VENTILATION AND THERMAL PERFORMANCE OF DESIGN OPTIONS FOR STADIUM AUSTRALIA

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ABSTRACT

Stadium Australia is to be the centrepiece of the year 2000 Sydney Olympics. The architects aimed to minimise energy consumption by incorporating passive design measures which would provide ventilation, natural cooling and warming and daylight. This paper describes the simulations undertaken to guide the design of one space in the stadium - a banquet hall.

Lighting simulations demonstrated that a facade design incorporating external fixed, horizontal shading and a light shelf can provide satisfactory daylighting levels and permit winter solar gains to offset heating demands, whilst excluding the summer sun.

Thermal analyses illustrated that natural stack-driven displacement ventilation can deliver conditions which might be considered comfortable despite the hot, sunny summer-time conditions. The strategy employed ground cooling during the day, and night venting to cool insulated thermal mass at night. Summer comfort cooling could easily be incorporated to guarantee satisfactory internal temperatures. This hybrid solution had much lower energy demands, plant loads and operating periods than a conventional air-conditioned solution.

Computational Fluid Dynamics (CFD) analyses demonstrated that sufficient fresh air could be well distributed throughout the hall and that night venting would occur.

State-of-the-art simulation enables innovative, low energy design solutions to be pursued by architects and clients with greater confidence. It will continue to play a vital role in the environmental design of the world's largest and most prestigious buildings.

INTRODUCTION

The winning design for the Stadium Australia, which will be the centrepiece of the year 2000 Sydney Olympics, was based on a bold structural solution and a firm commitment to a 'green' design. The design proposal promised "a mature and responsible attitude to the issues of ecologically sustainable development which [would] pervade every aspect of [the] approach to the design of the stadium so that it will showcase to the world the commitment of Sydney and NSW to the preservation and enhancement of the natural environment". The design team considered the breadth of relevant issues which included an assessment of the environmental impact of the building.

Most importantly for this paper, the aim was to "incorporate passive design measures to provide ventilation, natural cooling and warming, and daylight to minimise energy consumption". The architects, Bligh Lobb Associates, noted however that "the key to responsible design and construction is to have information on the true consequences of actions. This requires the collection and analysis of evidence rather than simply an opinion". The Multiplex company, which headed the consortium building the stadium, therefore commissioned detailed studies to gather this evidence. This included an integrated thermal, daylight, sunlight and airflow analysis by the Institute of Energy and Sustainable Development (IESD) at De Montfort University, using the state-of-the-art simulation programs ESP-r (ESRU 1995), RADIANCE (Ward 1994) and CFX-Flo3D (CFDS 1995). The IESD group worked closely with Cambridge Architectural Research (CAR), Max Fordham & Partners (MF&P), Simulation Technology Ltd. (STL) and others (see acknowledgements) in a team co-ordinated by Short Ford & Associates (SFA). The CAR group used water and brine and a physical model to investigate air movement in areas where many spaces link in a complex manner, MF&P investigated issues of thermal comfort whilst STL conducted wind-driven and buoyancy driven airflow analyses using the Sabre CFD program.

One area analysed was a large banquet hall located below the stadium seating. This was chosen as a 'litmus test' for the passive environmental control strategy since it would be densely occupied, and yet occupants would expect a plush, high quality and thermally comfortable environment. In Sydney, the normal approach would be to air-condition such a space.

The aim was to evolve a design which would avoid air-conditioning if possible but, recognising the severity of the climate, to reduce the size of the cooling (and heating) plant, the periods of their operation, and their energy consumption. By being involved at the early stages of the detailed design process, simulation had a real impact on the stadium's design.

THE BUILDING

The stadium (Fig. 1) is being built in Homebush, a suburb to the West of Sydney centre (latitude 39^{o}S) on a flat coastal site. It will seat up to 110,000 spectators in 'Olympic mode', and in post-Olympic mode, when the end-stands are simplified and the lower tier of the seating is retracted to facilitate a football pitch, up to 80,000 spectators.

