LOW ENERGY COOLING TECHNOLOGIES FOR SUB-TROPICAL/WARM HUMID CLIMATE BUILDING SYSTEMS

Ashfaque Ahmed Chowdhury, Mohammad Golam Rasul, Mohammad Masud Kamal Khan
School of Advanced Technologies and Processes
Faculty of Sciences, Engineering and Health
Central Queensland University
Rockhampton, Queensland 4701, Australia

ABSTRACT

The paper aims to investigate the technologies of low energy cooling that are compatible with existing buildings in order to reduce the energy consumption and peak demand associated with the cooling of institutional or commercial buildings in subtropical Queensland, Australia. The performance and effectiveness of a standard direct-expansion air-conditioning system are compared with those of a chilled ceiling radiant cooling system and a mixed-mode system that combines natural and mechanical ventilation within the building systems in a subtropical climate. The simulation results suggest that the chilled ceiling technique is preferable compared to the mixed-mode technique for efficient operation over the whole year and energy savings of 13-14% are achievable. An example of a building plan and materials is used to run the base case. DesignBuilder, an EnergyPlus based dynamic thermal simulation engine, is the simulation and visualization tool of the study.

INTRODUCTION

Today’s buildings and their HVAC systems are required to be more energy efficient to improve their economic feasibility. Low energy cooling technologies have the potential to provide better comfort and energy consumption compared to traditional systems. It is the aim of this study to explore the effect of different low energy cooling technologies on the energy performance of the whole building, taking into account the local weather data. Most of the office buildings of Queensland use a traditional cooling system. In this study the feasibility of low energy cooling technologies are examined to take full advantage of a subtropical climate. DesignBuilder, a unique tool for evaluating building conditions, is used to assess monetary savings of different low energy cooling technologies in an office building in Rockhampton, Queensland. DesignBuilder creates a virtual environment where the heating, ventilation, air conditioning (HVAC) and lighting systems of the building are evaluated in order to determine the feasibility of different alternatives. Low energy cooling technologies use a variety of approaches to reduce the energy consumption and peak demand associated with the cooling of occupied spaces. In the first instance, chilled ceiling and mixed mode with natural ventilation, are evaluated. In this study, a detailed performance analysis of a sample university office building has been simulated in order to investigate the effect of chilled ceiling and mixed mode ventilation techniques compared to existing direct expansion systems.

DESCRIPTION OF THE HVAC PLANT

The HVAC system was designed to work continuously throughout the year. During the operation, it was found that the cooling was continuous including winter months. This is because the heat loss of the building is lower than the designed value and internal heat gain is sufficient to cover all the heat losses of the building. The simulated building includes ten direct-expansion packaged units. The units are located in various plant rooms and ceiling spaces throughout the building and supply conditioned air to the ground, first and second floor office areas. Conditioned air from each of the units is distributed throughout the building by ducting located within the plant rooms and ceiling spaces feeding outlet grilles in each room and open foyer areas. The air conditioning system operates automatically during normal working hours via an adjustable time clock. Individual air conditioning units can be started manually (for out of hours work) by wall mounted push button stations located within the area to be conditioned. The temperature throughout the building is preset to maintain 24^{o}C. To maintain the temperature within the building it is essential that all doors and windows opening externally be kept closed at all times. Mechanical exhaust ventilation is provided to photocopy rooms, toilet areas and the lift motor room area. The photocopy and toilet ventilation operates automatically under the control of the main air conditioning plant. The lift room operates automatically under the control of thermostat presets to start the fan if the temperature rises above 24^{o}C. The temperature is allowed to drift up to two degree during normal conditions and up to four degree during extreme summer periods. The fan will not operate below 22^{o}C.

BUILDING MODEL DESCRIPTION

The building is located in north Rockhampton in the central Queensland region. The building consists of three levels and has a complete air-conditioned floor area. The building's geometrical representation and typical floor plan are shown in Figure 1 and 2 respectively. The modelled building has standard construction with lightweight concrete aggregate brick double glazed walls and suspended 10 mm ceiling tiles. A 20% double glazing clear internal blinds template is used in the modelled building with fixed height of 1 m. Both interior and exterior shading are included in the model. The input data of the simulation study are building constructional records, local climate data, occupancy, internal load, HVAC and lighting component data, equipment data etc. Far too often inputs are assumed due to a lack of documentation. In this situation, a good built-in library (template) with appropriate default value was found to be enormously useful.

