The Proposed Heating and Cooling System in the CH_2 Building and its Impact on Occupant Productivity

Lu Aye and Robert James Fuller (University of Melbourne)

ABSTRACT

Melbourne's climatic conditions demand that its buildings require both heating and cooling systems. In a multi-storey office building, however, cooling requirements will dominate. How the internal space is cooled and ventilation air is delivered will significantly impact on occupant comfort. This paper discusses the heating and cooling systems proposed for the CH_2 building. The paper critiques the proposed systems against previous experience, both internationally and in Australia. While the heating system employs proven technologies, less established techniques are proposed for the cooling system. Air movement in the shower towers, for example, is to be naturally induced and this has not always been successful elsewhere. Phase change material for storage of "coolth" does not appear to have been demonstrated previously in a commercial building, so the effectiveness of the proposed system is uncertain. A conventional absorption chiller backs up the untried elements of the cooling system, so that ultimately occupant comfort should not be compromised.

Keywords: heating, cooling, occupant productivity, performance, thermal comfort.

INTRODUCTION

The heating and cooling of buildings has a long history. Active heating systems began with cave dwellers, who lit open fires for warmth and light in their rock caverns. More advanced heating systems were adopted by civilizations such as the Romans, who operated furnaces below their buildings and ducted the hot gases to upper level rooms to provide warmth. The hypocaust, as it was known, has found a modern day equivalent in the form of advanced fabric energy storage systems such as the Termodeck™ system. The provision of cooling in buildings has always presented designers a greater challenge. Early cooling systems made use of natural draft and evaporative effects, and this knowledge is being revisited today as building designers strive to provide cooling that does not incur a heavy environmental cost.

Heating and cooling systems have become obligatory in most modern office buildings. Aside from issues of occupant comfort and expectations, some believe that the productivity of workers is related to the temperature and humidity of their working environment. A new commercial building, currently under construction in Melbourne, Australia, is hoping to demonstrate that it is possible to achieve a high quality office environment simultaneously with much reduced energy consumption. CH_2 is in the heart of the city's central business district. This study assesses whether the heating and cooling system proposed for the CH_2 building provides the necessary thermal conditions for its occupants. This study begins with an overview of the requirements for thermal comfort in terms of temperature, humidity and air movement. The heating and cooling system proposed for the CH_2 building is then described and evaluated in terms of previous experience, both in Australia and overseas. Finally, the thermal conditions likely to be created within the CH_2 building are briefly reviewed against the current research literature on productivity. Since the office is still under construction, no measured data from the building is available to verify performance. Therefore the proposed design has largely been evaluated using a selection of the design consultants' documentation and refereed literature in international journals. As the building is still being constructed, design changes made subsequent to this evaluation are obviously not considered.

THERMAL COMFORT

While the human species can tolerate extremes of temperature for prolonged periods of time, this is not the choice or expectation of today's office workers who will tolerate a much smaller range of thermal environmental conditions (temperature, air velocity and relative humidity). A widely accepted definition of thermal comfort is "that state of mind that expresses satisfaction with the thermal environment" (ASHRAE, 1992). Many factors (physical, physiological, and psychological) determine whether an individual perceives their environment to be comfortable. The purpose of any conditioning system is to create the local environment that will minimize feelings of thermal discomfort. In general, this means maintaining the body temperature within a certain narrow range with low skin moisture content. The ASHRAE Standard 55 "specifies conditions or comfort zones where 80% of sedentary or slightly active persons find the environment thermally acceptable." Summer and winter clothing levels are assumed to be 0.5 and 0.9 clo respectively (1 clo is equal to overall equivalent thermal resistance, R value of 0.16 m^2C/W). For a woman, the summer clo value is the equivalent of wearing a knee length skirt, a short sleeved shirt, panty hose and sandals, while for a man, the winter clo value is roughly the equivalent of wearing a suit with a short sleeved shirt.