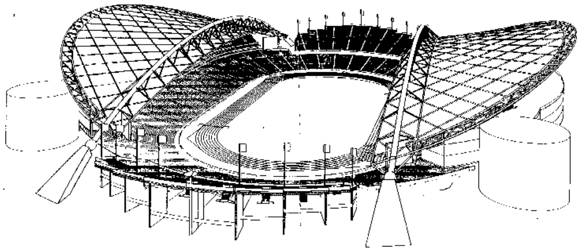

Figure 1 Design proposal for Stadium Australia (after Bligh Lobb)

The main stands, and the accommodation within them, are mirror-symmetric. Spiral ramps provide service access to each floor whilst a central escalator shaft offers occupant access.

The banquet hall on level 4 (Fig. 2) is double height and overlooked by a balcony on level 5. The floor measures 75m by up to 23m giving a total area of 1500m^2 to accommodate 1500 people. Floor-to-ceiling glazing which faces West (or East on the opposite side of the stadium) is shaded by both horizontal and vertical angled fixed external louvers. The top side of the ceiling is exposed to ambient conditions (as level 6 is effectively a large open patio), and administrative offices are below the back part of the floor.

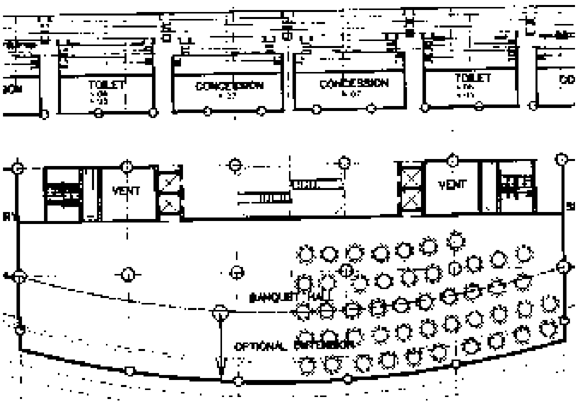

Figure 2 Plan of level 4 central area showing banquet hall

The design conditions for the hall were established with the architects as:

Winter-time minimum temperature: 18^{o}C
Summer-time maximum temperature: 26^{o}C
Minimum fresh air supply: 12 to 15 l/s/ person
Occupancy density: up to 1 person per m^2 before and after events.

For simulation purposes, a maximum heat gain of 100 W/m^2 was used, and the design temperatures were taken as the heating and (for simulations which assumed air-conditioning or comfort cooling) the cooling set-points.

THE CLIMATE

An annual climate file of hourly values was constructed from an average year (1984) at Sydney airport for solar radiation and wind values, and data from Bankstown (near Homebush) for dry bulb and wet bulb temperatures. Bankstown was roughly 2^{o}C warmer than Sydney airport in summer.

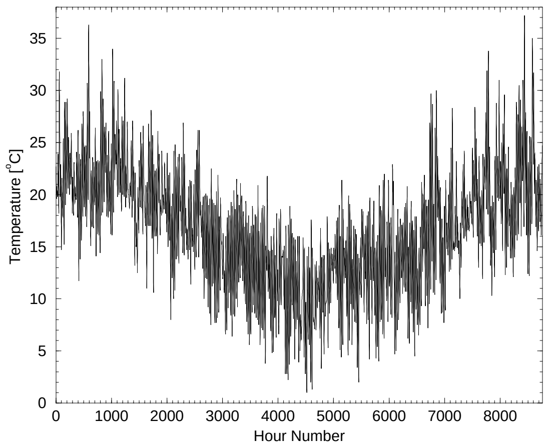

Figure 3 Hourly annual ambient dry bulb temperatures, Bankstown 1984

The dry bulb temperatures during the summer months reached 36^{o}C, whilst on one winter day the peak temperature was only 8^{o}C (Fig. 3). The cooling set-point of 26^{o}C was exceeded for a total of 380 daytime hours, with virtually all of those falling in the months October to February. In February, the hottest month, there were on average 3 hours per day when the temperature exceeded 26^{o}C. On the hotter days, the diurnal temperature swing was up to 15^{o}C, although a swing of about 8^{o}C was typical. Wet bulb temperatures peaked at 24^{o}C (Fig. 4).

The site was windy, with speeds of 3.5 m/s being common, whilst rates up to 14 m/s were recorded. The peak summer-time global horizontal solar irradiance exceeded 900W/m^2.

