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Thermal Simulation Studies of a Low Energy University Building in Australia

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A key criterion by which any building will be judged when its environmental impact is assessed is its thermal performance. This paper describes the simulation of an office module in a three-storey university building in south eastern Australia. The module, located at the north-west corner of the top floor of the building, was chosen because it is likely to have the highest cooling load - a primary concern of energy conscious designers of commercial buildings for most parts of Australia.

In the paper, the initial key assumptions are stated, together with a description of a "reference" or base case, against which improvements in thermal performance were measured. The simulation process identified the major influences on thermal performance. This enabled changes in materials and construction, as well as basic design concepts to be evaluated. Features incorporated into the base case such as a metal roof and glazed walkway were found to have adverse influence on energy consumption, and were consequently rejected in preference for an improved design which included a hypocaust slab system on the roof of the office module. The final design was predicted to reduce the annual energy consumption for heating and cooling by 72% and 76% respectively.

Keywords: Simulation, TRNSYS, Commercial Buildings, Hypocaust, Pre-cooling, Night-time Cooling

Introduction

Forecast growth in energy consumption in the commercial building sector in Australia between 1990 and 2010 is projected to rise by 138 PJ[1] per year or over 90% in a "business as usual" scenario. As a result, greenhouse gas emissions from this sector are projected to rise by 30 Mt of CO_2-e per year or 95% (AGO, 1999). Emissions are also projected to rise in most other sectors of the economy so that Australia's Kyoto commitment to limit its greenhouse gas emissions to eight per cent above the 1990 level by the first commitment period (2008-12) presents a considerable challenge. As part of the response to this problem, a variety of

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[1] Note: petaJoule = J x 10^{15}

initiatives have been implemented at Federal and State Government levels to improve the energy performance and reduce the greenhouse gas emissions of commercial buildings.

The Federal Government is proposing the addition of minimum energy performance requirements to the Building Code of Australia. The objective will be to eliminate worst practice within the industry by defining an acceptable minimum level of energy efficiency for new buildings in Australia. At a State Government level, a Building Energy Brief (SEAV, 2000a) has recently been released in Victoria. Clients can use this practical tool when briefing the project team responsible for the design, construction or refurbishment of any non-residential building. A directory of case studies and company profiles (SEAV, 2000b) has also been published by the same agency to showcase the commercial buildings of designers and architects with a proven track record in energy conscious design and practice. In New South Wales, the Sustainable Energy Development Authority has launched a star rating scheme for commercial buildings (SEAV, 1999). This voluntary scheme should enable building owners, managers and tenants to obtain recognition for buildings with low greenhouse gas emissions and to identify changes that can be made to improve performance.

Against this background, a multi-storey Science and Technology Building at the campus of Deakin University in Melbourne is currently under construction. The overall objective of the client, the Department of Building and Grounds, was to demonstrate environmental awareness and energy efficiency in the design and operation of their new building, within budget restraints. This paper describes the thermal simulation of the various building options considered during the design phase. By working through the alternatives in building concept, materials, equipment and operating strategy, the client was able to select a design whose thermal performance closely approaches one of their initial aims i.e. a building with little or (ideally) no air conditioning.

General Building Concept

The spatial requirements of the occupants and general design concept had already been developed prior to the commencement of the simulations. In plan, the structure measures 55 metres by 20 metres with the long axis running from east to west. The three-storey building is to contain laboratories, lecturing and teaching facilities, as well as offices. A floor plan (Figure 1) shows a central atrium dividing north and south facing rooms. This atrium is to provide a meeting area as well as natural light and ventilation. The concept and approach followed by the design team has been presented in detail elsewhere (Luther and Fuller, 2000).