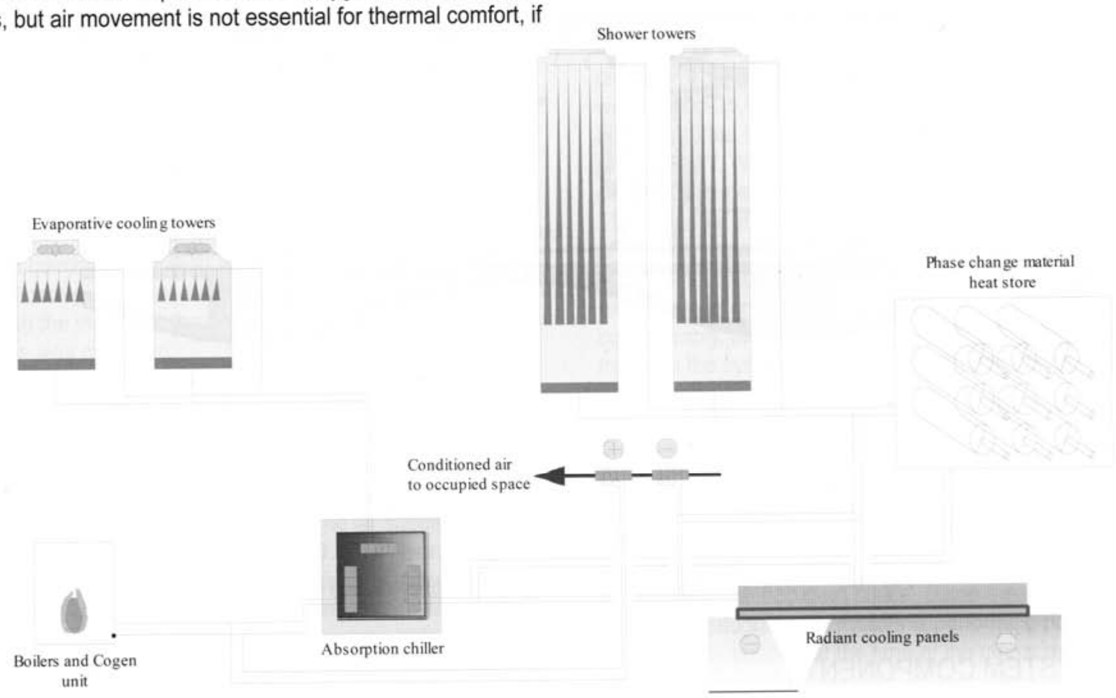
The boundaries of the comfort zones can be expressed as a function of operative temperature and the relative humidity (RH) of the surrounding air. As a result, the comfort zones in summer and winter are defined by two quadrilaterals superimposed on a psychrometric chart, as shown in Figure 5 of ASHRAE (2001). Broadly interpreted, in winter a range of 20-24.5^{0}C and 85-20% RH can be tolerated. As the temperature rises, the RH must be lowered to maintain thermal comfort. A similar picture is evident in summer, but with an extended range, based on the assumption that the occupants will wear lighter clothing. Thus in summer, the thermal comfort range varies from 22.5-27^{0}C with corresponding RH levels of 80% and 20% respectively. There is a small overlap between summer and winter zones. In the middle of each of the zones, a person would experience their environment in a neutral way, but at the boundaries sensations of slight warmth or coolness would occur.

The above boundaries may be extended if the building relies on the adaptive response of its occupants. The theory, advanced by researchers (e.g. de Dear and Brager, 2001) is that building occupants will adapt their behaviour, based on surrounding conditions, and hence tolerate wider extremes in a building's internal environment. The expanded comfort zones should result in energy savings. These ideas are particularly suited to buildings such as CH_2, which use a range of non-conventional technology and where natural ventilation might also be used. The designers of the CH_2 building, however, have proposed a climate-controlled office, rather than an adaptively controlled one, principally because they do not believe it would be feasible to open windows during the day due to the building's inner city location. The heating and cooling system of the CH_2 building has been designed to maintain office air temperatures in the range of 21-25°C and provided this is achieved with acceptable levels of relative humidity, the building should satisfy most occupants in terms of thermal comfort.

Air movement is important in a closed environment for a number of reasons. These include replenishment of oxygen and the removal of odours, but air movement is not essential for thermal comfort, if a thermally neutral environment is provided in terms of temperature and relative humidity. For air speeds of 0.25 ms^{-1} or less, thermal acceptability is unaffected in neutral environments (Berglund and Fobelets, 1987, cited in ASHRAE, 2001).

HEATING AND COOLING SYSTEMS

The main hardware components of CH_2's conditioning system are shown schematically in Figure 1. Thermal modelling by consultants of the CH_2 building indicated that heating should not be required (AEC, 2003b). The passive design principles adopted plus the heat generated by the people, equipment and lights have been predicted to produce a cooling load even in winter, rather than a demand for heating[1]. However, the fresh air introduced into the building via the displacement ventilation system will need to be heated on days when the outside air temperature is below 20°C. For this reason and to cover any direct heating requirements, a heating system is to be installed, which uses exhaust heat from the co-generation plant.