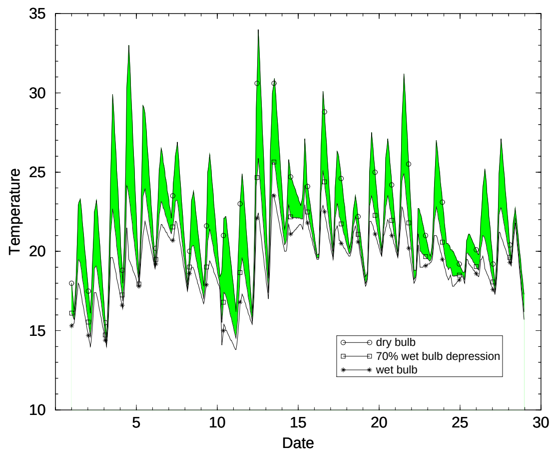

Figure 4 Hourly dry bulb and wet bulb temperatures in February and theoretical temperature reduction by evaporative cooling

ENVIRONMENTAL DESIGN CONCEPT

The main environmental design problem was to maintain thermal comfort during the summer-time in the face of the high ambient temperatures, intense solar radiation and, in the banquet hall, the intermittent but high internal gains. The deep plan space also made it difficult to ensure that adequate fresh air would reach all occupants. The space would also need heating in winter, particularly in the pre-occupancy period, and so some solar gain at these times could be beneficial.

To solve the ventilation problem, and to provide natural cooling in spring and autumn, an initial design evolved in which fresh air was introduced at the back and the front of the banquet hall at low level and extracted at high level through vertical shafts - a natural displacement ventilation system (Fig. 5). Based on previous experience in the Queens Building at De Montfort University (Eppel & Lomas 1991) each vent shaft was sized initially at 25m^2 cross sectional area. Initially the shafts extended to the stadium roof, so it was possible in principle to ensure a relative negative pressure at the termination for all wind speeds and directions, e.g. by using an aerofoil. This would enhance the buoyancy-driven air flows. The length of each chimney below the extract point was initially used to supply air up to the rear of the banquet hall. Louvres in the supply and extract vent would control the flow rates, and heating coils would warm the air in winter.

To reduce summer-time heat gains, alternative glazing areas and shading strategies were examined, along with improved insulation (see below). Nevertheless, it was evident that ventilation alone was unlikely to maintain thermal comfort in summer, so natural cooling strategies were explored: night venting to cool exposed concrete ceilings and walls; air-based ground cooling; and passive downdraught evaporative cooling (Bowman et al 1996). Direct evaporative cooling was quickly abandoned as an option for the banquet hall, although it was pursued more vigorously for cooling the members' lounges in a later, second phase, of the work.

The design which was analysed (Fig. 6) had high-level vents stretching around the whole glazed facade, which would be automatically opened at night only.

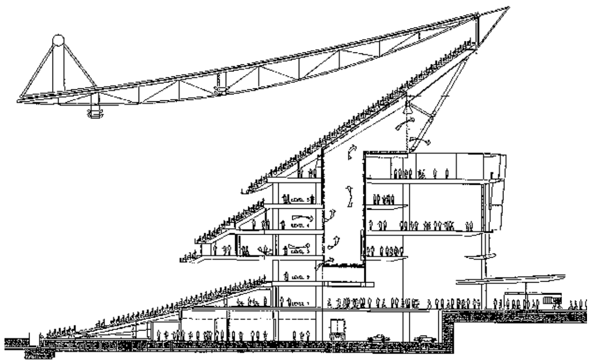

Figure 5 Section through stadium showing banquet hall and vent shaft

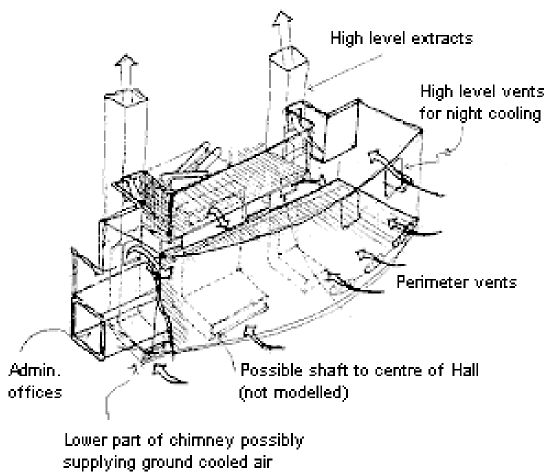

Figure 6 Axonometric of initial ventilation strategy proposed for the banquet hall

