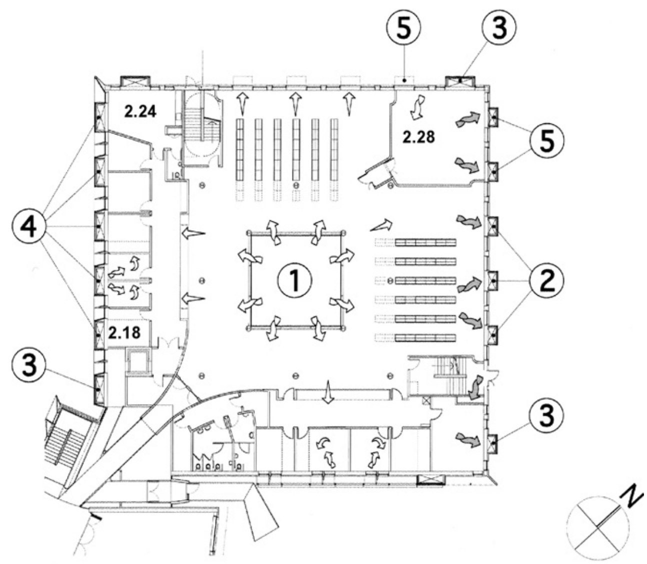

Fig. 3. Level two plan (adapted from [15]). (1) Lightwell air supply; (2) exhaust air ducts embedded in façade; (3) return air duct from roof; (4) riser ducts supply classrooms R2.18 (SW) to R2.24 (NW); (5) exhaust stacks for classroom (R2.28).

3. Thermal performance analysis

The aims of the thermal performance analyses were as follows: to confirm that the design concept was valid; to finalise the size and height of the stacks and the opening areas into them; to test the effect of alternative night ventilation strategies; to investigate what effect higher-than-expected internal loads would have on the passive operating mode; and to ensure that viable winter and summer time mechanical ventilation and temperature control strategies could be integrated.

The thermal model consisted of one quadrant of the third level of the library defined by the north west facing façade and diagonals radiating from the central lightwell. Level three was modelled as the stacks had the least height at this level. The model incorporated the shaded windows, the exposed thermal mass and the stacks, which were assumed to terminate at roof ridge level.

The library quadrant was assumed to be occupied from 08.00 to 18.00, with total internal heat gains of 34 or 50 W/m^2, and at 60% of this occupancy between 08.00 and 18.00 at weekends (20 and 30 W/m^2, respectively). The radiant/convective split of each heat source was accurately modelled and an infiltration rate of 0.2 ach^{-1} was used.

The simulations were undertaken with ESP-r [16], a DTS program which enables a zonal airflow model to be integrated so that realistic simulations of the coupled temperatures and airflows can be undertaken. The program predicts overall space temperatures, rather than the stratified and spatially varying space temperatures that would be encountered in the real building, and no attempt was made to model the effects of internal partitions or the flow resistances introduced by the plenum and pre-heating devices; these issues were studied using the CFD code. Because the building was designed to be 'wind neutral', i.e. the building should function adequately by buoyancy driven flows alone, wind effects were ignored.

All four operating modes were studied: spring/autumn passive ventilation (PV) with pre-heating of the air if necessary (PVH); summer mechanical ventilation and cooling (MVC); and winter time mechanical ventilation and heating (MVH). The different modes of operation were studied separately because it is difficult, and thus time consuming, to create ventilation and plant control files, which can, in a single simulation, properly represent the building's operation for an entire year.

3.1. Analysis of passive operating modes (PV, PVH)

The PV and PVH modes of operation were studied first, as this mode of operation was instrumental in driving the entire architecture of the building. In the simulations there was no cooling but a heating set point of 20 °C was used in the library and 17 °C for the air entering the lightwell. The lightwell and library had night set back temperature at 12 °C.

The operation of the air supply dampers was not modelled and so the inlets and outlets to the lightwell and occupied zone were open at all times during the working day. Preliminary simulations had shown that night ventilation was most effective when it could function, if necessary, during the entire unoccupied period. Therefore, the airflow openings were fully open outside the occupied period until the thermal mass in the space was cooled below 23 °C, at which time airflow was shut off completely.

At the time of the study, there was interest in trying to reduce the cross sectional area of the stacks so that they occupied less of the external façade (thereby enabling window sizes to grow) and so openings equivalent to both 0.5% and 1% of the floor area were investigated. There was also the prospect of terminating the stacks at the eaves, i.e. just above the ceiling height of level four (Fig. 2), however preliminary simulations indicated that the predicted internal temperatures were little different whether the stacks finished at the eaves or at the roof ridge. The cross section of the stacks and the size of inlets and outlets to the space did, however, have a material impact on the predicted internal dry resultant temperature (DRT). The peak daytime values in the spring and autumn were about 3 K higher with small cross-section stacks and, as a result, the occurrence of temperatures over 28 °C increased from 11% of annual occupied hours to 19% (without any mechanical cooling). The larger (1%) cross-sectional area was therefore used in all subsequent simulations.

The dynamics of the building during a 3 day period, in which the ambient daytime temperatures exceed 30 °C and thus no space heating or ventilation heating was required, is illustrated in Fig. 4. The first night shown is cool, so that night ventilation was curtailed because the ceiling slab temperature fell to 23 °C, giving a mean radiant temperature (MRT) of 22 °C. During the subsequent day (a Sunday), the internal dry bulb temperature (DBT) reaches 27.5 °C, which, like the lightwell DBT, is below ambient. The peak DRT, which is important in determining occupant comfort, is about 26 °C, i.e. 3 K below the corresponding ambient temperature. During the second and third nights, ventilation cooling was especially effective, reducing the peak MRT on the 2nd and 3rd days (Monday and Tuesday) to 4.5 K below ambient peak, thus providing an excellent sink for radiant heat. The predicted DRT in the space, on the Tuesday, was about 29 °C, a little outside the ASHRAE comfort envelope—which could actually trigger mechanical cooling (see Section 3.2).