(source: Kenton, 2004)

Figure 1: Schematic of early heating and cooling system originally proposed for the CH_2 building

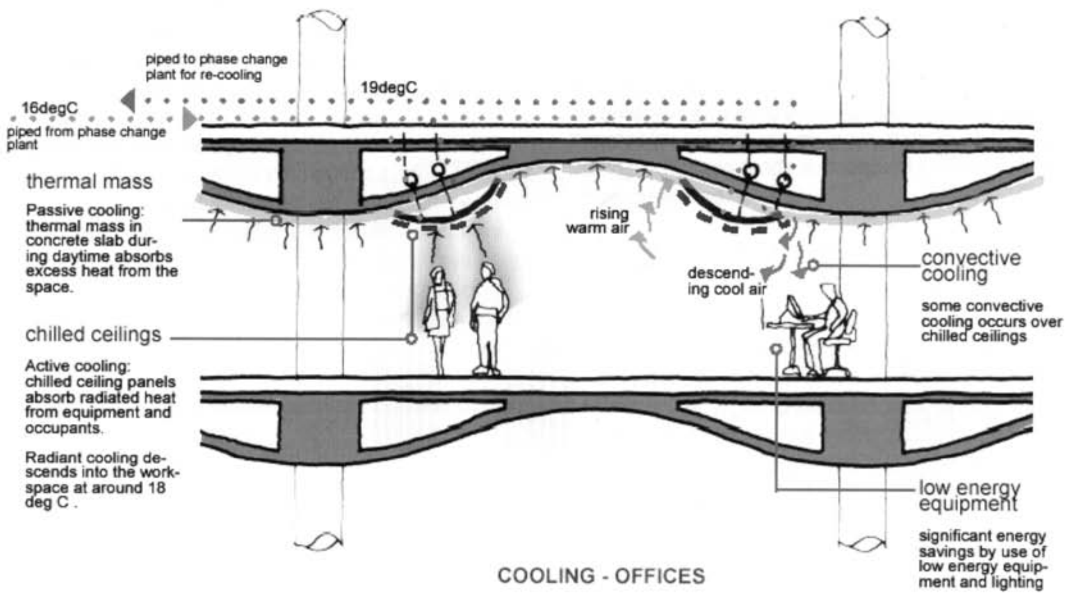
The cogeneration system, using a gas-fired micro-turbine, will produce electricity for the CH_2 building. It has been estimated that approximately 100kW of the heat generated by the plant will be recovered and used either for direct heating or to drive the vaporization process in the absorption chiller. Despite the potential to operate with a high overall efficiency (85-90%), the use of small combined heat and power (CHP) systems in buildings is relatively new. Alanne and Saari (2004) have reviewed the status of small-scale CHP systems for this application. In their assessment of micro-turbines, high costs and low electrical efficiency, particularly in the part-load condition, are the main disadvantages of the technology. Their low noise, weight and vibration level, and small space requirements are the main advantages. In a comparison with other small CHP technologies, namely fuel cells, reciprocating and Stirling engines, gas micro-turbines were not considered to be the most technically compatible with office buildings. Reciprocating engines and fuel cells were considered to be superior. According to a government funded study in Australia, small (up to 300kW) high-speed reciprocating gas engines were likely to be the most efficient and financially viable way to provide power and heat to buildings (SKM, 2001).

In the CH_2 building, heat will also be recovered from the air exhausted from the offices using a heat exchange system. It has not been possible to assess the heat recovery system, since no details have been made available. However this is a conventional technology and should work effectively if properly designed and operated. Waste or recovered heat will be distributed into each level by finned convective heaters "set into the floor near the windows" on the north and south sides of the building. The concept

[1] The energy required annually for space and water heating for most of a surveyed 31 commercial buildings in Melbourne was found to be between 130-310 MJ m^{-2} (PCA, 1997), so this modelling prediction may be overly optimistic.

is that the warm air from these heaters will create "a barrier of warmth around the external walls to prevent the cold air coming in" (AEC, 2003d). Assuming that some convective heating of the inside surface of the window also occurs, the adverse radiant effect of cold windows will also be reduced.

