Modelling and Simulation of the Effects of Passive Cooling Technologies on Energy Savings for Building Systems in Subtropical Climate

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Abstract: - The paper aims to investigate different measures of passive cooling that are compatible with existing buildings in order to reduce the energy consumption and peak demand associated with the cooling. Both the existing conditions and envisaged thermal comfort preference of the occupants of the building determine which retrofitting technology is most suitable in a particular case. Measures focusing on chilled ceiling, pre-cooling of building thermal mass and economiser usages are taken into account to evaluate the energy consumption, the indoor environment and green house emission by office buildings in the subtropical climate in Queensland, Australia. This study found that energy simulation process can provide a good projection of base loads of energy use and a reasonable projection of cooling energy savings by different passive cooling technologies.

Key-Words: - Building energy, Modelling and simulation, Subtropical climate, Passive cooling, Economiser, Pre-cooling, Chilled ceiling.

1 Introduction

The theory of building energy simulation is based upon the traditional methods of load and energy calculation in heating, ventilation and air conditioning. The purpose of energy calculation is to determine the energy requirements of the building to meet the required loads throughout the year [1]. Many approaches have been developed to analyse energy performance in different ways, at different levels of effort and precision and at different stages in the life of a building [2]. An important goal for the building sector is to produce buildings with a minimum of environmental impact. Energy use is a central issue as energy is generally one of the most important resources used in buildings over their lifetime. Low energy buildings have therefore become an important research field [3]. A survey on building's life cycle energy use in a total of sixty residential and non-residential cases from nine countries was performed that operating energy represents by far the largest part of energy demand in a building during its life cycle. The study revealed a linear relation between operating and total energy valid through all cases regardless of the climate and other background differences and showed that design of low energy buildings induces both a net benefit in total life cycle energy demand [4].

Building is an integration of energy system. Cooling accounts for a significant portion of the total energy consumption in buildings due to increasing use of information technology. The use of electricity is responsible for 89% of commercial buildings' greenhouse gas emissions and heating, ventilation and air conditioning (HVAC) and lighting account for 84% of commercial building sector greenhouse emissions. Operational energy applications responsible for greenhouse gas emissions are cooling (28%), air handling (22%), lighting (21%) and heating (13%) [5]. Impact on greenhouse gas emissions is enhanced because these cooling systems are usually electricity driven and electricity in Australia is predominantly produced by coal power plant. The prediction of energy use and temperature distribution of a building at different operating conditions is very important, especially when evaluating new concepts of heating, ventilation and air-conditioning systems in combination with different control strategies.

In this study DesignBuilder [6], based on a unique tool for evaluating building conditions, is used to assess energy and monetary savings of different passive cooling technologies in an office building in Rockhampton, Queensland, Australia. Current version of DesignBuilder (DB) allows EnergyPlus (EP) [7] as the calculation method to evaluate the energy performance of the building. DB creates a virtual environment where HVAC and lighting systems of the building are evaluated in order to determine the feasibility of different alternatives. Buildings and systems analysis based on simulation and monitoring as well as climate analysis are presented in order to estimate the potential of passive and low energy cooling technologies. Besides estimation of energy consumption, this study also accounts greenhouse gas emissions by an institutional building per year and potential savings on emission through passive cooling.

2 Simulation Principle

EP is primarily a heat and mass balanced based simulation engine which use Predictor – Corrector Method with user configurable modular systems and multizone airflow. The basic strategy of Predictor – Corrector Method is that it can predict the mechanical system load needed to maintain the zone air temperature then simulate the mechanical system to determine actual capacity. After that, it recalculates the zone air heat balance to determine the actual zone temperature [8]. Using EP, loads calculated on hourly basis are passed to the building systems simulation module at the same time step. EP has three basic components—a simulation manager, a heat and mass balance simulation module, and a building systems simulation module [7]. Building systems simulation manager handles communication between the heat balance engine and various HVAC modules and loops, such as coils, chillers, pumps, fans, and other components. EP integrated solution manager manages the surface and air heat balance modules and acts as an interface between the heat balance and the building systems simulation manager. The zone temperature derivative is calculated with a third order finite difference approximation. The surface heat balance module simulates inside and outside surface heat balance; interconnections between heat balances and boundary conditions; and conduction, convection, radiation, and mass transfer effects. The air mass balance module accounts for thermal mass of zone air and evaluates direct convective heat gains. After the heat balance manager completes simulation for a time step, it calls the Building Systems Simulation Manager, which controls the simulation of HVAC and electrical systems, equipment and components and updates the zone-air conditions. Integrated simulation models capacity limits realistically and tightly couples the air and water side of the system and plant. The radiant heating and cooling models are an expansion of the conduction transfer function and incorporate thermal comfort calculations.