On the Sunday and Monday, airflow reversal occurred, from the point where the lightwell temperature dipped below ambient (in the morning), until early afternoon, when the ambient temperature fell. In practice, the airflow dampers would be controlled to prevent this, opening only enough to ensure that maximum CO_2 levels were not exceeded when ambient temperatures exceed those inside the building. This also prevents the warmer ambient air adding heat into the occupied space.

During the nights there is vigorous ventilation at 3–5 ach^{-1} driven by the warmer-than-ambient air in the occupied spaces. As a result, the thermal mass, warmed by radiant and convective gains during the day, gradually gives up its heat and the MRT falls by about 3.5 K during the second night. The slowly changing mass temperature thus stabilises the comfort conditions, which is reflected in the DRT experienced by the occupants.

Buildings are frequently occupied at densities much lower than their design target, this is especially so of educational buildings outside teaching periods. One can readily appreciate how, under such circumstances, a thermally massive building can stay cool inside, even during rather hot days provided that night time ventilation cooling is possible. Conversely, if

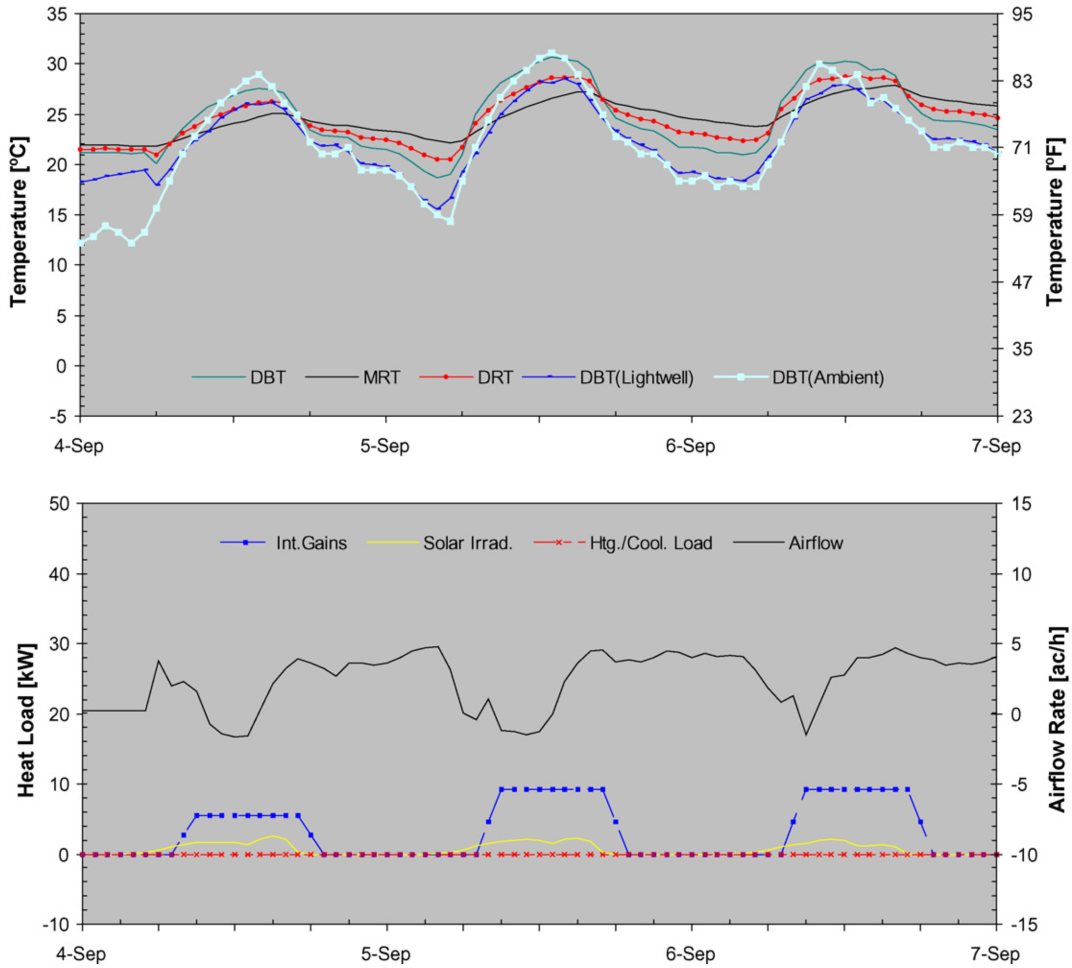

Fig. 4. Predicted space temperatures and airflow rates during a 3 day period in September: passive ventilation mode, 34 W/m^2 heat gain during the day.

occupancy is higher, then the cool thermal mass will help to curtail the rise in radiant temperature and any space temperature increases will induce additional buoyancy driven ventilation cooling. Simulations, in which the number of occupants was doubled, to produce a total internal gain of 50 W/m^2, resulted in an increase in the DRT of only 1 K compared to a space with gains of 34 W/m^2.

During the cooler periods of the year (Fig. 5) the space will be warmed directly by the perimeter heaters to 20 °C and the ventilation air heated to the target minimum value of 17 °C. On the 1st day, 29 September in Fig. 5, the ambient air temperature exceeds 17 °C and so is unheated. The stack effect drives an airflow of about 5 ach^{-1}, which is sufficient to keep the space comfortable, (DRT = 24 °C). On the subsequent day, some space heating is needed in the early morning to bring the space up to 20 °C with some ventilation preheating in the afternoon to warm the fresh ambient air to 17 °C. On 01 October both space heating and ventilation preheating are needed to produce comfortable conditions. However, in practice, the ventilation dampers would be operating to provide much lower airflows, thereby reducing, or avoiding completely, the need for such high heat inputs. From past experience, the design team are able to specify a suitable control strategy (see [15]) and so more detailed modelling was not needed for development of the architectural design.

