Numerical Simulation of Building Performance under Different Low Energy Cooling Technologies

Ashfaque Ahmed Chowdhury, M G Raul and M M K Khan

Abstract**—**Numerical simulation on building performance under different low energy cooling technologies are carried out in order to reduce the energy consumption and peak demand associated with the building cooling. The simulation is based on a heat and mass balance principle and verified by measured data. In simulation, the building zones, air-handling systems, central chiller plant and other equipments are integrated in the heat balance equations sequentially and the Euler formula is employed to solve and complete the numerical calculation. Various measures such as focusing on chilled ceiling, pre-cooling of building thermal mass and economiser systems are taken into account to evaluate the energy consumption, the indoor environment and greenhouse emission by office buildings in a subtropical climate - Central Queensland, Australia. Chilled ceiling, a radiant cooling system, is modeled using time series solution by extending the conduction transfer function method. A specific on-off control strategy is used to model pre-cooling and economizer system in the building simulation. The results indicate that low energy cooling techniques save operating energy in subtropical climates and also provide better thermal comfort for building occupants.

Keywords**—**Building energy consumption, Modeling and simulation, Subtropical climate, Low energy cooling, Economizer, Pre-cooling, Chilled ceiling.

I. INTRODUCTION

THE theory of building energy simulation is based upon the traditional methods of load and energy calculation in heating, ventilation and air conditioning (HVAC). The simulation of the buildings predicts the response of a building or building systems under different conditions by means of a computer aided model. 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 analyze energy performance, at various 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 found that operating energy represents the largest part of energy demand in a building during its life cycle. The study also revealed a linear relation between operating and total energy, 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].

Simulation is being increasingly used in design of modern buildings. Techniques are now available to evaluate building performance and to prepare retrofit strategies [5]. The interaction between climate, occupants, HVAC and electrical systems in a building is highly complex and, by simulation, it is now possible to understand the factors involved in the process. A simplified Monte Carlo method for finding an approximation of the building inside temperature distribution is used in conjunction with a more traditional deterministic building thermal simulation model by Haarhoff and Mathews [6]. Tavares and Martins [7] presented a case study of a public building to analyze the building performance and comfortability with the help of simulation. The study created a sensitivity analysis technique for the parameters relating to wall structure, wall material, window frames and HVAC system etc for a case study building. A study by Yezioro et al. [8] showed that the detailed simulation tools provide the best simulation performance in terms of heating and cooling electricity consumption, which is within 3% of mean absolute error. Through a simulation process, Fuller and Luther [9] identified the major influences on thermal performance in a base case. The predicted result of the simulation was the reduction in energy consumption for heating and cooling by 72% and 76% respectively. Setting energy consumption as the benchmark of an acceptable indoor environment is important for monitoring of energy efficiency in air-conditioned offices [10]. They suggested that the benchmarking models might be normalized with the floor area, temperature, operational hours or any other significant explanatory factors dominating the energy consumption.

Manuscript received January 31, 2007: Revised version received June 4, 2007.

Ashfaque Ahmed Chowdhury is a research assistant at Central Queensland University, Rockhampton, Qld 4702, Australia (phone: 61 7 4930 9634; fax: 61 7 4930 9382; e-mail: a.chowdhury@cqu.edu.au).

M. G. Rasul is a senior lecturer at Central Queensland University, Rockhampton, Qld 4702, Australia (e-mail: m.rasul@cqu.edu.au).

M. M. K. Khan is an associate professor at Central Queensland University, Rockhampton, Qld 4702, Australia (e-mail: m.khan@cqu.edu.au).

In this study, a building thermal simulation model is used to assess energy and monetary savings of different low energy cooling technologies in an office building in Rockhampton, Australia. In the simulation, the model 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 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.

II. LOW ENERGY COOLING TECHNOLOGIES

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 building simulation studies suggest that the saving potentials and best control strategies are very dependent upon the system and weather conditions [11]. The energy conservation potential of office buildings in five climatic zones were investigated for different passive retrofitting scenarios by Dascalaki and Santamouris [12]. However, the applicability of the results was limited because the study did not incorporate any occupancy schedule or internal loads for the buildings. In this section, previous works relating to low energy cooling control technologies such as pre-cooling of the building thermal mass, economizer system and application of the chilled ceiling are discussed.