During the day, air could be mechanically pulled through ground pipes and delivered up the lower part of the vent shafts. This air would ventilate the innermost part of the hall (and thus satisfy half the fresh air demand of the occupants), the remainder would be ambient air supplied along the outer perimeter.

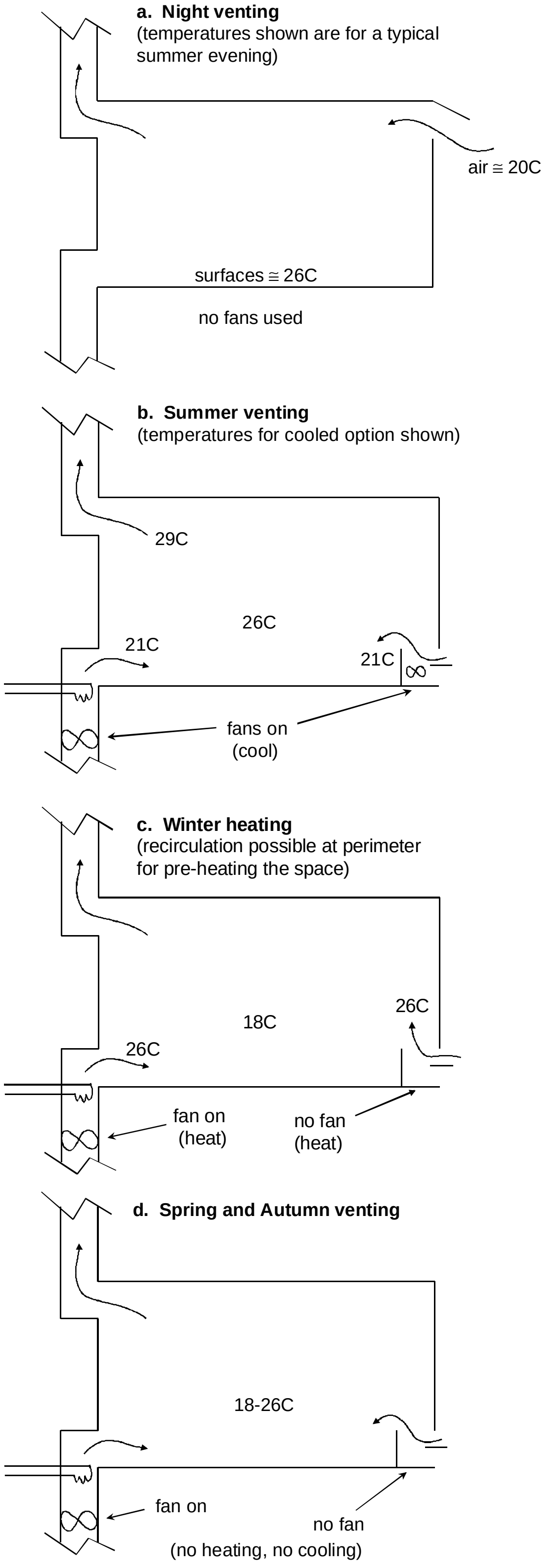

Figure 7 Operating modes for banquet hall

A hybrid solution was also analysed, in which the supply air could be mechanically cooled at the point of delivery. Since 'coolth' recovery is very difficult in a natural exhaust system, the supply rate would meet fresh air needs only, and the supply temperature would not be too low. In this hybrid mode, chilled air would be delivered by fans to positively pressurise the space and force the cool air up the vent stack (Fig. 7).

FACADE DESIGN

RADIANCE was used to predict daylight levels and solar penetration for the proposed design (full height glazing and angled vertical louvres), and for a number of alternative designs proposed by the environmental design team. The sunlight penetration was investigated for each hour of the chosen days, along with a daylight prediction using the standard CIE overcast sky distribution. The daylight results for the proposed design, and one alternative, are shown here (Fig. 8).