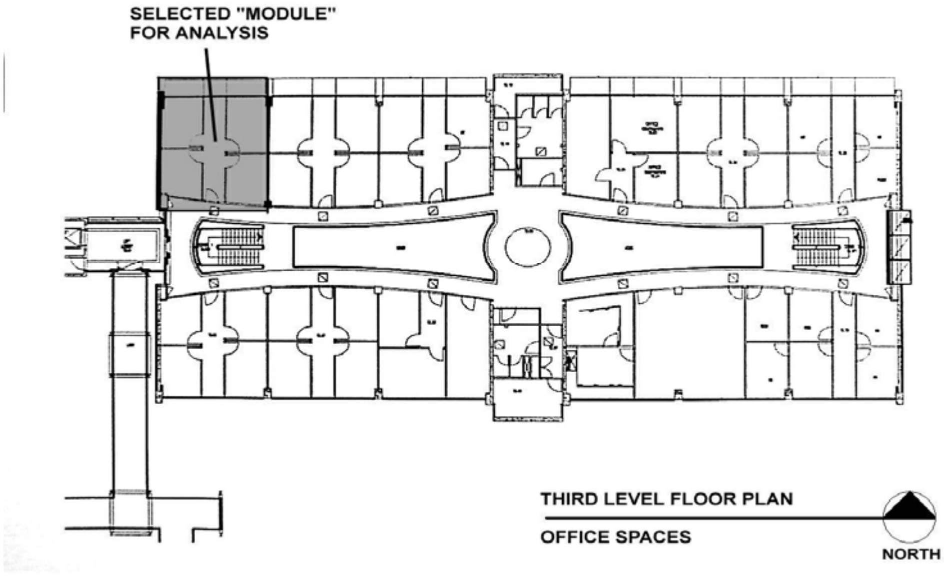

Figure 1 Third Floor Plan of the Proposed Building

(Note: a glazed walkway proposed for the north-western corner is not shown)

Commercial Building Energy Consumption

Internal loads and the external climate will determine commercial building energy consumption. There is some limited survey data (PCA, 1997) that indicates the current level of energy use of such buildings in Melbourne (Table 1).

Energy End Use	**No of Surveyed Buildings**	**Energy Consumption (kWh/m^2 year)**		
		Range	**Lower Quartile**	**Upper Quartile**
Conditioning and Ventilation (excluding heating)	8	24 - 97	43	67
Small Light and Power	7	10 - 61	-	-
Lifts	8	5 - 30	10	16
Gas Consumption (water and space heating)	31	4 - 215	36	89

Table 1 Energy consumption data for Melbourne commercial buildings

(**-** indicates sample size too small to determine meaningful quartile)

Although in most cases the sample size is small and the range of consumption levels for various end-usage is large, some indication of the energy consumption of a "typical" building i.e. one that lies between the lower and upper quartiles can be estimated. While internal loads, occupant behaviour, different usage patterns and even poor data collection may all contribute to the variability in consumption, all the buildings are subject to the same local weather conditions.

Melbourne, Victoria (latitude angle 37^0 49' S.) enjoys a temperate climate moderated by its coastal location. However, it is also subject to highly changeable weather and is famous around Australia for its "four seasons in one day" climate. On average, it has 1378 heating degree-days a year, calculated to the base temperature of 18^0C. Cooling degree-day data is not readily available. The climate for which a building in Melbourne must be designed is indicated by the long-term averages of some relevant data in Table 2. It should be remembered, however, that the normal building occupancy hours of 8 am to 6 p.m. will be modify this data to some extent.

Parameter	**Annual Mean**	**Summer Mean**	**Summer Mean Max**	**Winter Mean**	**Winter Mean Min**
Solar radiation (kWh/m^2/d)	4.4	5.6	n.a.	1.9	n.a.
Sunshine hours	5.7	7.4	n.a.	3.9	n.a.
Dry bulb temperature (^{0}C)	14.7	19.2	25.0	10.1	6.2
Relative humidity @ 9 am (%)	69	62	75	80	71
Wind speed (m/s)	3.6	3.6	n.a.	3.6	n.a.

Table 2 Melbourne climatic data

(n.a. indicates data not available)

Compared to other locations in Australia and internationally, the Melbourne climate would be regarded as relatively benign. These favourable conditions raise the question of whether careful and clever design could result in commercial buildings for Melbourne, which use very small amounts of conventional energy for conditioning.