The number of hours in the month, for which the DRT was predicted to exceed values towards the upper end of the ASHRAE comfort envelope using PV and PVH only, is shown in Table 1. This confirms an observation made by studying the hourly temperature plots, i.e. that there is a ‘season’ during which mechanical cooling is needed. This runs from around the end of May until the end of the first or second week in September. This period is barely changed if heat gains increase to 50 W/m^2. Outside of this period, PV or PVH and, in the depths of winter, MVH, are required.

3.2. Analysis of summer cooling mode (MVC)

In the summer months the building will operate during the day in MVC mode with cool air being supplied entirely from the central lightwell at the volume flow controlled by the air inlet dampers (point 5 in Fig. 2). There is little doubt that sufficient cool air could be supplied provided the mechanical plant is adequately sized, but lower flow rates and higher supply temperatures will reduce fan and chiller energy

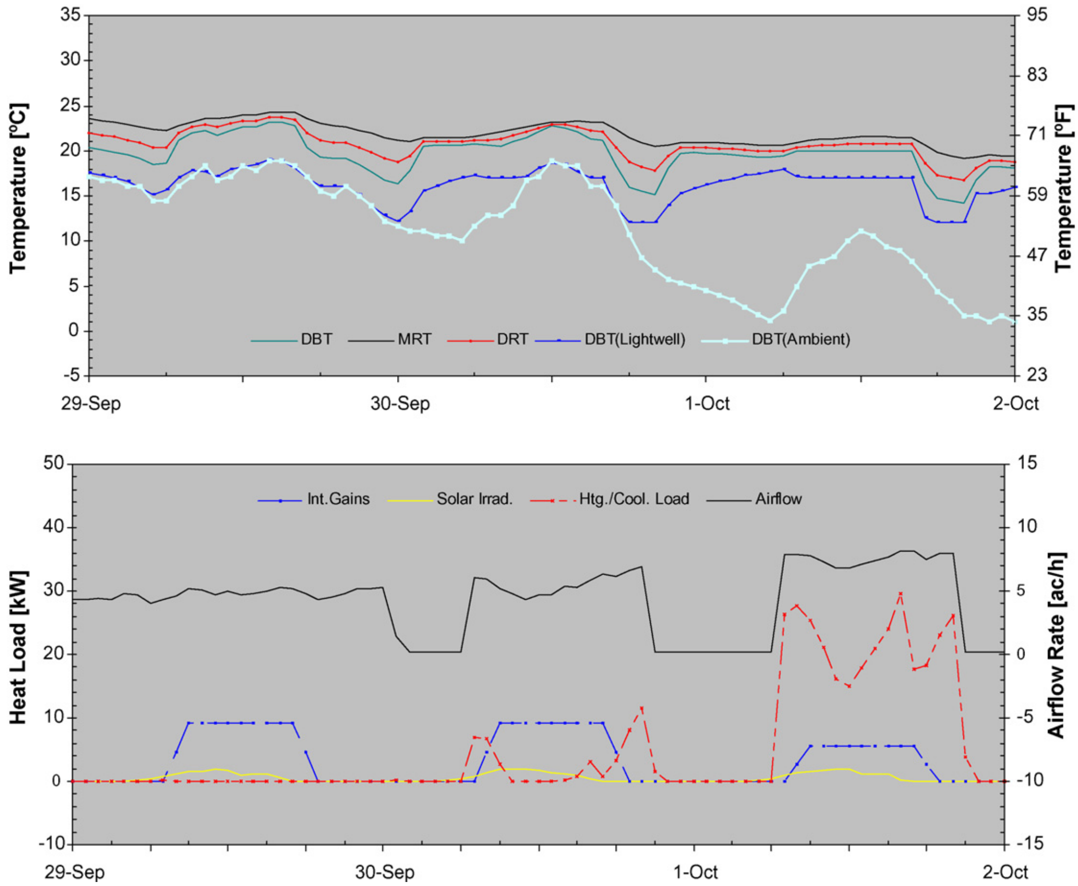

Fig. 5. Predicted space temperatures, airflow rates and heating loads during a 3 day period in Autumn: passive ventilation and heating mode, 34 W/m^2 heat gain during the day.

Table 1
Hours in each month for which the stated dry resultant temperature is exceeded during occupied hours when operating in passive ventilation mode: opening areas equal to 1% of floor area

Casual heat gain	DRT (°C)	April	May	June	July	August	September	October	Total
34 W/m2	25	0	51	202	295	268	99	0	915
	26	0	24	175	274	229	66	0	768
	27	0	12	135	246	144	24	0	561
	28	0	2	91	208	82	12	0	395
51 W/m2	25	0	97	248	307	296	157	12	1117
	26	0	65	209	296	272	112	5	959
	27	0	37	186	278	241	79	0	821
	28	0	23	156	250	170	48	0	647

There were no hours over these temperatures in any of the other months of the year.

consumption and decrease the risk of occupants experiencing cold draughts in the vicinity of air inlets.

In the simulations, air was supplied from the lightwell at 5 ach^{-1} at a temperature of 21 °C[1] between 08.00 and 18.00, with passive ventilation cooling operating during the night (22.00–05.00). With a heat gain of 34 W/m^2, the internal DRT never exceeded 28 °C, with 27 °C only being exceeded for 22 h in working hours. The results illustrate clearly how, after the daytime cooling period, the space temperatures increase when the cooling is switched off (Fig. 6, 5 August). On cool nights, however, the night time ventilation is able to draw the space temperatures down below the temperature that the space experiences during the subsequent day; this reduces the cooling energy needs. In practice, the building energy management system would determine the times at which the night ventilation to any particular space should start and stop based on the prevailing ambient and space or slab temperatures, thus the

[1] Preliminary simulations had shown that, with a supply temperature of 23 °C, the DRT would exceed 28 °C for about 55 working hours in July with typical occupancy levels.