3 Base Case Model

The building consists of four levels and has a complete air-conditioned floor area. The modelled building has standard construction with lightweight concrete aggregate brick double glazed walls and suspended 10 mm ceiling tiles. Both interior and exterior shading are included in the model. The thermal performance of a HVAC system in a building is influenced by a number of factors as outdoor climate, heat gain and losses through the building envelop, building thermal mass, internal loads, occupant behaviour etc. Whole building performance simulation is a powerful tool because it considers building structure, indoor environment, outdoor environment, mechanical, electrical or structural system, traditional and renewable energy supply systems in order to analyse and achieve better indoor environment for the occupants in a sustainable manner. The aim of the low energy cooling technologies is to provide cooling in an energy efficient manner thus reducing energy consumption and peak electricity demand. The boundary conditions used for the simulation are listed below

Building Size: 3 storied, nearly rectangular shaped plans with entrance on the ground floor.
Front Orientation: NE
Width: 34 m; Length: 74 m; Height: 16 m
Operating Schedule: 8:00 to 18:00 [5 days/week]
Walls: Double Brick Plaster
Roof Ceiling: Concrete and Plasterboard
Floor: Concrete slab with carpet
Internal Partition: Lightweight 2X25 mm gypsum plasterboard with 100 mm cavity
Component Block: Lightweight concrete block
Thermal Mass Construction: 130 mm concrete slab
Windows Width 1.5 m; Height 1.5 m
Window Shading: Blind with high reflective slats
Local Shading Type: Overhang and side fins
Windows Type: Single glazed, clear float with blinds
Occupancy: 1 person per 10m^2
Outside air rate: 10L/s/person
Lighting Type: Compact fluorescent
Lighting Power Density: 18w/m^2
Office Equipment Power Density 15w/m^2
Cooling Type: Air Cooled
Cooling Power Density 40w/m^2
Ventilation Power Density 5w/m^2

3.1 Model Description

DB models were structured in order of Site, Building, Block, Zone, Surface data. This structure sets up data globally in a building model. Building blocks are basic geometric shapes that are used to assemble a 3D model as similar to building physical model using bricks. Component blocks are added to the building to create non air-conditioned spaces, visual and shading structures which do not contain zones and are not part of the model. In the modelled building (Fig. 1), building blocks, which represent the outer shell of the model or part of the model, are composed of building elements such as walls, floor slabs and roofs, and are partitioned internally to form thermal zones. The partition of the space boundaries of the thermal zones were modelled according to the HVAC drawing for the consistency in specifying according to building management system. DB uses the thermal characteristics of the constructions for each of the walls, floors, roofs, partitions etc. in each zone and accounts for the thermal mass in the simulations. The defined thermal mass was lumped together for each zone and modelled in EP. The features discussed in the building description section were major consideration for creating the geometric model.

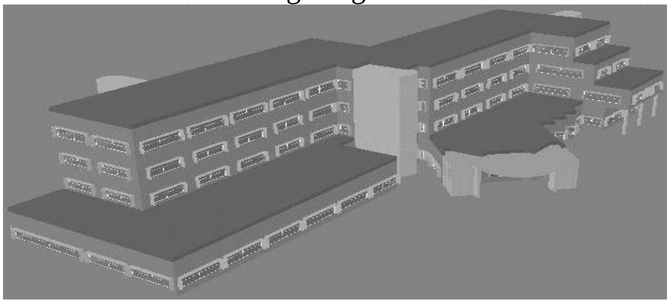

Fig. 1 Geometric representation of the building

3.2 Internal gain

The types of internal gain include occupancy, computer, office equipment, and lighting gains etc. In some cases, the load data associated with each zone were taken as the average for a specific zone or for the whole building. When defining internal loads, geometric information, infiltration method and day lighting were also specified. DB was used to automatically calculate heating and cooling capacity in each zone based on the output from the heating and cooling design calculations. The Occupancy schedule setting (Typical workday or Schedule) was used to control internal gains and/or HVAC systems by defining appropriate Model options. The highest heat gain is due to solar transmittance both in summer and winter. The next priority gains are due to occupancy and lighting, computer and office equipment. The cooling requirement throughout the day remains approximately same with an exception during the start of the day. The cooling requirement which is almost one third in winter compared to summer. Internal heat gain after hours and in the early morning is almost negligible.