Design and Simulation Process

The Base Case

Initially the client and the consultant team determined the key parameters and assumptions for a "base-case" against which the results of any design and operational changes could be compared. Three separate zones were defined. These were an office "module", and the adjacent walkway and atrium (Figure 1). It was also decided that the office module would be located at the northwest corner of the top floor. Thermally, therefore, it should represent the "worst-case" in terms of its cooling energy requirements. In most parts of Australia, the cooling load is generally perceived to be the most difficult to minimize in commercial buildings. The parameters and main assumptions for the three zones are given in Table 3. Some of the key features of the "base-case" are:

- a lightweight metal insulated roof
- a top floor north-west corner location
- no shading devices on windows
- pre-cast concrete walls with 74% glazing on north wall
- office module conditioned to 24°C

Building Zones	**Description**	**Area (m^2)**	**Vol (m^3)**
Office	¾ wall height offices in module	$74m^2$	$241m^3$
Central atrium	adjacent to office on south side	$40m^2$	$130m^3$
Walkway	adjacent to office on west side	$22m^2$	$107m^3$

Structural Element	**Construction**
Roof	metal decking, 50mm fibreglass insulation, 13 mm plaster
Floor	192 mm concrete with 15 mm typical floor covering
North wall: office	150 mm concrete with 13 mm plaster
Internal west wall:	2 - 12mm cement sheet with 50mm airspace
Internal south wall:	Same as west internal wall
Glazing	6mm standard clear window glass covering 74% of north wall

Internal Loads	**Description**	**Schedule**
People:	6 @ 150 W per person	8:00am–6:00pm -5 days
Equipment:	6 computers @ 50 W per unit	8:00am–6:00pm -5 days
Lighting:	17 W/m^2	8:00am–6:00pm -5 days

Ventilation / Infiltration	**Description**	**Schedule**
Ventilation (office):	1 ACH or @ 11 l/s per person	8:00am–6:00pm -5 days
Infiltration:	0.75 ACH for non-pressurised areas	continuous

Table 3 Base Case Parameters

The Simulation Process

In this project, the simulation process can be divided into two distinct stages. In the first, a range of options was canvassed and evaluated, starting with a base case and progressing to an improved concept (see Stage One Scenarios). In the second stage, the best of the Stage One Scenarios was then refined further, particularly in order to improve occupant comfort (see Stage Two Scenarios). The software used to simulate the thermal performance of the building was TRNSYS (Transient System Simulation Program) version 14.2 [Klein et al., 1975].

Stage One Scenarios

In Stage One the various design, operating and material options investigated were as follows:

- The effect of relaxing the temperature range in the office zone
- The effect of installing significant levels of shading on north facing glazing
- The effect of replacing the metal roof with a concrete slab
- The effect of pre-cooling a fixed quantity of ventilation air and using this instead of unlimited quantities of fully conditioned air
- The effect of night-time cooling of the office zone
- The effect of improved daylighting and reduced lighting loads

A brief summary of the key details of the scenarios investigated in Stage One and the purpose of the investigation are given in Table 4.

Case	Assumptions	Purpose
A	As per Table 3 @ a constant 24°C	To provide Base Case values
B	As above except conditioning now between 18°-28°C	To show effect of relaxing conditioning requirements
C	As Case B but 1.0m overhang shading 83% of north glazing	To show effect of shading the “vision” region of north façade
D	As Case C but metal roof replaced with insulated concrete roof	To show effect on energy consumption of additional thermal mass in roof
E	As Case D but conditioning reduced to 1 ACH @ 16°C to the room i.e. ventilation air only	To show effect on peak air temperatures attained during occupied hours with limited cooling
F	As Case E but with night-time (3 ACH) ventilation in summer months	To show effect of night-time cooling
G	As Case F but with special glazing above shading & 10 W/m^2 lights	To show effects of reduced lighting level & laser-cut panel in clerestory

Table 4 Summary of Stage One Scenarios

Stage One Results

The results of the Stage One simulations in terms of peak energy demand, annual energy consumption and the maximum office air temperature during occupied hours are shown in

Table 5. Note that TRNSYS calculates the amount of energy that must be delivered to the space and therefore system efficiency has not been included.