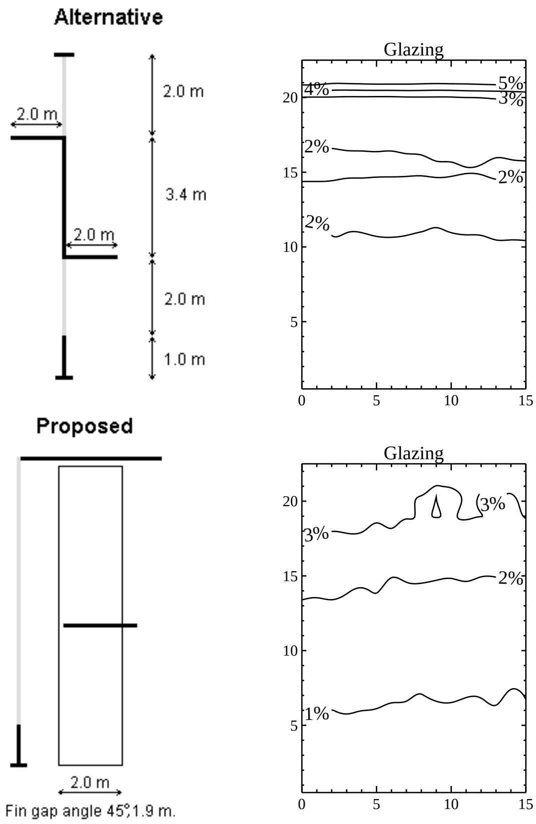

Figure 8 Alternative and proposed facade glazing and shading with predicted daylight factors across a section of the banquet hall

The proposed design prevented any sun penetration in mid-summer, but the daylight levels at the rear of the hall, assuming a standard CIE overcast sky, were below 1%. Only around 35% of the floor had a daylight factor over 2%.

The alternative design incorporated an internal light shelf and external horizontal shading. These also precluded any sun penetration in mid-summer, but the daylight levels were higher (about 55% of the floor with a daylight factor above 2%, and none below 1%). This alternative also had the following advantages: it should precipitate lower electricity use for lighting; it preserved panoramic views from both the floor of the hall and the balcony; it provided high-level windows which could be opened to facilitate the night venting; the thermally massive inside light shelf, which would intercept direct solar gain, would be vent-cooled again at night; and the low-angle sun would penetrate the hall, helping to warm it (and also bring a psychological 'sparkle') in mid-winter. The alternative design is the analyst's preferred solution and one which could be applicable in other buildings. It was used as the facade design in the thermal simulations.

GROUND COOLING

The potential benefits of drawing the air supplied to the rear of the banquet halls through ground pipes was investigated using ESP-r. Pipes were assumed to be of square section with a concrete wall. There was 2m of earth above the pipes and 6m below, at which point a deep ground temperature (which varied monthly) was assumed. Pipes of different lengths, horizontal separation, cross-sectional area and roughness (which affects the surface heat exchange) were simulated. The results indicated that:

a) pipes can be designed which will deliver air below the cooling set-point in summer;
b) the same pipes could, and indeed should, be used to pre-warm supply air in winter;
c) for a given mass flow rate, the exit temperature reduces as the pipe length increases, the cross-sectional area decreases and the roughness (and hence turbulence) increase; and
d) pipe performance was relatively insensitive to deep ground temperature. This suggests that heat exchange between the air and the ground immediately surrounding the pipe are most important.

By using the pipes in winter, the temperature of the pipe walls and, more importantly, the surrounding ground, is re-cooled so that the pipes are effective during the subsequent summer period. If used only in summer, the surrounding ground gradually warms and the pipes' cooling performance degrades (over a long time period).

A pipe array suitable for supplying half the fresh air needs of the banquet hall (e.g. $18m^3/s$ at 12 l/s/p) would consist of 36 pipes each 60m long with cross-section $0.5m^2$ carrying air at 1 m/s. Separated at 2m intervals horizontally, this array would cover an area 108m wide. This might be feasible because there are large paved areas for spectators to congregate outside the stadium. The energy required by the fans would be similar to that needed if the air were delivered by a conventional ducted system.