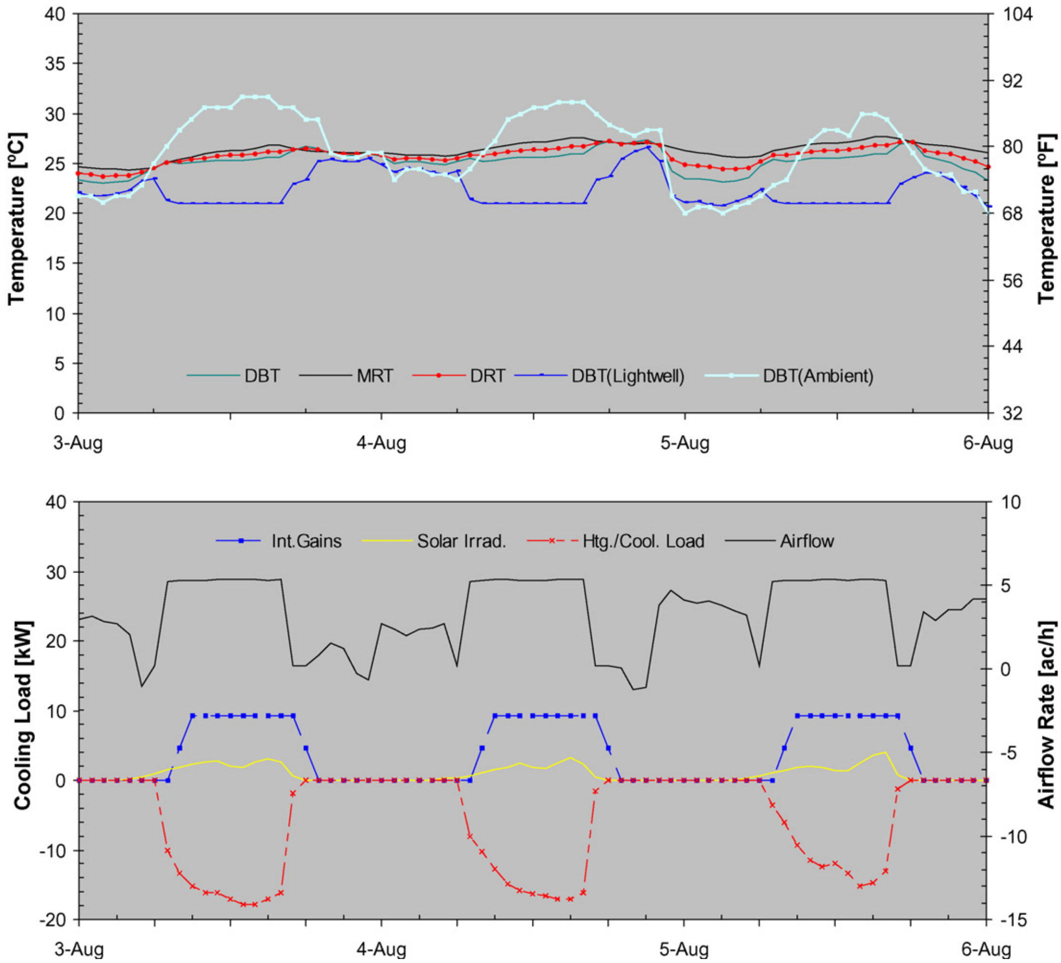

Fig. 6. Predicted space temperatures and airflow rates during a 3 day period in August: mechanical ventilation and cooling mode, passive night ventilation, 34 W/m^2 heat gain during the day, 5 ach^{-1} at 21 °C air supply.

performance of the actual building could be better than these simulations imply.

A supply of 5 ach^{-1} would not, given the basic building design, create an uncomfortable draught in the vicinity of the air inlets. Indeed, the airflow would have a pleasant cooling effect, making the region around the lightwell a desirable place to study. Higher volume flows of air, up to 8 ach^{-1}, may be necessary to accommodate higher internal heat gains or unusually hot weather and so the mechanical cooling plant was sized with this in mind.

3.3. Analysis of winter heating mode (MVH)

There is little risk that the building would be inadequately heated or ventilated in winter because there is direct warming of the space from perimeter baseboard emitters and the buoyancy forces driving the airflow will be strong. It was, nevertheless, interesting to analyse the winter performance to see what the internal temperatures would be when air was supplied during the day at the minimum fresh air requirement and at a temperature commensurate with the desire to maintain a displacement-type flow (i.e. at about 8 l/s per person, which is equivalent to 1.4 ach^{-1} in the model and a temperature of about 3 K below the target space temperature of 20 °C). In cold weather the air would be heated and, if necessary, humidified and then supplied mechanically to the lightwell. There would be secondary heating at the point of air outlet, plus perimeter heating (and internal heat gains), to bring the space temperature up to the desired value. In spring and autumn, when the ambient temperature exceeds a pre-defined value, say 6 °C, the air could be supplied purely passively, with pre-heating undertaken at the entrance to the supply plenum (Fig. 2).

The simulations indicated that, during the period from December to the end of February, the building could operate with air supplied at 17 °C and the minimum flow rate (8 l/s) and maintain internal temperatures below 23 °C (with 34 W/m^2 heat gain). During this period, most of the heating energy was required to raise the supply air to 17 °C, with little heat input needed by the perimeter heaters. During the day, temperatures in the spaces tended to rise gradually but the compact 33 m square form of the building, together with high levels of fabric insulation, meant that the DRT fell slowly at night (e.g. by about 4 K or so with an ambient external temperature falling to −5 °C, Fig. 7). It is interesting to note how the flow of heat back from the library into the (unheated) lightwell at night causes its temperature to rise. This is useful as it avoids the need for protective heating and