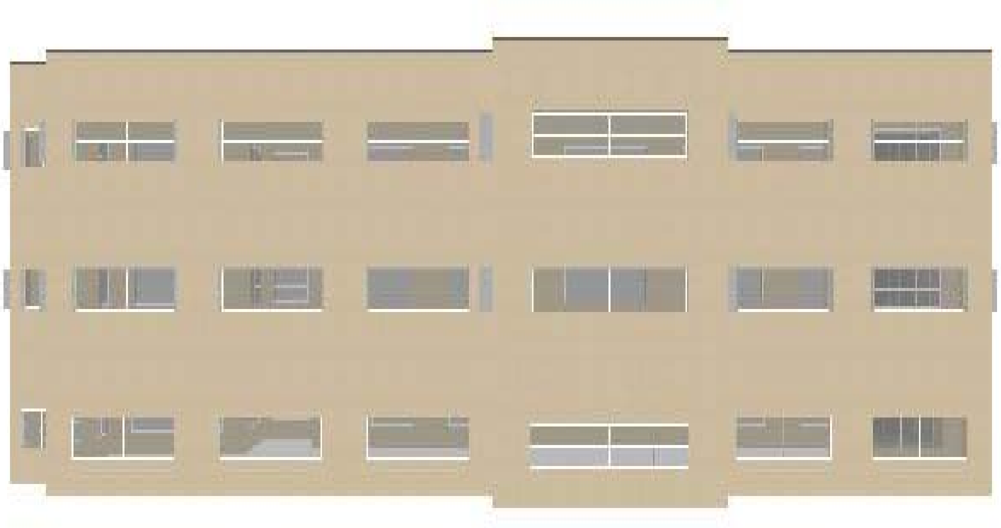

Figure 1 Geometric representation of the modelled building

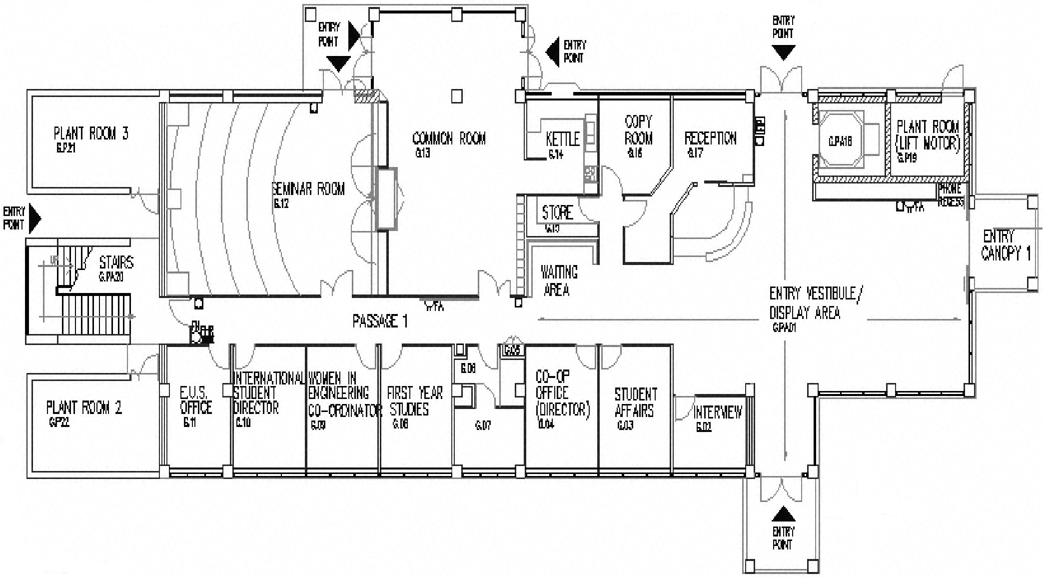

Figure 2 Typical office floor plan of case study building

The modelled building characteristics are as follows:

Size: 3 storied, nearly rectangular shaped plans with entrance on the ground floor.
Operating Schedule: 8:00 to 18:00 [5 days/week]
Occupancy: 0.2 people/m^2
External Walls: Lightweight
Internal Partition: Lightweight 2X25 mm gypsum plasterboard with 100 mm cavity
Component Block Material: Lightweight concrete block
Thermal Mass Construction: 130 mm concrete slab
Glazing: Double glazing, clear
Layout: Fixed height 1 m, 20% glazed
Window Shading Type: Blind with high reflective slats
Local Shading Type: Overhang and side fins
Lighting: Compact fluorescent
HVAC Type: Packaged direct expansion
The base model was built using all this information.