Practical problems with such pipes include the need to provide: a sloped floor to drain any condensation or rain water that penetrates (although anecdotal evidence from some installations suggests moisture problems do not occur); access for cleaning; grillages across inlets and outlets to exclude animals; protection during construction to prevent crushing by heavy machinery; and an inlet which is designed so that the security of the building is not compromised. (Security is given a very high priority at the Olympics).

Given these factors, the large array size needed, and structural constraints, cooling using ground pipes was not adopted. The simulations had, however, succeeded in proving the theoretical benefits of ground cooling.

THERMAL ANALYSES

At the heart of the study was a sensitivity analysis using ESP-r. This focused on the West facing banquet hall which, in preliminary simulations, had been shown to be most susceptible to overheating.

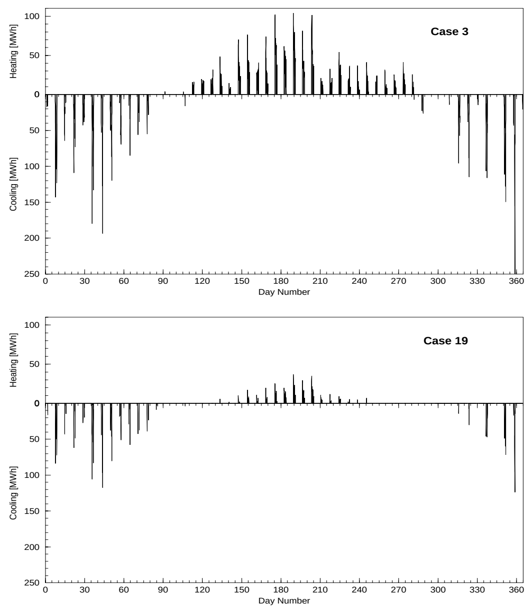

Figure 9 Heating and cooling plant usage profile

Table 1 Some of the variations explored using thermal simulation

Case	3	9	13	17	19	25	20
Facade[1]							
Proposed	•	•	•	•	•		
Alternative						•	•
Ventilation[2]							
Mechanical	•						
Passive with night vent		•	•			•	
Passive with ground pipes				•	•		•
Insulation[3]							
None	•	•		•			
150mm			•		•	•	•

[1]Proposed - full height glazing with angled vertical louvre shading. Alternative - half area of glass, external horizontal shading and light shelf.
[2]Mechanical - fan driven ducted air (6ach^{-1}). Passive with night vent - (6ach^{-1}) exhaust via chimney, passive supply at perimeter and rear, passive night vent also. Passive with ground pipes - supply air to rear mechanically delivered via ground pipes (3ach^{-1}).
[3]None - no insulation as design proposal. 150mm - external insulation thickness above roof deck and below floor.

It was assumed that, throughout the year, there was an evening fixture on Saturday followed by an afternoon fixture on Sunday. Whilst this produced more 'fixtures' than are likely in practice, thus energy demands will be over-estimated, it enabled the impact of sequential events at any time of the year to be studied.

The impact of the facade design (area of low-emissivity double glazing and shading), the use of external insulation, and the method of ventilation and cooling, were studied (Table 1). Each design variation was simulated with the space being (a) naturally controlled (except for winter heating); and (b) in hybrid mode, i.e. with summer-time mechanical cooling as well.

The results for 7 cases (see Table 1) are shown in Table 2. This includes, for the hybrid option: the heating and cooling energy demands (excluding latent loads and parasitic energy users such as fans and pumps); the peak (sensible) loads; and the hours of plant operation. Air temperatures would be between 18°C and 26°C during the occupied periods (09:00 - 02:00 Saturdays and 09:00 - 24:00 Sundays). From the hourly loads (Fig. 9), it is evident that, for case 19, there is a large period of the year when neither heating or cooling is needed, i.e. the design functions purely passively.

The summer-time temperatures, when operating without any cooling, are also given in Table 2 as: the number of occupied hours when either the air temperature or dry-resultant temperature exceeds 27°C and, the hottest temperatures obtained on a hot summer day (19 February), ambient peak temperature 27°C). The frequency of occurrence of specified temperatures are given in Figure 10.