	Heating		**Cooling**		
Case	**Peak Demand (W/m^2)**	**Annual Energy Consumption (kWh/m^2.y)**	**Peak Demand (W/m^2)**	**Annual Energy Consumption (kWh/m^2.y)**	**Max Temp during occupied hours (^{0}C)**
A	99	24	141	57	24.0
B	59	4	119	29	28.0
C	60	5	93	15	28.0
D	53	6	71	6	28.0
E	53	6	22	5	34.7
F	58	8	22	5	34.2
G	61	10	22	5	32.1

Table 5 Results of Stage One Simulations

Stage One Discussion

Relaxing conditioning requirements

The impact of relaxing the range of acceptable office temperature can be seen clearly by comparing Cases A and B. In Case A (Base Case), temperatures are set and controlled at 24^{0}C, whereas in Case B, the office temperature is allowed to drift between a minimum of 18^{0}C and a maximum of 28^{0}C. As a consequence, the peak heating and cooling demands fall by 40% and 16% respectively. Big reductions in annual energy consumption for heating

(85%) and cooling (50%) also result from this design decision. Clearly, it is important that conditioning requirements are scrutinised and relaxed where possible because traditional prescriptions can be costly. In this case, the occupants are expected to "adapt" to the prevailing conditions in the building e.g. by wearing appropriate clothes or turning on a ceiling fan to achieve an acceptable level of thermal comfort.

Shading

In Case C, shading is introduced on 83% of the glazing of the office module. A combination of an overhang and blinds is proposed to give a shading factor of 80% to all but the top 4m^2 of window on the north wall of the office. TRNSYS is a thermal simulation program and does not compute natural light levels. Separate modelling of the office module using the program "Radiance" indicated that adequate light levels in summer could be achieved through the top unshaded window when combined with the light entering via the atrium. While the overhang is fixed, it is anticipated that the occupants will open the blinds in the winter months. As expected, the peak cooling demand is reduced by a further 22%, and the annual energy consumption for cooling almost halved. However, the addition of shading does slightly increase both the peak demand and annual energy consumption for heating due to the reduced penetration of solar energy into the office space.

Concrete versus Metal Roof

A comparison between a flat insulated metal roof and an insulated concrete roof clearly shows the thermal advantages of the latter with respect to both heating and cooling. In Case D to Case J (Table 5), the slab thickness is assumed to be 192mm. Peak heating and cooling demands fall by 12% and 24% respectively because the extra capacitance of the roof reduces the swings in office temperature. The penalty is an increase in the heating energy consumption of 1.4 kWh/m^2 per year (29%) but this is offset by a big decrease in cooling energy consumption of 9.4 kWh/m^2 per year (63%)

Ventilation-Cooled versus Fully Conditioned Air

Up to this point in the simulation process, full air-conditioning is assumed. Although heating and cooling energy requirements have been substantially reduced compared to Case A (Base Case), one of the objectives of the design team was to minimise or eliminate, if possible, the need for air-conditioning in the building. As an intermediate step therefore, the notion of pre-cooling the ventilation air (1 ACH) down to 16^{0}C, if the ambient air temperature exceeded 20^{0}C, was simulated in Case E. The positive effect on the peak cooling demand is evident as it falls from 71 to 22 W/m^2. However, now the maximum temperature in the office zone during working hours rises from 28^{0}C to the unacceptable level of 34.7^{0}C. It should also be noted that peak cooling demand is now a function of outside air temperature and the quantity of ventilation-cooled air (ACH), rather than the thermal load on the office.