Baseline Model:

The current version of DesignBuilder (DB) allows EnergyPlus (EP) as the calculation method to evaluate the energy performance of the building. The HVAC system can be modelled using a compact HVAC description, which is automatically expanded into a full HVAC system data set prior to simulation. Parametric analysis allows an investigation of the effect of variation in design parameters on a range of performance criteria. The unitary multi-zone option makes it possible to model constant volume direct-expansion based mechanical ventilation and air conditioning (MVAC) configurations with several different heating options. In this system, central cooling coils are used to condition air, which is delivered to the each of the zones in the system through an air delivery system. Air deliveries are set up to ensure minimum fresh air supply. The thermostat is located in the control zone as set by the thermostatic control zone for a unitary system.

Heating design calculation predicts the heat loss of each zone of the building. This is based on worst-case winter design data for the location of the building. It is carried out in a steady state with no solar gain. The calculation is shown in the graph (Figures 3 and 4) highlighting air temperature, radiant temperature, comfort temperature, outdoor temperature, and heat gain and losses. The fabric and ventilation data shows the heat losses due to glazing, walls, roofs, ceiling, and external infiltration related to the number of air changes to the building and heat gain due to internal floor and external mechanical ventilation. The highest heat losses and gains are due to glazing and external ventilation.

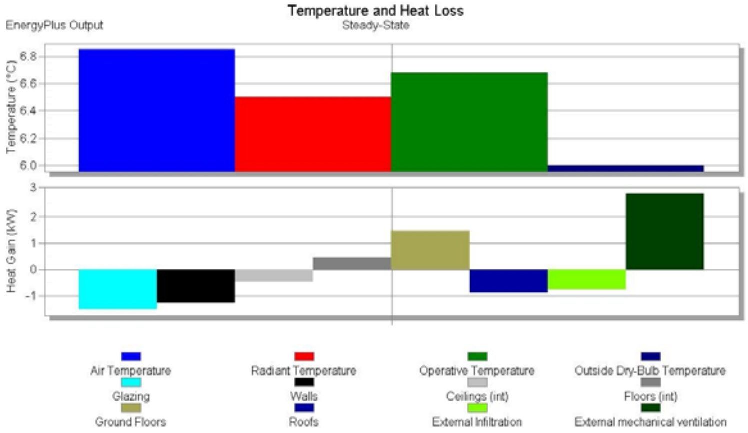

Figure 3 Temperature and Heat loss of the base modelled building

The cooling design calculations are based on simplified sinusoidal worst-case summer design conditions. The results comprise temperature, heat losses and gain in relation to cooling design. Comfort data illustrates that the average comfort temperature of the air-conditioned spaces of the building are within twenty ranges. That is due to optimized glazing and shading. The internal heat gain due to lighting, occupancy, transmitted solar heat, computer and other office equipment is shown on an hourly basis in Figure 5. The highest heat gain is due to turning on the computer and office equipment during the morning. The next priority gains are due to occupancy and lighting. All the heat gains are typically linear throughout the day. The cooling requirement throughout the day shows an almost linear pattern with an exception during the start of the day that certainly increases building operating cost due to demand charges. Figure 5 shows the heat gain in a typical summer day. There is almost zero internal heat gain after hours and in the early morning.

The whole building simulation has been performed based on data from the nearest available hourly weather station (Brisbane). Annual performance of the building has been simulated to check whether the building is performing as expected or not. The outputs of the simulation are bit similar to earlier results. The annual simulation of the building helps to study the building operation strategies throughout the year due to seasonal variation. It is noticed that there is no occupancy and internal gain in the building during weekends and holidays. The cooling requirement of the building for working days and its variation due to seasonal changes are shown in Figures 5 and 7. It is higher in the summer months and gradually lower in the cooler months. The highest cooling energy is required at the start of the day, which is nearly 240 kW. Although March is not the hottest month of the year, the cooling requirement is the highest then due to the start of the session and the return of people from annual leave. After winter, cooling requirements increase due to seasonal variations and this continues nearly until the end of summer. Figure 8 shows the total electricity consumption by the building throughout the year and it is typically similar to the building cooling requirement due to internal heat gain and outdoor air temperature. The aim is to reduce the summer energy requirements of the base building.