For much of the year, the design simulations indicate that cooling will be required. During the daytime, it is proposed that chilled beams and ceiling panels provide cooling for the occupants in the main office zones (Figure 2). The intention is that the cooling and 'shower' towers will primarily produce the cool water for these panels at night. This 'coolth' will be stored in phase change material (PCM) and used to chill the water circulated through the beams and ceiling panels during the day. An absorption chiller will be used as a back-up cooling system, in the event of insufficient capacity in the primary system. During the night-time, it is proposed that heat accumulated in the building fabric be removed by 'night purging'. This technique uses the diurnal temperature difference of the outside ambient air to flush unwanted heat stored in the building's thermal mass during the day with cooler night-time air. This purging will be achieved by natural ventilation assisted by wind-driven extractor turbines. Since some components of the cooling system are unconventional, a more detailed description of these is presented below.



(Source: CoM, 2004)

Figure 2: Schematic overview of cooling system operation in CH_2 building

COOLING SYSTEM COMPONENTS

Phase change material

A critical component of CH_2's cooling system is the PCM. The function of the PCM is to store 'coolth' transferred from the exit water of the shower-cooling tower combination at night. In the storage process, it is intended that the PCM will be cooled sufficiently to change phase and solidify from its previous liquid state. During the daytime, a closed loop will circulate water through the PCM to the chilled beams and ceiling panels, thus providing cooling to occupants. Throughout the day, the PCM will release its 'coolth' through this process and be returned to a liquid state by the evening, so that the process may be repeated the following night.

The use of PCMs in buildings is not new. Solar researchers have investigated their potential as an alternative to the traditional, but more bulky, thermal storage media i.e. water and rock (e.g. Morrison and Abdul-Khalik, 1978). A number of buildings have been built using PCMs and Duffie and Beckman (1991) describe some of the results of these installations. In recent times, phase change research has focussed on the impregnation of building materials themselves to overcome the problem of the large areas required if the PCM is to be melted by direct solar radiation (Khudhair and Farid, 2004). In general, PCMs have been used to store excess heat and thus experience in the way proposed for the CH_2 building is limited. Zalba et al. (2004) evaluated an air-based PCM cooling system designed for a residential building. The PCM used had a phase change temperature interval of 20-24^{0}C. Although their simulations and experiments indicated the feasibility of using PCMs for cooling, the difference in operating temperature, heat transfer medium and application limits the relevance of this research to the CH_2 application.

The PCM for the CH_2 building is currently being developed by the supplier (Environmental Process Systems Ltd, UK) and will be a low (15^{0}C) melting point material. The PCM is reportedly a mixture of non-toxic salts and organic compounds (AEC, 2003c). The CH_2 system has been designed to supply a daily cooling load of 4539 kWh, i.e. 25% greater than the estimated cooling load. The PCM will have a latent heat value of approximately 210 MJ m^{-3} and therefore at least 78 m^3 of PCM encapsulated in the (proposed) 0.1 m diameter polypropylene tubes will be required. The life expectancy and chemical stability of PCMs are the critical issues, which determine their viability. The PCM to be used is a new material under development and therefore no long-term operating experience is available.

Chilled ceilings and beams

Chilled ceiling panels, fixed to the curved ceiling in the offices, have been sized to cater for the internal cooling loads generated by occupants, lighting and equipment. The chilled panels cover 35% of the curved ceiling. Chilled beams are to be located in front of the windows around the perimeter of each office zone. Their function is to cater for the loads generated by direct solar gain and heat conducted through the windows. The radiant temperature of the panels is designed to be 18^{0}C, achieved by pumping water at 16^{0}C through the panels. The shower/cooling tower-PCM combination will produce this chilled water. The internal cooling loads in the central office zone are estimated to be 35.5 Wm^{-2} for 95% of the time. The air temperature design criteria for this zone is 21-25^{0}C, but since the panels will provide radiant cooling, the objective of the system is to achieve a maximum resultant temperature of 23^{0}C.

In the UK, chilled ceiling panels are generally believed to be capable of dealing with cooling loads of 40-50 Wm^{-2}. When cooling loads exceed these levels, perimeter chilled beams are recommended and then capable of handling loads up to 80 Wm^{-2} (DLE and MGW, 2001). Chilled ceilings and beams are used in combination with displacement ventilation in 60-80% of UK applications (DLE and MGW, 2001). The effectiveness of this cooling strategy on occupant comfort has been demonstrated at the UK's Building Research Establishment (BRE) by Alamdari et al. (1998). These authors introduced air at 19^{0}C into a test cell at the rate of 3.5 air changes per hour (ACH^{-1}) or 2.6 l s^{-1} m^{-2} at ground level. The air temperature and airflow rate were determined by thermal comfort rather than air quality requirements. Some downward convection was determined, but upward convection was dominant in the vicinity of the occupants. A 90% or better occupant satisfaction was predicted.