Night Cooling

In an attempt to reduce the maximum daytime temperature, the strategy of cooling the office space with ambient air at night at a rate of 3 ACH during the summer months was simulated. Although some positive effect from this was achieved, the maximum temperature only fell by 0.5^{0}C. This strategy also had the adverse effect of increasing the peak demand and annual energy consumption for heating by 9% and 27% respectively. These results are surprising, and possibly indicate a weakness in the control strategy developed. This aspect warrants further investigation. It is also possible that the ventilation rate used should be increased. Balaras (1996), for example, recommends that the night-time hourly ventilation rate should be 25 l/s per m^2 of floor area which is nine times the rate used in these simulations. Blondeau et al. (1997) measured decreases of 1.5-2 ^{0}C using 8 ACH and computer predictions of a similar magnitude have been reported by Birtles et al., 1996. However, even at this stage in the design process, the idea of integrating a hollow concrete floor into the ventilation system was viewed as a possibility (see later discussion). Increased ventilation rates would have resulted in an unacceptably high air velocity through the slab and was therefore rejected.

Increased Daylighting and Reduced Lighting Load

In Case G, the glazing of the small clerestory window above the overhang was replaced by an "Azurlite" laser-cut panel to increase the amount of daylight experienced in the office, while reducing the heating effect of solar radiation. At the same time, lighting levels were reduced to 10 W/m^2. This decision had the expected effect of reducing the maximum temperature by over two degrees. However, a temperature of 32.1^{0}C was still considered to be unacceptably high. Peak heating demand and energy use increased as expected because of the reduced internal load and passive solar gain.

Stage Two Scenarios

Although the simulations in the previous stage had revealed an acceptable design concept in terms of low energy consumption compared to typical commercial building energy use (see Table 1), the maximum temperature in the office was still unacceptably high. In Stage Two, further efforts were made to overcome this problem, and to minimise the number of hours when the office temperature exceeded 28^{0}C. Accordingly, the following strategies were investigated:

- an increase in the quantity of pre-cooled air introduced into the office zone
- removal of the glazed walkway
- use of a hypocaust system in the concrete roof of the office

A brief summary of the key details of scenarios investigated in Stage 2 and their purpose is given in Table 6.

Case	Assumptions	Purpose
G	As in Stage 1	Starting point for Stage 2 Scenarios
H	As Case G but quantity of pre-cooled ventilation air is doubled. 2 ACH of pre-cooled air also used at night if ambient > 22^0C.	To show the effect of doubling the quantity of pre-cooled ventilation air on maximum office temperature, and using pre-cooled air at night
J	As Case H but glazed walkway removed on west wall	To show the effect of removing a glazed component on the west face
K	As Case J but roof slab thickness reduced by 45%	New concrete slab dimensions were used, effectively halving thermal capacitance
L	As Case K but with ambient air flushed through the slab in summer to remove heat. Insulated and vented roof space added above slab	To show the cooling effect of using a hypocaust system with ambient air.
M	As Case L but slab flushed with pre-cooled 16^0C air to cool slab if ambient air temperature is too high	To show the cooling effect of using a hypocaust system with pre-cooled air.
N	As Case M but exit air from slab is introduced into office	To show the cooling effect of the above system, but with a closed rather than open loop.

Table 6 Summary of Stage Two Scenarios

Stage Two Results

The results of the Stage Two simulations in terms of peak energy demand, annual energy consumption, maximum office air temperature during occupied hours and the number of hours when that temperature exceeded 28^0C are shown in Table 7.

Stage Two Discussion

Increasing pre-cooled ventilation rate

In previous simulations, the quantity of pre-cooled ventilation air used had been limited to one air change per hour (1 ACH). It was decided that it would be still acceptable to double this amount, given that the equipment to pre-cool and deliver the conditioned air was already in place. Comparing Cases G and H shows the effect of this strategy. A further small reduction (0.3^0C) in maximum temperature and a 27% reduction in the number of hours when the office temperature exceeded 28^0C resulted. Interestingly, the peak demand and annual energy consumption for heating is also reduced by this strategy. The reason for this is not clear and requires further investigation. Once again, further development of the control algorithm is probably required.