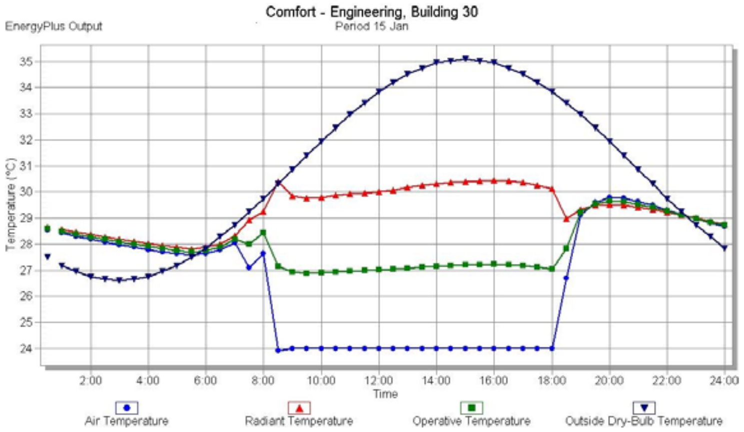

Figure 4 Comfort Temperature of the modelled building

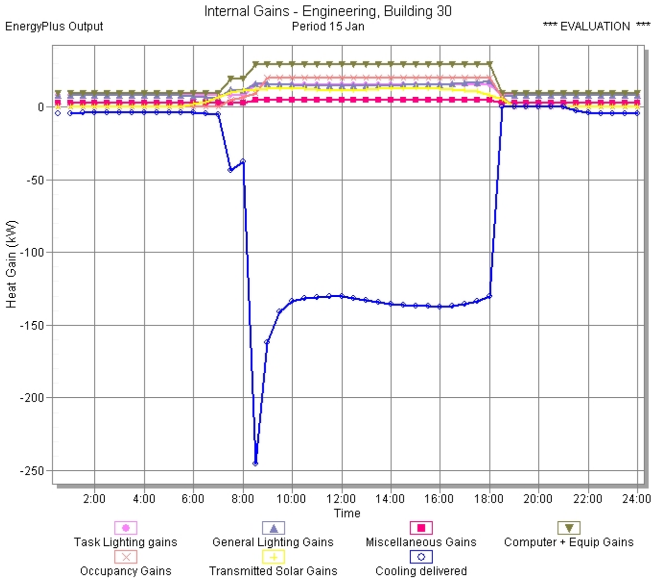

Figure 5 Hourly Internal heat gain and Cooling requirement in the base modelled building

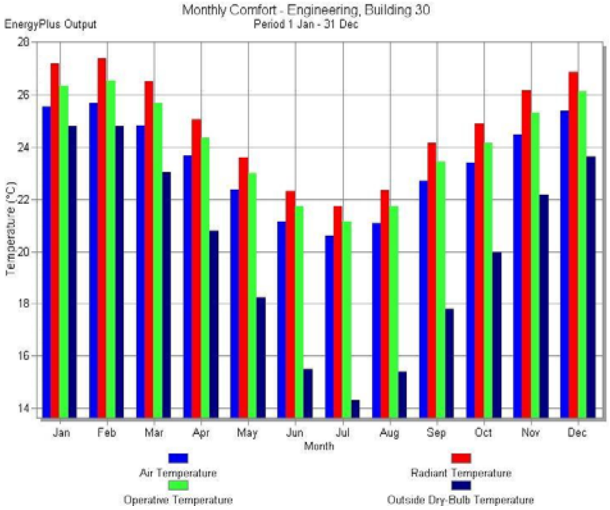

Figure 6 Internal comfort temperatures in the modelled building

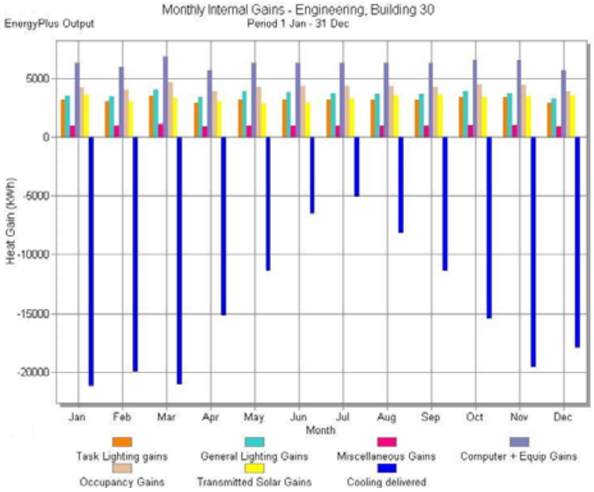

Figure 7 Average annual internal heat gain and Cooling requirement in the base modelled building