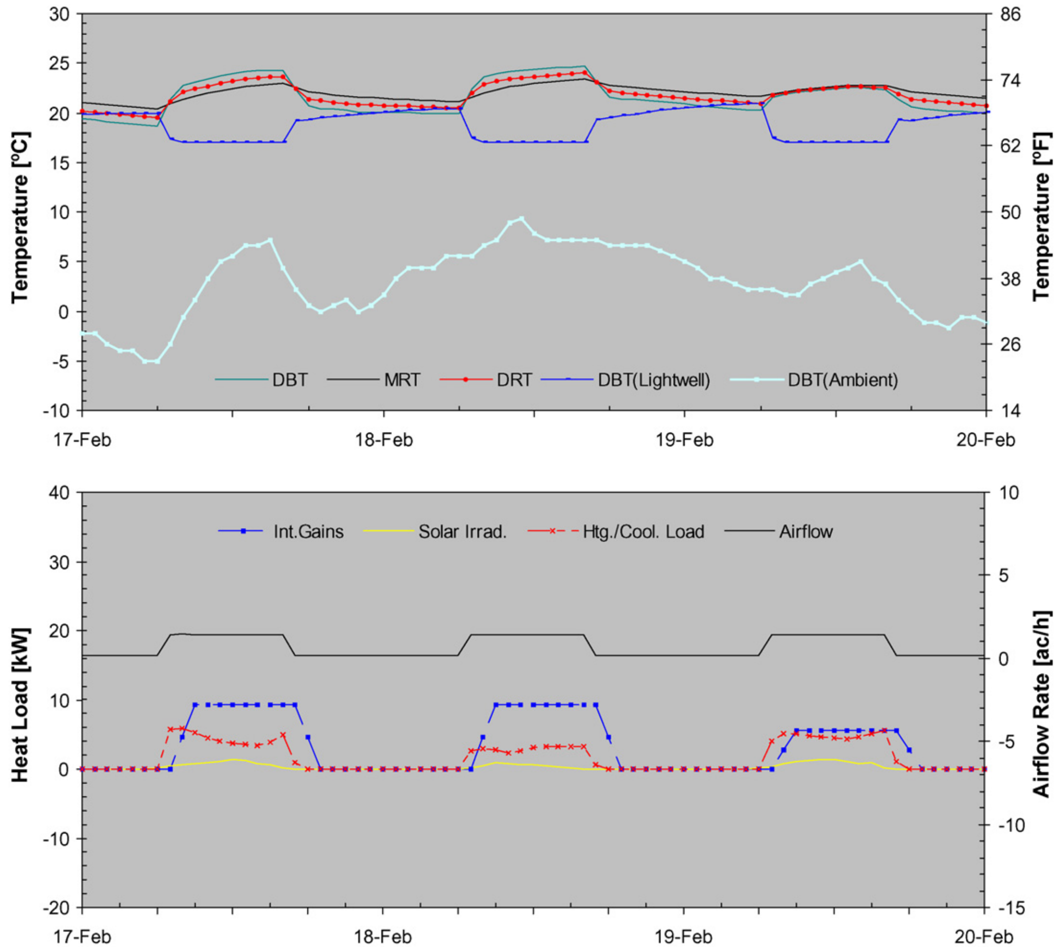

Fig. 7. Predicted space temperatures and airflow rates during a 3 day period in February: mechanical ventilation and heating mode, no night ventilation.

stops a reservoir of cold air building up in the lightwell overnight.

When the library is less densely occupied, the volume flow of air would be reduced in response to the measured CO_2 levels in the space. With higher occupancy, flow rates would be increased, perhaps beyond the level needed to maintain air quality, in order to restrain winter time space temperatures to acceptable levels. The top floor studio space was expected to be more densely occupied and here a raised platform around the lightwell provides a larger free area from which the higher volumes of air can issue and places the air delivery point away from occupants seated around the lightwell. This reduces the risk of cold draughts in winter (as well as providing a space for acoustic attenuation between the studio and the library below).

4. Airflow analysis

The thermal simulations provide an indication of the variation of temperatures with time, however they give no idea of the spatial distribution of temperatures. The purpose of the CFD model was to analyse such spatial variations and in particular to ensure that hot spots did not occur in an otherwise equable building, thereby tipping the whole building into mechanical cooling mode. CFD modelling also enables air speeds and flow directions to be studied thus identifying areas which are likely to be draughty or places where unexpected, and undesirable, airflows may occur (e.g. backflow from perimeter stacks into floors above). Identification of such problems can feed back into the design (e.g. through recommendations for larger opening areas or a need to partition exhaust stacks).

The CFD code CFX5 [17], was used for the analysis. It is a general purpose, state-of-the-art CFD code which uses the finite volume method for solving the governing equations of mass, momentum and enthalpy. It differs from many other codes in that it uses a *coupled* solver which solves for pressure and velocity simultaneously without the need for a pressure correction algorithm. It uses an unstructured mesh, although this capability is of less importance for the relatively simple geometries often encountered in buildings.

The CFD model was rather complex, consisting of one half of the building, from the plenum level to the roof, defined by a diagonal running from the north corner to the south corner (where the library entrance lies). At the time of modelling, level four was imagined as having a horizontal ceiling with the perimeter stack discharging into a flat-floored attic space. The model included: the main plenum; the distribution fingers running out of the plenum to the main perimeter upfeed stacks; the perimeter stacks; the separate ventilation outlets from level

Table 2
Details of CFD model: airflow paths, free opening areas, heat gains, predicted airflow rates and predicted air temperature elevations