3.2 Energy end uses

The whole building energy simulation has been performed based on data from the nearest available hourly weather station (Rockhampton). Generally, summer is from December to February and winter is from June to August. Fig. 2 shows the Equipment, lighting, chiller energy and total electricity consumption by the building in a year. Energy consumption by the chiller and system are proportional to the building cooling requirement due to internal heat gain and outdoor air temperature. It can be noted from the energy simulation that the electrical energy use increases during the summer months (December to February) when the outdoor air temperatures are high. During winter (June to August), the consumption is relatively lower and the variation of electrical energy consumption is consistent and can be attributed mostly to internal heat gain by lighting, office equipment and room electricity. The simulated results depicts that the daily total electricity consumption of the building do not cross 0.6 kWh/m^2/day in summer which has good agreement with previous published data [9].

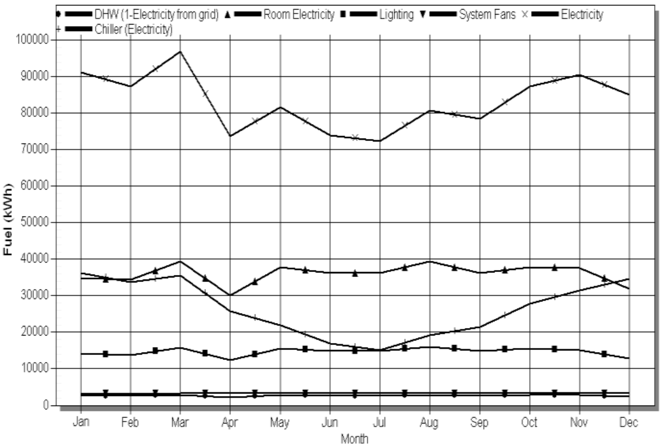

Fig. 2 Consumption breakdown of the base model

3.4 Validation of the base model

The capacity of EP to predict zone loads, cooling coil loads, cooling equipment energy consumption and resulting zone environment agreed within 1% of the analytical results except for mean zone humidity ratio which has agreed to within 3% for high sensible heat ratio cases and 0.2% for low sensible heat ratio cases [10]. Most recent studies showed that EnergyPlus results generally agreed within 1.1% of the analytical results except for the mean zone humidity ratio which agree within 2.7% for high sensible heat ratio cases but within 0.65% for low sensible heat ratio cases [11]. For calibrating the base model data from the building energy management system, data acquired from local monitoring of inside temperature and humidity and smart meter reading for end energy use were used. In the simulation using the existing system (base case) 23^{o}C temperature was maintained during the occupied period of the day. The simulated temperature profiles found to be within 5% of the measured value which is very significant from a statistical point of view (Fig. 3). The simulated values of the energy consumption by the air conditioner during weekdays are compared with the smart metered readings and they are within 12% of the measured value (Fig. 4). The comparison of chiller energy consumption during weekdays are not so satisfactory (although the simulated and measured values have similar consumption pattern) because of the fact that the chillers are quite old (15years) and during the measured periods both the chillers were running on part load (Fig. 5).

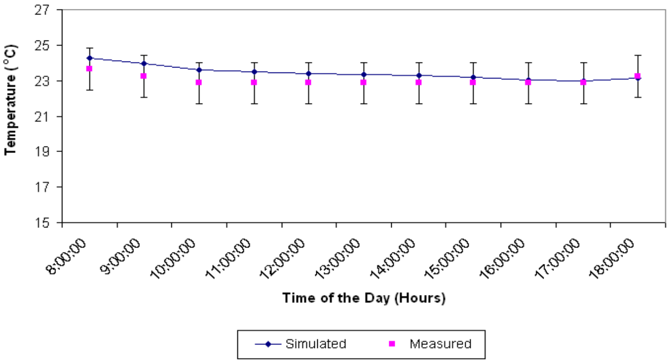

Fig. 3 Comparison of simulated and measured temperature profile in a typical day

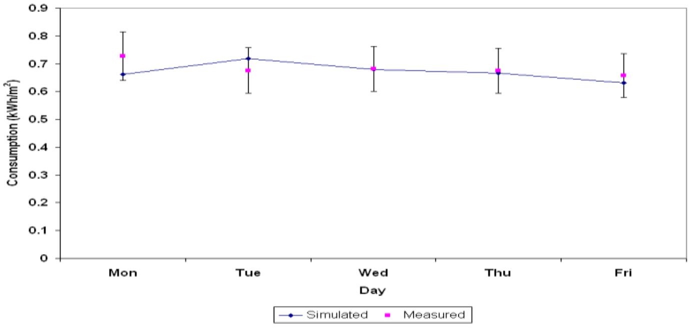

Fig. 4 Comparison of simulated and measured air conditioning electricity consumption