Table 2 Heating energy and loads, and either cooling energy and loads for hybrid (mechanically cooled) space or temperatures for free-floating (non-cooled) space

Case	Annual Energy Predictions			Plant Loads		Hours of Operation[1]		Hours Temp. > 27°C[1]		Peak Temp[3].	
	Heating MWh	Cooling MWh	Total MWh	Heat kW	Cool kW	Heat hrs	Cool hrs	Air hrs	DRT hrs	Air °C	DRT °C
3	16.4	15.4	31.8	104	251	617	477	341	300	31.3	30.7
9	16.4	14.3	30.7	104	248	617	270	154	146	30.6	29.6
17	12.8	4.0	16.8	102	122	542	143	50	61	28.8	28.4
13	4.2	16.4	20.6	69	251	298	306	172	202	30.0	30.4
19	2.1	4.9	7.0	37	123	183	165	61	82	29.0	28.9
25	8.7	10.9	19.6	76	225	536	306	66	113	30.0	28.3
20	5.6	2.2	7.8	49	95	429	108	20	2	28.1	26.8

1 *Saturdays 09:00 to 02:00; Sundays 09:00 to midnight; total possible hours per year = 1664.*
2 *The alternative shading strategy precludes the transmission of direct solar radiation in summer. Movable blinds ensure direct solar gain in winter for cases 20 and 25 and this would reduce tabulated heating energy demands.*
3 *Value for typical hot day.*

Numerous observations could be made about these simulations, and readers may wish to study the results for themselves in detail. In the context of this paper we simply note that for the assumed intermittent occupancy, the insulated, night vented and ground cooled design (case 20) seems to be capable of maintaining conditions which may be considered to be comfortable for almost all the year (Fig. 10) even without mechanical cooling. If the additional 'security' of a hybrid system is sought, then the design will induce only small sensible cooling loads. The air flows for the hybrid strategy were studied further using a CFD program.

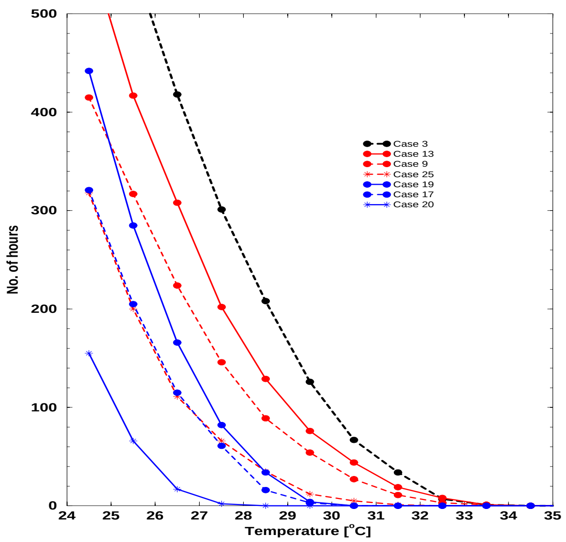

Figure 10 Cumulative number of hours for which particular dry resultant temperatures are exceeded in naturally controlled option

CFD ANALYSIS

With the proposed strategies it was important to ensure: that the assumed air flow rates (6ach^{-1}) would be achieved by the stacks; that there was a good distribution of fresh air throughout the space; and that night venting could occur passively i.e. without the use of the fans. To explore these issues, analyses were undertaken using the CFD program CFX-Flo3D.

It was assumed that the aerofoil over the stacks would create a small negative pressure of about 7Pa under the average wind speed of 3.5m/s. It was also assumed that all interior surfaces were adiabatic - i.e. not cooler than the space air.

With perimeter and ground vent supply fans in operation to deliver 5.0ach^{-1} (12 l/s/person), the average interior temperature was around 28°C for a supply temperature of 21°C (Fig. 11). However, in the centre of the hall, poor distribution generated a hot-spot. This might be avoided by re-directing the fan-delivered air, and in any case occupants would cause some mixing.

Night venting was successfully induced at an air flow rate of 7ach^{-1} under typical summer conditions (Fig. 12).