	Heating		**Cooling**			
Case	**Peak Demand (W/m^2)**	**Annual Energy Consumption ($kWh/m^2.y$)**	**Peak Demand (W/m^2)**	**Annual Energy Consumption ($kWh/m^2.y$)**	**Max Temp (^{0}C)**	**No of Hours > 28^{0}C**
G	61	10	22	5	32.1	80
H	53	6	44	13	31.8	58
J	53	8	44	13	28.6	12
K	62	9	44	14	29.5	23
L	56	7	44	13	28.8	18
M	56	7	44	13	28.1	1
N	51	7	44	13	29.6	23

Table 7 Results of Stage Two Simulations

Glazed Walkway

Up to this point in the design process, an unconditioned glazed walkway on the west face of building had been proposed. Case J shows the significant effect of removing the glazing, and replacing the former internal west wall (Table 3) with a windowless concrete block wall insulated with 50 mm of mineral wool and faced with 13 mm of gypsum board. Maximum temperatures in the office fall to 28.6^{0}C and the number of hours above 28^{0}C fall from 58 to 12. These benefits have been achieved at the expense of user comfort and protection in moving from one floor to another via a covered walkway.

Hypocaust System

In addition to displaying environmental awareness, another client objective was to demonstrate innovation in their new building. Having agreed to a concrete floor, the possibilities of incorporating a hypocaust system to achieve further benefits was explored. The system proposed is shown in Figure 2. A ceiling air supply system was chosen because the ceiling surface is unobstructed, unlike the floor on which furniture and a floor covering will be placed. Cooled ceiling systems with ceiling air supply have been shown to thermally effective (Niu and Kooi, 1994) but the intention is also to install ceiling sweep fans, which will ensure satisfactory mixing. An insulated and ventilated roof space above the hypocaust was also added at this point in the simulation process.

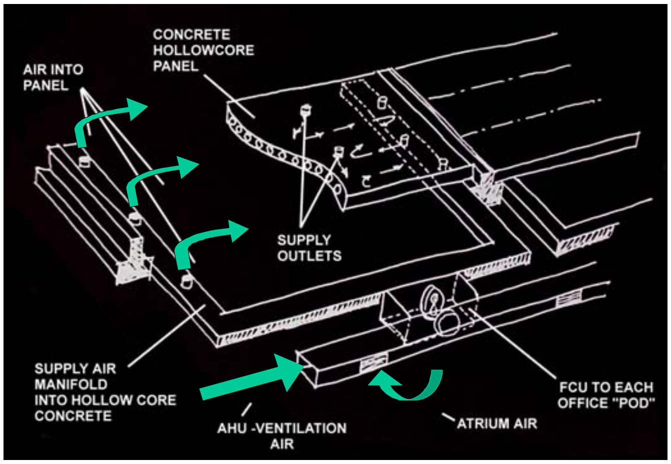

Figure 2 Proposed hypocaust system

Three different variations in airflow were simulated (Figure 3). In Case L, ambient air is flushed through the slab only when it is advantageous to do so i.e. when the slab will lose energy to the air. In Case M, pre-cooled air (either ambient air below 20^0C or pre-cooled air at 16^0C) is flushed through the slab to cool the slab. In both these cases, the air exiting the slab is exhausted to the outside. Case N is identical to Case M, but in this instance, the exhaust air is directed into the room via the supply outlet holes in the hypocaust (Figure 2). In all variations, the effect of the hypocaust slab on the cooling of the office was determined by simulating its operation for the summer months only. Its effect on the heating demand has not yet been evaluated.

Unfortunately, the hypocaust has less thermal mass than the solid slab. Case K shows the effect of reducing the slab thickness from 192 to 106 mm. Heating demand and energy use rise, as well as the maximum temperature experienced by occupants, which climbs by almost one degree to 29.5^{0}C. Two of the hypocaust options, however, bring the temperature and number of hours above 28^{0}C back down again. As expected, the most effective hypocaust option is the one where pre-cooled air is flushed through the slab and the exit air is dumped to ambient i.e. Case M. This strategy results in effectively meeting the objective of the client of a building where the temperature does not exceed 28^{0}C. Flushing with ambient air (Case L) is the second most effective option, while Case N shows no net reduction in maximum temperature or the number of hours experienced. However, in this last scenario, heating demand and energy use is reduced because of the introduction of the warmer exhaust air into the office zone.