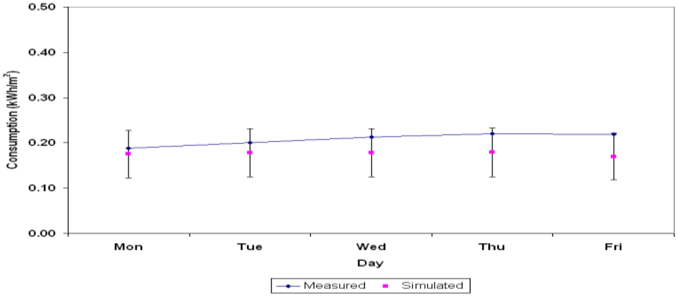

Fig. 5 Comparison of Simulated and Measured Chiller Electricity Consumption

4 Passive Cooling Technologies

The baseline model referred to the actual operating condition of existing building systems actually operating. Passive cooling technologies, namely chilled ceiling, pre-cooling and economiser usages are evaluated to take advantage of energy savings opportunities.

4.1 Chilled ceiling (CC) system

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. Energy savings can be increased by changing the CC panel area [12]. An earlier study in CC reported that there is possibility of reducing energy consumption by running the CC overnight [13]. The result was not satisfactory 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. Studies proposed temperature control strategies by constant water temperature with variable flow and constant water flow with variable temperature [12, 13]. To prevent condensation on the chilled ceiling, air humidity and panel surface temperature need to be controlled. Conroy and Mumma (2001) suggested an additional central dew point temperature control of the conditioned space to stop condensation [14]. Present simulation approach used in the current study, the building was considered as enclosed surfaces facing the air and divided into window surfaces, wall surfaces and chilled ceiling surfaces. In the study 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.

4.2 Pre-cooling strategies

The potential for utilizing building thermal mass for load reduction has been demonstrated in a number of simulation, laboratory, and field studies [15]. Studies have shown that when an effective control strategy is used, up to 35% in energy cost savings can be achieved [16]. Pre-cooling and zone temperature reset strategies shifted 80-100% of the electric load of the cooling plant without thermal discomfort even with a relatively high outside air temperature of 32°C [15]. In a recent study it has been found that increasing the zone temperature set point by four degrees can reduce chiller electricity consumption by about 33% and MVAC electricity consumption by 25% over four hours shed even on a hot day [17]. The principle of pre-cooling and demand limiting is to pre-cool buildings at night or in the morning during off-peak hours, storing cooling in the building thermal mass and thereby reducing cooling loads and related electrical demand during the peak periods. The warm-up period was used to reset the zone air temperature set point so that the cooling system turns off. During this time, the zone air warms due to lighting and equipment load. The set point was set to a value low in the comfort region so that the building mass charge is held as long as cooling capacity is available. This set point is maintained until the limit on cooling capacity is reached. After this point, the temperatures in the zone floated upwards and the cooling stores in the building mass were discharged. The pre-cooling and occupied set points were chosen in such a way that the zone conditions remain within the comfort region throughout the occupied period with the capacity limit in place.

4.3 Economiser usages

An economiser system is a mixed air control system that utilizes outdoor air as the first stage of cooling to reduce energy usage. A cooling system with an economiser can use cool outside-air to satisfy all or part of the cooling demand. This reduces the cooling energy required by the system. Economisers use controllable dampers to increase the amount of outside-air intake into the building when the outside-air is cool and the building requires cooling. Simulation models have been developed and verified by a number of studies for realistic control economiser retrofit simulations [18, 19]. Studies have shown that energy savings of around 30% can be achieved through use of the economiser cycle along with fan scheduling and set point setback as retrofit options in existing buildings without compromising the indoor comfort [19]. Economiser control strategies based on Return air temperature has been simulated in this study using the compact MVAC option of EnergyPlus. This has been done by limiting the upper temperature limit for economiser operation. The options for economiser control strategies was that if the outside air temperature was above the upper temperature limit (23^{o}C), the outside air flow rate would set to be the minimum and no input in this field means that there is no outside air temperature high limit control.