Space	Inlet type	Outlet type	Free opening areas[a]		Heat gains[b]		Predicted airflow rates			Air temperature elevation at 0.9 m above floor (K)
			Actual m^2	% Floor area	W	W/m^2	m^3/s	ach^{-1}	L/s pp	
Plenum NW	Ambient	Lightwell	9.29	–	–	–	4.0	–	–	–
Plenum SW	Ambient	Lightwell	9.29	–	–	–	4.0	–	–	–
Level 2[c]	Lightwell	3 no. stacks	4.6	1.1	7306	17	2.18	3.9	84	2
R2.18	Upfeed shaft	Stack	0.23	1.9	423	35	0.12	10.1	123	2
R2.19	Upfeed shaft	Stack	0.12	1.4	326	40	0.07	8.3	68	3
R2.20	Upfeed shaft	Stack	0.12	1.4	334	39	0.07	8.2	70	3
R2.21	Upfeed shaft	Stack	0.23	1.7	453	34	0.13	9.3	125	2
R2.22	Upfeed shaft	Stack	0.12	1.0	421	35	0.06	4.6	57	4
R2.23	Upfeed shaft	Stack	0.12	1.0	481	33	0.07	3.9	72	4.5
R2.28	Upfeed shaft	Stack	0.60	1.8	744	46	0.38	11.3	23	2
R2.24	Upfeed shaft	Stack	0.23	1.4	1496	45	0.14	8.4	69	3.5
Level 3[c]	Lightwell	10 no. stacks	5.20	1.1	10313	20	2.43	3.6	85	2
R3.17	Low level from core	Stack	In: 0.4	1.2	620	19	0.20	6.0	200	3
			Out: 0.74	2.2						
Level 4[c]	Lightwell	3 no. stacks	6.4	1.2	11492	21	2.32	3.4	33	4
		5 no. stacks	11.4	2.1	11492	21	2.80	4.1	40	2.5
Roof Void	Stacks	Ambient	12.7	–	–	–	–	–	–	–

[a] Values are free area into and out of the space listed except plena which gives inlet areas only, the outlet area into the lightwell (i.e. half cross sectional area of lightwell) was 34 m^2.
[b] Total convective gain, people at 60 W, computers at 60 W, lights and solar gain at 4 W/m^2.
[c] Central open plan core area of stated floor.

four; the raised platform around the lightwell on level four; desks, below which air could circulate freely; book stacks; and the cellular offices and classrooms. The model thus includes all the complex air distribution routes. The realistic nature of the model was useful in conveying the ventilation concepts to the client and the rest of the design team (a simple animation was also generated).

The heat gains to each space were taken to be the convective gains under the full anticipated occupancy conditions; it was assumed that the radiant part of the gains were absorbed by the exposed thermal mass in the building. Solar gains were determined from specialised lighting studies using the RADIANCE software [18].

The ambient temperature was set to 21 °C, there was no wind, and the passively supplied air was not pre-heated. The resistance to flow at the plenum inlets and outlets was modelled by assuming a discharge coefficient of 0.61 (i.e. a loss coefficient of 2.69). Details of the spaces, their heat gains, the inlet and outlet sizes, the volume flows of air predicted and the elevation of air temperature in the occupied zone (above the supply value of 21 °C) are given in Table 2. Results for level two, which had many cellular spaces (Fig. 3), and level four, which had a reduced stack height, are discussed below.

4.1. Passive ventilation of level two

The CFD simulations predicted robust ventilation of all the level two spaces, with volume flows of air well in excess of those required to meet fresh air requirements (Table 2). As expected, spaces with larger openings have larger airflows for the same internal heat gain (compare, for example, rooms 2.18 and 2.22) and a room with higher heat gains is more vigorously ventilated than a similar room with similar % floor area openings but lower heat gain (compare rooms 2.28 and 2.21). This is the ‘self-rectification’ mechanism expected of a buoyancy driven flow regime but the greater sensitivity of flow rate to opening area rather than heat gains is clear. There were no occurences of unwanted backflow (e.g. from an exhaust stack into an occupied space).

The predicted temperatures in the open plan (book stack) area of level two at 0.9 m above the floor are 2–3 K above the supply (ambient) temperature (Fig. 8). The cellular spaces (rooms 2.18–2.21) are 2–3 K above the supply temperature whilst rooms 2.22–2.24 are about 4 K warmer—which suggests that these openings are a little small given the heat gains in these spaces. These temperature elevations are not too dissimilar from the values predicted by the DTS model on days when the ambient temperature was reasonably stable (eg. Fig. 5, 29 September)[2].

The vertical temperature distributions are characteristic of displacement ventilation with warm air stratifying at high level (Fig. 9). In the well ventilated areas the ceiling level temperature is about 2–3 K higher than in the occupied zone, although in room 2.28, which is rather densely occupied, the variation between the low level and ceiling temperature is about 4 K. In the under-ventilated rooms, 2.22–2.24, the temperature gradient is similar (i.e. about 2–3 K), but the occupied zone is warmer.

The dedicated supply to, and exhaust from, each cellular perimeter classroom space should be tailored to the expected use (heat gains). However, unlike the large open plan library

[2] Of course, the CFD code produces a steady state solution and so dynamic thermal effects are not represented.

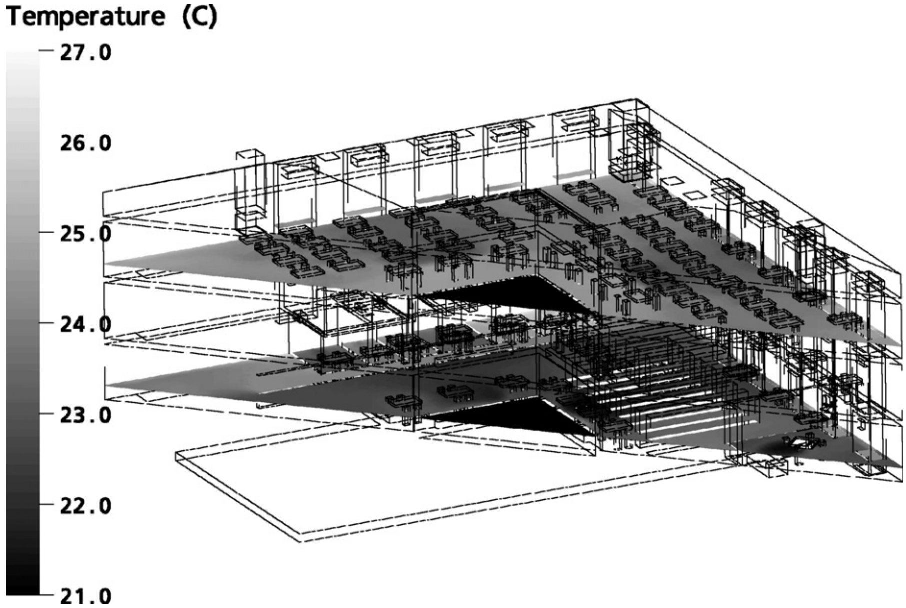

Fig. 8. Predicted temperature distribution across level two and level four at 0.9 m (3 ft) above floor level.