Similar positive results in terms of occupant comfort were obtained in other experiments conducted in the UK using a 16.2 m^2 and 2.8 m high test room (Hodder et al., 1998). In this case, the supply air mass flow rate was set at 3 ACH^{-1} and its temperature was set at 19^{0}C, as in the BRE experiments. The air supply rate in the CH_2 building is to be 1.5 l s^{-1} m^{-2} or 1.9 ACH^{-1}, assuming a 2.9 metre average ceiling height, and the supply air temperature is to be 20^{0}C. Based on the UK experiences, the chilled ceiling-displacement ventilation combination may not be able to meet comfort requirements because the displacement airflow rate is lower and supply temperature is higher.

Shower towers

A novel feature of the cooling system is the five shower towers. These are lightweight fabric tubes, 1.4 metres in diameter and 8 m in height, fixed to the outside facade of the south side of the building. In theory, when fine droplets of water are sprayed vertically down the towers, the momentum of the falling water entraps a certain volume of air, which establishes a flow of air down the towers. Any evaporation of the droplets cools the air, water and internal surfaces of the towers. It is intended that during the daytime the cooled and humidified air will be directed into the ground level retail spaces. At night-time, any cooled water collected at the base of the shower towers will be directed to the cooling towers.

Givoni (1994) claims to have developed the shower tower to cool outdoor rest areas for the '92 EXPO in Seville, Spain. A search of the literature, however, indicates that the concepts employed in the shower towers are not new. Bahadori (1985) provides an analysis of Baud-Geers, which are the traditional wind towers used in Iran. The wind towers rely on the use of baffles to force wind down the tower, and while not part of the design for the CH_2 shower towers, the performance of these systems is of interest. The traditional Baud-Geer had a number of disadvantages and Bahadori (1985) lists these and analyses a system modified to overcome these drawbacks. One of the modifications is the provision of a wetted surface to evaporatively cool the induced air. The author provides charts estimating the dry bulb temperature of the air leaving the evaporative cooling column for given inlet conditions (ambient dry bulb, relative humidity and wind velocity) for various tower heights. Figure 5 of Bahadori (1985) shows that for a wind velocity of 5 ms^{-1} and ambient conditions not dissimilar to a summer day in Melbourne (25^{0}C and 33% RH), the dry bulb temperature leaving the evaporative cooling column is approximately 16^{0}C for a 10 m high tower. The condition of the air at 35^{0}C for a 9 m high tower is likely to be 90% RH and approximately 20^{0}C.

Pearlmutter et al. (1996) provide a theoretical analysis and experimental experience with a direct evaporative cool tower (DECT) used to cool a 500 m^2 glazed courtyard located in the middle of a multi-use complex in Israel. Following some prototype testing, the authors found the cooling potential for a natural draft system was low and hence they chose a mechanically drafted system. The effective height of the tower was 10 m and had a diameter of 3.75 m. The fan-forced air flow induced in the tower was 20,000-25,000 m^3 h^{-1} i.e. had a velocity of 0.5-0.63 m s^{-1}. It was found that the maximum cooling power of the system was just over 100 kW. Water consumption was 1-2 m^3 d^{-1}. The ability to cool the water as well as the air depends on a number of factors. The diameter of the drops sprayed into the tower and the length of time they spend in the tower are two key parameters. No final water temperatures were reported but the authors noted "the excess water collected in the pool beneath the tower is cooled considerably, and if more efficiently utilized could potentially increase the system's effectiveness" (Pearlmutter et al., 1996).

In Australia, shower towers have been installed at the 1500 m^2 Interactive Learning Centre at Charles Sturt University on its Dubbo Campus in NSW (CADDET, 2002). Located in the central space of the building, the four 8.8 m high towers use two water spray systems. Large droplets are sprayed into the tower at the top and smaller water particles are then misted into the air just prior to its entry into the occupied space. Some measurements taken at the building suggest the system is performing poorly (Yeo, 2004). Flow into the building at the time of the measurements was only 8% of the design flow, resulting in much reduced cooling capacity. This occurred on calm days. On windy days, airflow direction in the towers was upward i.e. reversed and consequently provided no cooling at all.