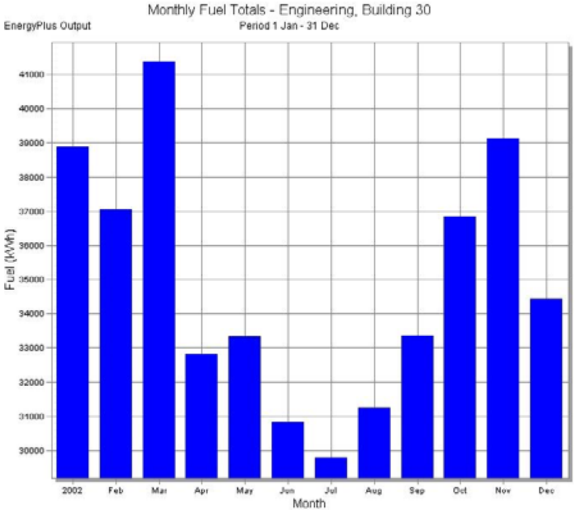

Figure 8 Annual electricity consumption of the base modelled building

It can be noted from the annual energy simulation that the electrical energy use increases during the summer months (November to March) when the outdoor air temperatures are high. During the other months, the variation of electrical energy consumption is consistent and can be attributed mostly to internal heat gain by lighting, office equipment and occupancy. The result of the base line building model illustrates that the average annual comfort temperature of the building is 24°C with annual relative humidity of 60%. The annual cooling energy delivered for internal heat gain is 172762 kWh and annual electricity consumption is around 419087 KWh.

LOW ENERGY COOLING TECHNOLOGY

The baseline model referred to the actual operating condition of existing building systems actually operating. The existing building as it is currently operating has opportunities for energy savings. In the baseline model building, the influence of the outdoor air temperature is limited because of the ventilation system. Mechanical cooling is required throughout the year to remove internal heat gain and to achieve thermal comfort in the building. Low energy cooling technologies, namely chilled ceiling and mixed mode technique, are evaluated to take advantage of energy savings opportunities.

Chilled ceiling system

The chilled ceiling (CC) technique is used in many office buildings as an air conditioning alternative. The CC technique can remove heat from heat sources (sensible cooling load) by radiation and convection. Employing chilled ceiling to treat cooling load individually improves thermal comfort because cooling is provided directly and more evenly to the occupants without causing drafts. The system also needs a ventilation system to maintain indoor air quality. As a passive cooling alternative CC has higher potential for energy and peak demand savings. Therefore, applications of CC to subtropical regions like Rockhampton are much more necessary. Energy savings can be increased by changing the CC panel area (Novoselac and Srebric, 2002). Sodec (1999) reported the possibility of reducing energy consumption by running the CC overnight. The result was not satisfactory, however, as total energy costs with and without overnight operation is the same and the need for longer operation creates expenses equal to the savings.

The performance of the CC technique can be rectified by implementing different control strategies. Novoselac and Srebric (2002) proposed temperature control strategies by constant water temperature with variable flow and constant water flow with variable temperature. To prevent condensation on the chilled ceiling, air humidity and panel surface temperature need to be controlled. Conroy and Mumma (2001) suggest an additional central dew point temperature control of the conditioned space to stop condensation. In the present simulation approach, the building will be considered as enclosed surfaces facing the air and divided into window surfaces, wall surfaces and chilled ceiling surfaces. Defining the surfaces and analysing the dynamic behaviours, for instance, energy consumption, is a realistic approach to thermal comfort.