4.4 Comparison of the passive cooling technologies

To minimize the high cooling load and to reduce the use of air conditioning, the application of passive cooling retrofitting measures were considered. The current indoor environmental control strategies have been checked and thermal comfort ability of the building has been determined using the above passive cooling technologies. Thermal comfort index (Fanger PMV) has also been simulated on nine point thermal sensational scale. The DB simulates extensive data on environmental conditions within the building and occupants' comfort level. The results of the Fanger PMV simulation are plotted in Fig. 6 for each of the control strategies and they are within the -0.5<PMV<+0.5 limits for 10% PPD as per ISO 7730 – 1994 [20] during office hours on summer and winter days. In all instances, simulated PMV with chilled ceiling was much closer to neutral/comfortable (0.0) than the other two cooling options; that is economizer and pre-cooling control strategies. The simulated thermal comfort index has also good agreement with previous study in subtropical climate in Australia [21].

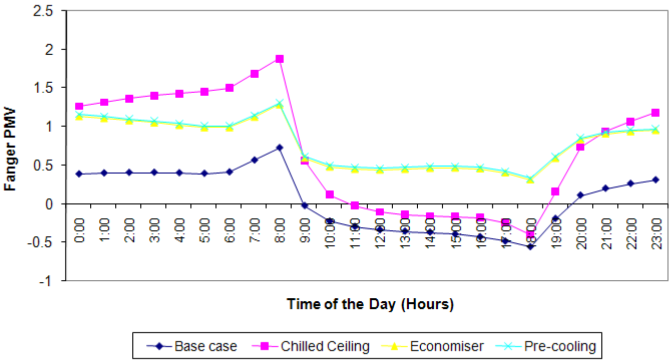

Fig. 6 Comparison of thermal performance index in a typical day

The application of passive cooling measures decreases the chiller energy consumption up to 5kWh/m^2/month (Fig. 7). The highest cooling energy is required in summer at the start of the day, which is nearly 325 kW and 220 kW in winter at the end of the day. It is typically similar to the building cooling requirement due to internal heat gain and outdoor air temperature. It can be noted from the energy simulation that the electrical energy use increases during the summer months (December to February) when the outdoor air temperatures are high. During winter month (June to August), the consumption is relatively lower and the variation of electrical energy consumption is consistent and can be attributed mostly to internal heat gain by lighting, office equipment and occupancy.

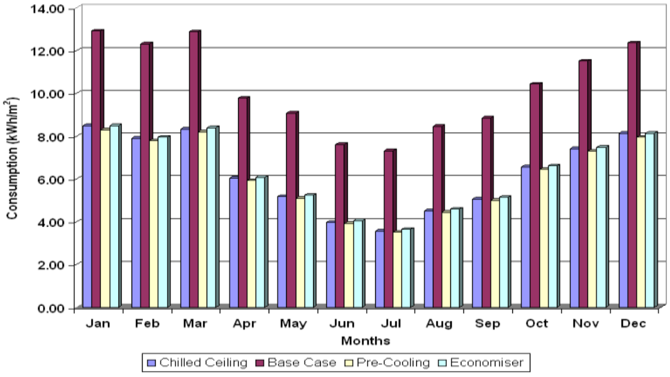

Fig. 7 Comparison of normalised chiller energy consumption

Fig. 8 shows the total greenhouse gas emissions caused by current and passive cooling technologies per month over one year. In terms of emissions, chilled ceiling is the best passive cooling technologies compared to current practice and produce 566 tonnes less emission. Other passive cooling control technologies are also significant because they provide up to 463 tonnes less CO_2 to the environment compared to current practice.

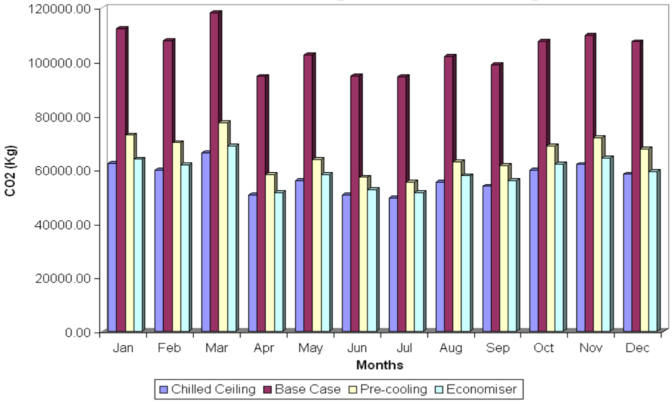

Fig. 8 Comparison of greenhouse gas emission

5 Conclusion

The effect of passive cooling technologies on energy consumption and indoor thermal environment are studied. As a passive cooling alternative CC has higher potential for energy and peak demand savings. The applications of CC to subtropical regions like Rockhampton are highly recommended. The use of passive cooling technique can have an important role to play in reducing dependency on mechanical systems in an office building. Moreover, the study revealed that passive measures can be successfully applied to buildings located in warmer climates where high energy use of an air conditioning system.

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