To date all installations and analysis of shower towers has been performed for climates with high dry bulb temperatures and low relative humidities. In the three summer months (December, January and February) in Melbourne, the average dry and wet bulb temperatures during office hours (8am to 6pm) is 21.9^{0}C and 15.9^{0}C respectively (Roy and Miller, 1981). The exit air temperatures and airflow rate from an 8 m shower tower with a water flow rate of 15 l min^{-1} can be predicted using the expression developed by Givoni (1994). For the above dry and wet bulb temperatures, an exit air temperature of 16.5^{0}C is predicted, which will be adequate to cool the retail space on the ground level, as proposed. The predicted airflow rate would provide approximately 4 ACH^{-1} for the retail spaces. During the night, the function of the shower towers is to precool the water entering the cooling towers. A 0.5-1.0^{0}C reduction in temperature is anticipated. As mentioned, no data could be located to substantiate this expectation, but according to Pearlmutter et al. (1996) considerable cooling occurs and so this estimation appears to be reasonable.

Cooling towers

There will be two Baltimore Air Coil RCT series counter-flow cooling towers installed at the CH_2 building. Their main purpose is to reduce the temperature of water at night to the level where freezing of the PCM occurs. In the three summer months (December, January and February) in Melbourne, the average dry and wet bulb temperatures during non-office hours (7pm to 7am) is 17.9°C and 14.5°C respectively (Roy and Miller, 1981). The manufacturer has claimed that an exit water temperature of two degrees above the ambient wet bulb temperature can be expected. To freeze the PCM a temperature of below 15°C is required and therefore it appears the cooling towers will not achieve this temperature, even if the water has been pre-cooled by the shower towers. This conclusion agrees with the consultant's analysis, which found that the cooling towers could only be used for nine days over the three main summer months to freeze the PCM (AEC, 2003c). The absorption chiller will therefore be the main source of cooling during the summer months. The cooling load in the three summer months is estimated to represent approximately 36% of the total annual cooling load of the building (AEC, 2003c).

Night purging

Night ventilative cooling or night purging has the potential to reduce cooling loads where there is sufficient diurnal difference in ambient air temperatures. Outside air is drawn into the building at night and heat is transferred to the moving air as it passes through the building. The effectiveness of night purging is a function of the airflow rate, surface area and thermal effusivity, the final factor being the root of the product of the conductivity, density and specific heat of the building material (van der Maas and Roulet, 1991). In the CH_2 building, the movement of air is to be induced by natural means and assisted by wind-driven extraction vanes or turbines. When the outside air temperature is below the concrete ceiling temperature, windows on the north and south facades will be opened automatically to allow outside air to be drawn in. The thermal mass of the exposed concrete ceilings will absorb some of the daytime heat gains and the cooler outside air will remove some of this heat at night as it moves through the building. Design calculations indicate that the use of night purging can reduce the daily cooling load requirement of the CH_2 building by approximately 14% in summer (AEC, 2003a).

Blondeau et al. (1997) conducted a series of experiments in a three-storey office building in France to investigate the impact of nocturnal cooling on energy consumption and its effect on occupant comfort. In their building, outside air was induced by mechanical, rather than natural, ventilation. Purging began at 9 pm and continued until 8 am. The required airflow rate was the equivalent of 8 ACH^{-1}, which agreed with the finding of Agas et al. (1991). As in the CH_2 building, the windows were kept closed and shutters restricted thermal gains during the daytime. Internal temperatures could be reduced to within 2-4°C of the minimum ambient temperature and the temperature of the air in purged rooms was 1.5-2.0°C lower than the reference room. These results were obtained for an average outdoor temperature range of 8.4°C, which Blondeau et al. (1997) believed was unfavourable[2]. When translated into cooling energy needs, savings of 25% were predicted for a set point temperature of 24°C.

Similarly high air exchange rates were used by Birtles et al. (1996). In a simulation study, rates of 5-15 ACH^{-1} were used. It was found that the higher the air exchange rates the lower resulting internal temperature. Increasing from 5 to 15 ACH^{-1} reduced the internal temperature by 1.5°C during the daytime. At the lowest ACH^{-1}, the internal temperature was at least 2.0°C lower than the 'no purge' case. Purging temperature was set at 16°C. The effect of thermal mass on peak temperatures was also investigated. High mass interiors reduced peak daytime temperatures by 1.5-2.0°C.