space, where the utilisation is rather predictable and stable over time, the classroom occupancy may change rather frequently during the day and their substantive function could alter over the lifetime of the building. This variability can be accommodated however, because the cellular spaces are located at the building perimeter where they can be passively ventilated directly from the outside by operable windows. In passive mode, this will generate both bi-directional mixing ventilation and, by virtue of the increase in the air inlet area, enhanced stack ventilation flow. The design envisages lower level operable windows with fixed windows above thereby introducing the cooler ambient air at low level and preserving the vertical temperature stratification. In active ventilation mode, sensors on the operable windows will relay their status to the BMS curtailing the mechanical air supply.

If a hybrid building were designed using the Judson strategy, but in a context where the operation of perimeter windows was undesirable, or impractical, the possible changes in occupancy over time, especially increases in heat gains, could be dealt with using localised cooling devices, either fan coil units or static cooling (chilled beams and panels). In fact the need for such devices was considered carefully at the preliminary design stage. But the perimeter location of cellular spaces and the provision of opening windows is a more elegant solution, and is lower cost, less energy intensive and in line with the client's preferences.

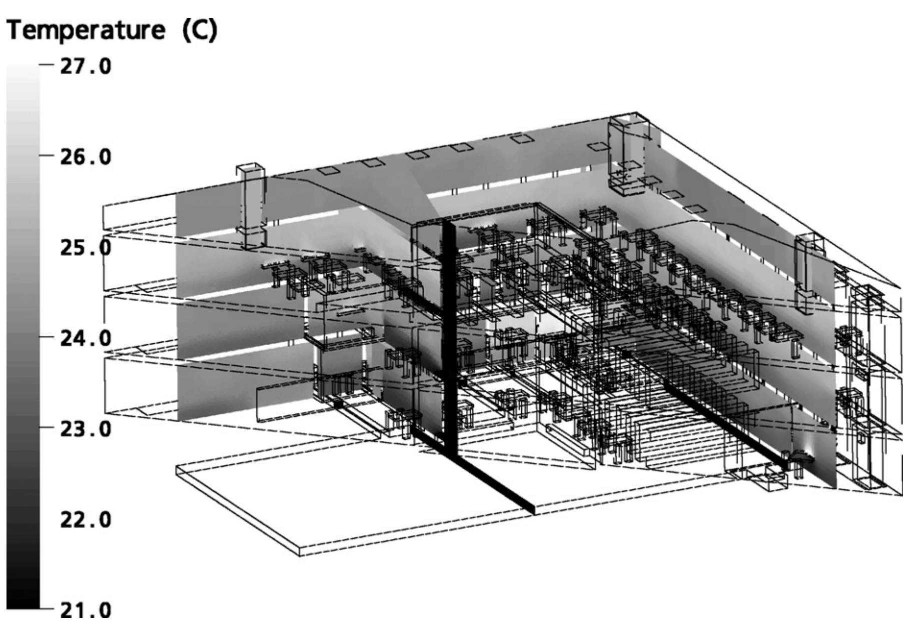

Fig. 9. Predicted vertical temperature distribution.

4.2. Passive ventilation of level four

Considering the level four results from the CFD analysis, it is evident (Table 2, Figs. 8 and 9) that the air temperatures are higher than desirable. At 0.9 m above the floor the temperature is 4–5 K above the supply temperature with the warmer stratified layer descending towards the occupied zone. By adding additional high level outlets in the ceiling, penetrating through the roof void to ambient, with a total area of 10 m^2, the ventilation rate was increased by 44% and floor level temperatures were close to ambient. These results added strength to the design team's argument that the level four ceiling should be of angled concrete planks which follow the roof line, thereby raising the ceiling height to create a reservoir within which stale warm air could accumulate. It also led to the building having operable clerestory windows at high level on level four as a mechanism for increasing the ventilation rate (see (12) in Fig. 2).

More generally, the level four results illustrate the frequently experienced 'top floor problem'. On this floor the stack heights are small, the solar heat gains (e.g. through perimeter windows and the roof) are often higher than on lower floors and, as the top floor is often a most desirable area to work, so the internal heat gains can be high. In the Judson building, level four is a studio filled with computers with the added complication of air delivery (and the flow resistance) below the raised acoustically lined staging.

4.3. Mechanical ventilation

A set of CFD simulations (not shown here) were conducted to test the impact of mechanical ventilation at 6 and 8 ach^{-1}. At a volume flow rate of 6 ach^{-1}, all occupied areas were within 3 K of the supply temperature (and at 8 ach^{-1} within 2 K of the supply temperatures). This, and the dynamic thermal simulations, suggest that a supply temperature of 21 °C would be low enough to maintain comfort in the space for the heat gains modelled without causing local draughts at the air inlet to the space (i.e. supply rate 6 ach^{-1} or less).

It is worth emphasising that the CFD program predicts air temperatures, whereas the thermal simulation results have shown that the dry resultant temperature, which is a better indicator of the likely comfort conditions, could be 2 K lower.

5. Discussion

The design of the Harm A. Webber Library at Judson College evolved from the experience gained through designing the Coventry University Library [9,10] and the SSEES building [12]. There are many design differences between the three buildings. Most importantly, the Judson building incorporates mechanical ventilation with associated heating, cooling and air recirculation to combat the severe winter cold and summer warmth experienced in the Chicago hinterland. It also incorporates operable perimeter windows and a more sophisticated network of air delivery ducts so that cellular spaces are directly ventilated.