The CC technique is modelled using DesignBuilder/EnergyPlus. Weather data for the whole of the year 2002 has been used in the simulation model. The time step in the simulation is daily. The air-conditioned zones are redefined in the design section under the chilled ceiling technique. The perimeter cooling set point is 24°C and the heating set point is 20°C. In the present modelling, all chilled ceiling panels are treated as a single element. The modelling uses an air system and includes standard system efficiencies to estimate the likely energy consumption of CC systems by scheduling the flow rate and temperature of the chilled water supplied to the ceiling systems. So the total energy consumption is the sum of the energy consumed by the ceiling panels. One third of the total ceiling is assumed to be chilled for the operation. The CC technique is simulated individually and is allowed to run after hours. The intent is to pre-cool the building's thermal mass to reduce internal gain in the daytime. As an individually operated system, the CC technique will not meet all cooling loads. The ventilation schedule consists of weeks and days, with the days containing the ventilation temperature setting at 22°C for each hour of the day. This ventilation temperature is the temperature above which the windows/doors will be opened if the conditions described under the following ventilation control mode are met. Zone temperature is controlled by a thermostat, which determines whether the system is in heating, cooling, or “float” mode. If the zone thermostat determines that the system should be on, the radiant temperature schedule determines the response of the system. System fluid flow varies linearly around the set point temperature. In determining the system response, the radiant control set point can be compared to zone mean air temperature, zone mean radiant temperature, zone operative temperature, outside air dry-bulb temperature, and outside air wet-bulb temperature. The control schedule ensures that during the occupied period, the operative temperature of the room is maintained using a temperature gradient. The result is that operative temperature tends to exceed the required comfort temperature at peak load during the day. There is a need to optimize the critical parameters, for instance, ceiling temperature, ventilation air temperature (dry and wet bulb temperature) and supply volume flow rate, in relation to the space cooling load and comfort criteria. EnergyPlus performs a reasonable job of predicting energy consumption. Annual energy consumption using CC varies significantly from baseline annual energy consumption. The overall simulation result is an 13-14% decrease of the total energy consumption in summer and a 11-12% decrease in winter seasons due to the high thermal capacity of the water-cooled panel, built in to the ceiling (Figure 9).

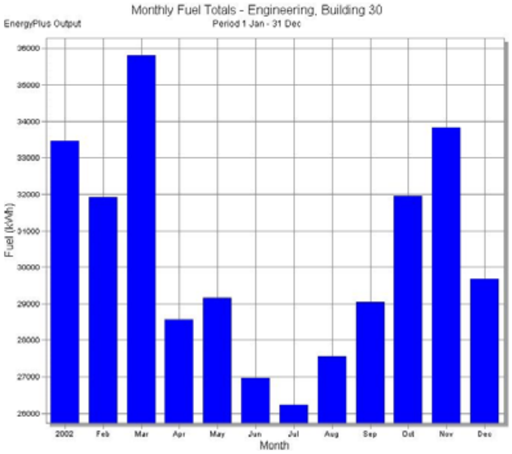

Figure 9 Annual electricity consumption of the base modelled building using a chilled ceiling system.

Mixed Mode Ventilation

Mixed mode ventilation and local comfort cooling combine natural and mechanical ventilation. They provide the many advantages of natural ventilation and other benefits, for instance, greater control over internal conditions, night ventilation, occupant density, internal loads, etc. For most active systems, a mixed-mode approach is generally preferred to full time mechanical ventilation, which affords building occupants very little control over their environment. Natural ventilation also realizes the benefits of free cooling, i.e. ventilation without fan operations because they account for a significant proportion of the energy used in mechanically ventilated buildings. Shaviv et. al. (2001) reported night ventilation is effective as a passive cooling design strategy in a hot and humid climate. Night ventilation should take maximum advantage of ambient conditions whilst avoiding overcooling. Mixed-mode systems default to natural ventilation whenever possible so the energy consumed by running fans is minimized. To achieve these objectives, natural ventilation is initiated from after hours to the start of the office day as being of great importance. The ventilation cooling set point temperature controls the activation of natural ventilation. If the inside air temperature is greater than this set point temperature (and the natural ventilation operation schedule is on) then natural ventilation can take place. The way this works depends on the natural ventilation building model option. The maximum natural ventilation input-output temperature difference is used for scheduled natural ventilation only and is the temperature difference between the indoor and outdoor air-dry bulb temperatures below which ventilation is shut off. This is to allow ventilation to be stopped if the temperature outside is too warm and could potentially heat the space. A maximum delta temperature of 2°C is mentioned; ventilation is assumed to be available if the outside air temperature is at least 2°C cooler than the zone air temperature. If the outside air-dry bulb temperature is less than 2°C cooler or warmer than the indoor dry bulb temperature, then ventilation is automatically turned off. The natural ventilation is scheduled by zone. Scheduled natural ventilation is active at any time in the simulation when the air temperature in the zone is higher than the ventilation cooling set-point temperature and the difference between inside and outside air temperatures (Tin - Tout) is less than maximum ventilation in-out delta T and the operation schedule is on at that time in the simulation. To avoid temperature control of natural ventilation, very low ventilation cooling set point temperature is set and to avoid temperature difference control of natural ventilation, a high negative value of maximum ventilation input output delta T is set. The actual natural ventilation rate at any one time in the simulation is calculated by multiplying the maximum natural ventilation rate (ach) by the value of the operation schedule. The highest cooling energy is required at the start of the day which is about 130 kW (Figure 10) and around 31% lower compared to baseline energy consumption. In this case, the highest cooling energy is required at 3:00 pm to 4:00 pm which is due to solar gain by the building envelops throughout the day. A combination of different design strategies with a mixed mode system can further decrease the cooling energy requirement. With this technique, peak cooling demand can be reduced and a stable cooling energy requirement can be achieved which substantially reduces total energy consumption.