Ventilation by natural means (i.e. the stack effect) can be achieved but obviously without the reliability of a fan-forced system. Van der Maas and Roulet (1991) carried out an experimental study of natural ventilation study on a three storey building and developed a simple algorithm to predict exit air velocities knowing the inside-outside air temperature difference, the inlet-outlet opening area ratio and the height between inlet and outlet. Application of this algorithm, however, may be inappropriate in this case because of the indirect air path in the CH_2 building. Van der Maas and Roulet's model did predict that heat removed from a building could be maximized by increasing the surface area and the thermal effusivity of the exposed materials.

In the case of the CH_2 building, the area of the ceiling has been increased by approximately 10% by adopting an undulating profile. Surprisingly, however, the consultants found little difference in cooling loads when external walls of concrete, aerated concrete and plasterboard were compared (AEC, 2003a). The thermal effusivity of concrete is approximately 1864 J m^{-2} K^{-1} $s^{-0.5}$, which is over five times higher than plasterboard. Their finding appears to contradict the research relevant to night purging. The fresh air entering a typical perimeter zone was calculated to be 4.2 kg s^{-1} (on average) or 12600 m^3 h^{-1} (AEC, 2003a), which is the equivalent to approximately 4.1 ACH^{-1}. This level of ventilation is lower than the overseas researchers cited believe is appropriate for effective night purging.

COMFORT AND PRODUCTIVITY

While avoiding uncomfortable internal environmental conditions would appear to be commonsense and may produce a happier workforce, the gains made from making marginal changes in those conditions are much less certain. The weak link between thermal comfort and productivity is acknowledged by the designers of the CH_2 building (AEC, 2003d). In assessing the potential productivity gains resulting from CH_2's indoor environment, only the research conducted in offices has been used in this study. Similarly, only aspects of the indoor environment related to this study (i.e. temperature, humidity and air movement) are considered.

In a discussion following a series of papers investigating the impact of the building environment on indoor productivity (Lorsch and Abdou, 1994), the first author stated that "there is no direct link between worker satisfaction and productivity, nor *is discomfort* (emphasis added) always linked to nonproductivity." The authors also state that "although there is a preponderance of opinion that improving the work environment leads to productivity, quantitative proof of this statement is sparse and controversial." A sample of the research literature confirms this view.

Fisk and Rosenfeld (1997) review the literature "on the linkage between thermal environment (primarily air temperature) and selected indices of work performance." These authors state that although there is substantial evidence of an association between work performance and air temperature, ... not all studies found such associations" and not all studies showed a positive association between comfort and productivity. For example,

[2] In Melbourne, it is 7.5°C, based on the long term average temperatures at 5am and 3pm in the three summer months (December, January and February).

one study cited found that 18-49% more typewriting work was performed at 20°C compared to 24°C. Other studies of mental work performance (but not necessarily in offices) showed that reading speed, memory and learning performance also might improve at temperatures outside of the traditional comfort range. Slight thermal discomfort appeared to increase arousal, according to Fisk and Rosenfeld (1997).

A study of call centre workers, however, showed that a reduction in workers' talk time, i.e. an increase in their productivity could be achieved by increasing the airflow rate from 5 to 10 $l\ s^{-1}p^{-1}$ at an air temperature of 24.5°C. This result indicates that the adverse effect of a higher air temperature on their activity could be ameliorated by increasing air movement (Tham, 2004). Other studies (e.g. Fang et al., 2004) of office workers, while "confirming the observed impact of temperature and humidity on perceived air quality ......" found that "performance of office work was not significantly affected by indoor air temperature and humidity".

Leaman and Bordass (1999), using occupant surveys from 11 UK buildings over a 15-year period, arranged possible factors affecting productivity into four clusters. Only the first of these clusters i.e. 'personal control' includes factors relevant to this study. Perceptions of personal control were measured by the average of five variables, namely heating, cooling, lighting, ventilation and noise. Of these, noise was most strongly associated with productivity, which perhaps confirms the decision to keep the windows of the CH_2 building closed during the day. Leaman and Bordass (1999) state that in "study after study, people say that the lack of environmental control is their single most important concern, followed by lack of control over noise." In the CH_2 building, occupants have only control over the air movement through the displacement air inlet vents, so by this measure it may be concluded that they will not perceive significant productivity benefits from the heating and cooling systems.