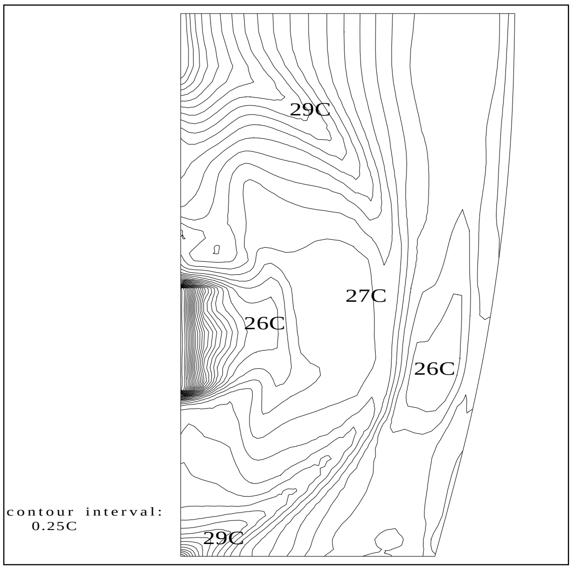

Figure 11. Horizontal temperature distribution under full load conditions, mechanical supply 21°C at about 1m^3/s

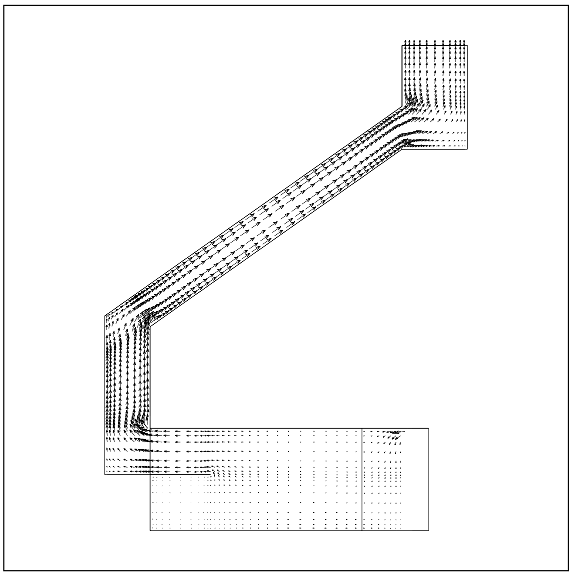

Figure 12. Air flow in banqueting hall under night time venting conditions, intake open area 25m^2, surface temperatures 26°C, ambient temperature 20°C
(a vector of 1cm corresponds to a speed of 4m/s)

ACKNOWLEDGEMENTS

The authors worked closely with others in an interactive way to evolve the passive environmental design concept and to analyse the performance of alternative strategies, in particular, Brian Ford and Peter Sharratt of Short Ford & Associates, and Geoff Whittle of Simulation Technology Limited who advised on the CFD analyses presented here. Others in the team were: Cambridge Architectural Research; Max Fordham and Partners; Peter Heppel Associates; and, BDSP Partnership.

CONCLUSIONS

1. An integrated lighting, thermal and CFD simulation analysis has been undertaken to assist with the ventilation and environmental design of Stadium Australia in Sydney.
2. A strategy for maintaining thermally comfortable conditions in the large 1500m^2 banquet hall, which was intermittently occupied to a density of 1 person/m^2, was proposed and tested.
3. Natural ventilation and cooling strategies were employed: fresh air was exhausted passively through vertical chimney vents; thermal mass was cooled by night venting; and air was supplied at low-level partly by using fans.
4. Ground cooling was shown to be viable. However practical design issues, the large array size required and structural constraints precluded its use in the final stadium design.
5. A hybrid approach, using fan coil units which heat in winter, cool in summer, but permit night venting would ensure comfort. The hybrid design, would have reduced cooling load, the systems could be of smaller capacity, and operate for a shorter time.
6. Whilst the final stadium and banquet hall design will differ from that which was analysed here, many of the passive environmental control concepts will be adopted in other spaces.
7. Simulation analysis continues to play a vital role in the environmental design of some of the worlds most prestigious and innovative buildings.

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