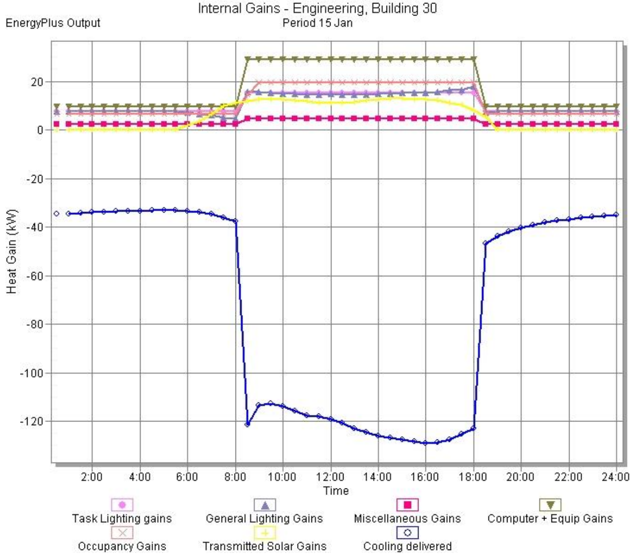

Figure 10 Hourly internal heat gain and cooling requirement using mixed mode ventilation

COMPARISON

Both chilled ceiling and mixed mode with natural ventilation for comfort cooling have been investigated through a simulation study. Major driving simulation parameters are operation scheduling, internal heat gain, set point temperature and building construction materials. Compared to the mixed mode technique, the chilled ceiling saves more energy throughout the year. The main complex, where the base building is situated, spends 456 thousand dollar per annum on its utility bill. A chilled ceiling can offer up to 14% monetary savings. Mixed mode ventilation for local comfort cooling is not considered to be a realistic approach to implement because normalised energy consumption shows that it may be feasible only for the winter months while the chilled ceiling has potential throughout the year in subtropic climate region (Figure 11).

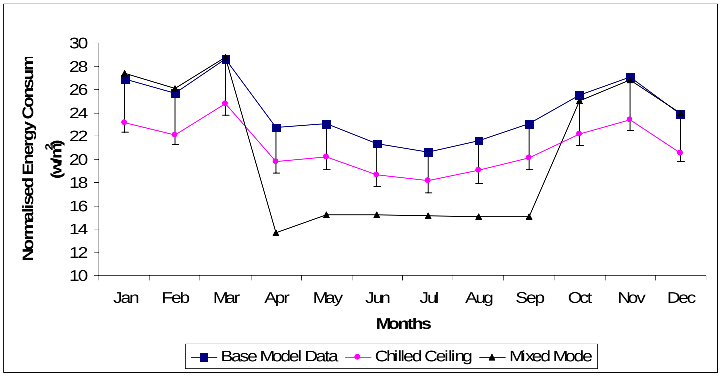

Figure 11 Comparison of normalized energy consumption

CONCLUSION

Computer-based building energy simulations are a reusable, effective technique in determining an energy conservation approach. Utilisation of the chilled ceiling as a low energy cooling system has a significant effect in the interaction of the thermal comfort measures. Both thermal comfort parameters and energy consumption are examined to accurately predict the overall performance of the system. The results of the simulation presented in this paper are the prediction of thermal behaviour and energy consumption based on a good set of default values adjusted to the case study building using DesignBuilder. The application of the chilled ceiling technique in an office building shows potential savings as a low energy cooling technology in a subtropical Queensland climate. It improves thermal comfort and reduces the energy consumption of the building.

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