CONCLUSIONS

The heating and cooling system for the CH_2 building will use some novel technologies and concepts such as shower towers, PCM and natural night purging. However, these innovations are supported by more conventional technologies such as an absorption chiller, evaporative cooling towers and waste heat recovery. Properly engineered, these latter systems should ensure that thermally comfortable environmental conditions are achieved in the CH_2 building.

A review of the technologies proposed to provide cooling against previous experience indicates that the displacement ventilation airflow rate is low compared to overseas experience, although the cooling loads predicted are in the same range. While evaluation of the shower towers using empirical formulae indicates that useful temperatures and airflow rates may be obtained, Australian and overseas experience indicates that reliance on natural air flow is inadequate. The shower-cooling tower combination cannot be used to produce useful temperatures in summer and the absorption chiller must be used. Although design calculations indicate that approximately 64% of the cooling load occurs in the non-summer months, the wisdom of incorporating cooling technologies that cannot be used during the main period of continuous and peak cooling demands and that are unproven is questionable. Natural ventilation for night purging, while effective in favourable ambient conditions, does not achieve the air exchange rates found necessary in overseas studies.

Because the indoor conditions chosen for CH_2 are within the accepted range of comfort zones for a climate controlled building, productivity is unlikely to be increased by the air temperature and humidity. The small level of control offered by the vents in the displacement ventilation system does not constitute significant control over individual environments, which has been cited as the single biggest concern of workers. Finally, it should be remembered that in terms of office worker productivity, ... "HVAC and IAQ are rated well below such items as privacy, interpersonal communications and relationships, office arrangement and managerial attention" (Lorsch and Abdou, 1994).

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CITY OF MELBOURNE RESPONSE

In their research paper into CH2's heating and cooling systems, Aye and Fuller raise a host of interesting questions about the success of green technologies worldwide and how they might operate in CH_2.

Some of these points have been and continue to be critical issues for the CH_2 team. Other points have been superseded by design changes made since Aye and Fuller completed their research in early 2005. Several more points relate to examples in other buildings that at first blush appear to be relevant to CH_2 but on closer examination are like comparing apples with pears – interesting but ultimately not the same thing at all.

For instance, Aye and Fuller compare CH_2's shower towers with traditional Baud-Geer wind towers in Iran and a shower tower system at Charles Sturt University in Dubbo, Australia. Neither of these systems can be compared directly to CH_2. For instance, the Baud-Geer relies on wind as well as a wetted surface. However, the CH_2 towers, based on the passive downdraught evaporative cooling concept, rely on momentum from water droplets, not mist, falling under gravity.

Conversely, the authors discount comparisons with other phase change material (PCM) systems when a connection clearly can be made. They argue PCM materials traditionally are used to store excess heat, not "coolth", and thus the CH_2 system is "untried" and cannot be seen to have been successful elsewhere. On the contrary, CH_2's PCM system most certainly does store excess heat. The issue here is merely a naming issue: "cooling material" or "heat-absorbing material" – call it "half a dozen" or "six", the process is identical. It is on these mistaken assumptions the authors have based their comments questioning the choice to use these environmental technologies in the building.

Elsewhere, Aye and Fuller appear to criticize CH_2's cooling towers for being useful only on nine days during the three summer months. Rather than being a failing, this is a reality that is clearly understood by the CH_2 team, which measures the towers' worth by their effectiveness during the other nine months of the year and has built in additional green measures to help during summer. For instance, for maximum financial and environmental efficiency the electric chiller will be used only at night when it will have most effect. During the day the recovered-heat absorption chiller will be used.

The authors make repeated comments about the "sparse and controversial" link between thermal comfort and productivity and make a point of mentioning the CH_2 team acknowledges this. They highlight a 1994 study that found no direct link between worker satisfaction and productivity. However, what is not pointed out is the broad range of CH_2 features that – read collectively rather than individually – may well make profound changes in the ability of staff to be healthy, effective and productive at work.

Agreed, being able to adjust an air vent under the floor will not alone make healthy and satisfied workers. However, the thermal comfort provided by cool surfaces rather than refrigerated recycled air, a personal supply of air that has minimal mixing with colleagues' air, the use of materials with low emissions, adjustable lighting, access to outdoor areas, plentiful emission-absorbing plants and a host of other features must, in concert, make significant and substantial inroads into this area, which has the potential for such lucrative gains.

Perhaps the most important point to be learned from this paper by Aye and Fuller is that the ongoing discussion about the use of green technologies will continue to be spirited for a great deal more time. Scepticism will remain until there are plentiful case studies, a cornucopia of academic papers and a great many CH_2s.