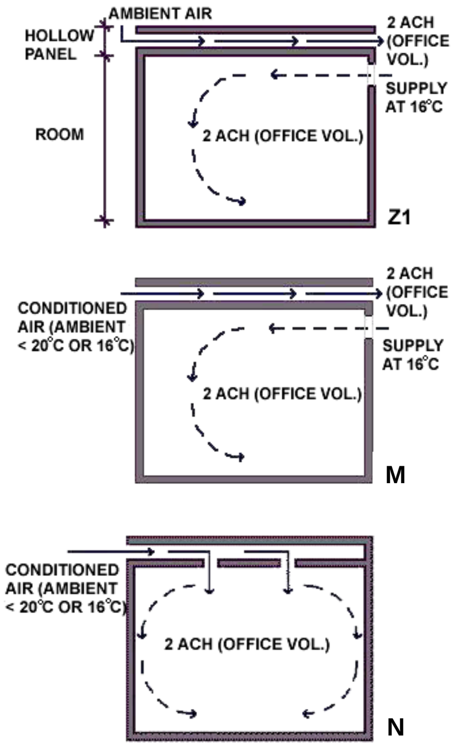

Figure 3 Three variations of airflow through hypocaust

Control Strategy

The simulation study described above required the development of a complex control strategy for the ventilation and cooling systems. This strategy developed incrementally, as our understanding of both the limitations and possibilities of the conditioning equipment became apparent. For example, it became obvious that it would be sensible to use the pre-cooler, installed primarily for daytime use, for night-time cooling in those hours when the ambient air temperature does not fall below 20^{0}C.

The control strategy in the final simulations had the following features.

- Night-time cooling in the summer months (October-April inclusive) if the office temperature is above and ambient is below 22^{0}C.

- Night-time cooling with pre-cooled @ 16^0C if the office temperature and ambient is above 22^0C.
- Daytime cooling with pre-cooled air @ 16^0C if the office temperature is above 22^0C.
- Daytime ventilation rate of 1 ACH when building in use in winter months (May-September inclusive).
- Infiltration rates of 0.75 ACH during winter months when building is not in use. No infiltration when ventilation or cooling equipment operating.

Selected Design

The simulation process and results described above allowed the client and design team to make informed choices as they progressed towards the final design. Most of the features modelled are to be incorporated into the new building, including the use of pre-cooled ventilation air and a hypocaust system. In doing so, however, it was recognised that energy consumption may be higher than the lowest prediction with full air-conditioning (Case D) for an equivalent office air temperature. Nevertheless, the simulation results indicate that heating and cooling energy consumption can still be reduced by 72% and 76% respectively compared to the Base Case (Case A).

However, it was felt that the new system was a viable and attractive option for the following reasons.

- The peak cooling demand was reduced by 38%, allowing a smaller system to be used.
- Reductions in heating energy could be achieved by pre-heating ventilation during the winter months as the hypocaust will often be warmer than ambient air.

- Operative temperatures in both summer and winter may be improved by the exposed "hypocaust" ceiling.
- The system would meet the clients' objective of being innovative.

Conclusions

Two principal conclusions can be drawn from the simulation study described above.

The value of simulating the thermal performance of the building is demonstrated as follows:

- Design, equipment, material and operational options can be evaluated against each other to indicate which are the most thermally effective. These results provide the basis for determining the most cost-effective options.
- Complex control strategies can be developed and simulated and then form the basis of the actual building management system.

The simulations strongly indicate that an office building using minimal quantities of conditioned air can be designed for the Melbourne climate. In this building, key design decisions were:

- relaxing of the conditioning requirements from 24^0C to $18-28^0$C
- installing a concrete rather than a metal roof
- installing high levels of shading on north-facing glazing
- reduced lighting load through increased day-lighting
- removing a glazed walkway on the west side of the building

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