In developing the Judson design, various US design codes were consulted. It has been noted above that the ASHRAE Standard 62.1 [2] on ventilation, is written on the presumption that buildings will be mechanically ventilated. The standard states, however, that NV systems are permitted '*in lieu of, or in conjunction with, mechanical ventilation systems*' but goes on to list a number of pre-requisites which should be met. These include '*naturally ventilated spaces shall be permanently open to and within 8m of operable wall or window openings to the outdoors, the operable area of which shall be a minimum of 4% of the net occupiable floor area*' and '*the means to open required operable openings shall be readily accessible to building occupants whenever the space is occupied*'. Such guidelines reinforce the notion that NV is (only) appropriate to shallow plan, perimeter ventilated and occupant controlled buildings, which severely limits the applicability of the technique. The standard does, however, provide an exemption to the requirement in the case of '*an engineered natural ventilation system when approved by the local authority*'. The term '*engineered*' is not defined, which could be rather helpful for innovative designers, but proving the concept to the satisfaction of 'a local authority' unfamiliar with ANV buildings could prove burdensome and ultimately fruitless.

The Judson library building differs dramatically from this ASHRAE guidance. Admittedly it has the support of a mechanical system but it's predecessors (the Coventry Library and SSEES building) do not, and the former would appear to function well in the temperate UK climate. These buildings have, typically, openings of 1–2% of occupiable floor area, which are usually not occupant controlled and may not open to the outdoors. They represent a form of ventilation (i.e. C–E or C–C), which could be usefully deployed in the more temperate regions where ASHRAE Standard 62.1 is used as the ventilation standard.

As we come to terms with the need to curb CO_2 emissions through the more efficient use of energy, it seems sensible, through the eyes of the European authors of this paper, to have standards, supported by design guides, which presume in favour of NV and against air conditioning rather than the other way round. New standards might also usefully make the status of hybrid buildings, and the recommendations which apply, clearer. A useful starting point would be to adopt such standards in US states which have a temperate climate, thereby reducing the complexity of the necessary NV design solution, reducing the risk of design failures (and the impact on building owners and occupiers if buildings emerge which are less than ideal) and creating a body of expertise within the US building design community. There are encouraging signs that such developments are underway (e.g. [19]) and certainly the LEED initiative [20] is broadly supportive of such developments.

This paper has suggested that hybrid buildings could have wide spread applicability within the USA. They would assist in our global efforts to mitigate climate change: nationally they would help to improve security of energy suppliers and locally they could reduce the loads on the electricity supply system (due to air conditioning). Clients would benefit from buildings, which are cheaper to operate, tolerant of mechanical or operational failures,[3] and occupants would enjoy a healthier, quieter and well daylit working environment.

6. Conclusions

This paper presents some general observations of the efficiency of naturally ventilated buildings and discusses how ANV buildings incorporating stacks can be turned into a temporal hybrid form, which combines passive and mechanical ventilation. The idea is embodied in the new Harm A Webber Library, for Judson College, Illinois, near Chicago. The design represents an evolution from two earlier UK ANV buildings, in Coventry and London, which will combat, in an energy efficient manner, the severe climate of the region.

The maximum *U*-values for building envelope components given in ASHRAE 90.1 [21], for the Chicago climate, are much higher than those specified in the current UK Building Regulations, and the proposed future Regulations. This is surprising given the severity of the Chicago climate compared to those experienced in the UK. The final design *U*-values used are well below the ASHRAE 90.1 maxima.

The performance of the proposed library building was predicted using a dynamic thermal simulation model. This identified, for the anticipated occupancy, four clear operating seasons: mechanical ventilation with heating, from December to February (MVH); mechanical ventilation with cooling, from June to mid-September (MVC); and passive ventilation, with heating if necessary, from March to May inclusive and from mid-September through to November (PV and PVH). The results illustrated how, in PVH mode, solar shading, good insulation and internal exposed thermal mass together with night ventilation, can yield internal DRTs which are over 2 K below the ambient air temperature, even on a succession of hot days with full indoor occupancy. Night ventilation was also valuable for cooling exposed thermal mass on summer evenings thereby reducing the load on the mechanical cooling system on the following day (MVC mode).

A large CFD model of one half of the library confirmed that robust ventilation throughout both open plan areas and cellular spaces was likely to be achieved. By locating cellular spaces at the building's perimeter, operable windows could be used to combat abnormally high internal gains thus avoiding the need for distributed cooling plant. The model indicated that the top floor of the building, a design studio, would be warmer than the lower levels. The final library design has an increased ceiling height on the top floor and operable clerestory windows to enhance airflow.

The CFD simulations illustrated how a buoyancy driven ventilation system 'self rectifies', i.e. naturally provides greater ventilation to more densely occupied, and thus warmer, spaces. This, together with the provision of space-specific opening areas and thermal mass means that denser occupancy in one part of the building will not lead rapidly to thermal discomfort or tip the whole building from passive into mechanical cooling mode.

The actual building will have a building management system to control dampers and thus the airflows and its performance is likely to be better than that predicted by the simulation models.

The building's natural ventilation strategy differs significantly from the guidance given in ASHRAE Standard 62.1 and yet evidence from the precedents on which it is based, and the environmental design analyses, suggest that it will perform satisfactorily. It is suggested that the standard should be reviewed so that it encourages low-energy natural ventilation solutions, particularly in more temperate regions and to clarify the status of hybrid ventilated buildings.

At the time of writing, the Judson building is under construction. Hopefully this paper will whet the appetite of other architects and engineers to embark on the design of innovative hybrid buildings.

[3] Ironically, during a transatlantic telephone conversation, the Chicago area design team found themselves in a centrally located office, in a deep plan building with no operable windows during a power blackout. Their discomfort would have been much less acute had they been occupying an office in the very building they were designing at the time (even without its mechanical systems operating)!

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