A. Chilled Ceiling System

The Chilled Ceiling (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 [13]. Other study reported the possibility of reducing energy consumption by running the CC overnight [14]. The result was not satisfactory, however, as total energy cost 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. To prevent condensation on the chilled ceiling, air humidity and panel surface temperature need to be controlled. Conroy and Mumma [15] suggested an additional central dew point temperature control of the conditioned space to stop condensation. Ayoub et al. [16] developed a simplified thermal transport model for spaces cooled by the combined CC system and tested the applicability and found satisfactory results. They have suggested that energy consumption using chilled ceiling depended on the supply air temperature, the outdoor airflow rate, and the cooling load. Ghali et al. [17] studied the design and performance of a cooled ceiling and displacement ventilation system application for buildings in humid climates for the purpose of achieving energy savings, better indoor air quality and thermal comfort. The study has confirmed that a chilled ceiling system consumed 21% less cooling energy than the conventional fresh air system over the cooling season.

B. Pre-cooling System

The potential for utilizing building thermal mass for load reduction has been demonstrated in a number of simulation, laboratory, and field studies [18]. Studies have shown that when an effective control strategy is used, up to 35% in energy cost savings can be achieved [19]. Pre-cooling and zone temperature reset strategies have shifted 80%-100% of the electric load of the cooling plant without thermal discomfort even with a relatively high outside air temperature of 32^{o}C [18]. In recent studies 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 [20]. A series of parametric analyses have been performed by Morgan and Krarti [21] to evaluate the impact of key design and operating conditions on the effectiveness of pre-cooling control strategies at reducing peak demand and overall energy costs. In particular, it has found that 4–8 hours pre-cooling periods were most effective at reducing peak cooling loads without increasing energy use dramatically.

C. Economizer System

An economiser system is a mixed air control system that utilizes outdoor air as the first stage of cooling to reduce energy usage. Most commercial buildings generally have a cooling requirement even during mild and cold weather conditions because of the internal loads. 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 [22]. Studies have shown that energy savings of around 30% can be achieved through the use of the economiser cycle along with fan scheduling and set point setback as retrofit options in existing buildings without compromising the indoor comfort [23].

III. SIMULATION PRINCIPLES

DesignBuilder [24] and EnergyPlus [25], state of the art building energy simulation softwares, are used to evaluate energy and monetary savings of different low energy cooling technologies in a reference building. Current version of DesignBuilder (DB) allows EnergyPlus (EP) as the calculation method to evaluate the energy performance of the building. EP is primarily a heat and mass balanced based simulation engine, which use Predictor – Corrector Method for modular systems and multi-zone 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 [26]. In EnergyPlus documentation [25] the air heat balance is given by,

$$C_Z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right) + \sum_{i=1}^{N_{zones}} m_i c_p \left(T_{zi} - T_z\right) + m_{\inf} c_p \left(T_{\inf} - T_z\right) + Q_{sys} \qquad (3.1)$$

Where,

$C_Z \frac{dT_z}{dt}$	Rate of energy storage in air (W)
$\sum_{i=1}^{N_{sl}} Q_i$	Sum of internal convection loads from people, computers etc. (W)
$\sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right)$	Convective heat transfer from zone surfaces(W)
$\sum_{i=1}^{N_{zones}} m_i c_p \left(T_{zi} - T_z\right)$	Heat transfer due to inter-zone air mixing(W)
$m_{\inf} c_p \left(T_{\inf} - T_z\right)$	Heat transfer due to infiltration (W)
$Q_{sys} = m_{sys} c_p \left(T_s - T_z\right)$	Air system output (W)

The steady state system output can be found by omitting the air capacitance

$$-Q_{sys} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right) + \sum_{i=1}^{N_{zones}} m_i c_p \left(T_{zi} - T_z\right) + m_{\inf} c_p \left(T_{\inf} - T_z\right) \qquad (3.2)$$

The system is then simulated to determine its actual supply capability of the system including plant simulation. The resulting zone temperature is then calculated by

$$T_z^t = \frac{\sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} m_i C_p T_{zi} + m_{\inf} C_p T_\infty + m_{sys} C_p T_{\text{supply}} - \left(\frac{C_z}{\delta t}\right)\left(-3T_z^{t-\delta t} + \frac{3}{2} T_z^{t-2\delta t} - \frac{1}{3} T_z^{t-3\delta t}\right)}{\left(\frac{11}{6}\right)\frac{C_z}{\delta t} + \sum_{i=1}^{N_{surfaces}} h_i A + \sum_{i=1}^{N_{zones}} m_i C_p + m_{\inf} C_p + m_{sys} C} \qquad (3.3)$$

In EnergyPlus version 2.1 [25], 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. Building systems simulation manager communicates between the heat balance engine and various HVAC modules, 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. As indicated in EnergyPlus documentation [25], 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 passes to the Building Systems Simulation Manager, which controls the simulation of HVAC and electrical systems, equipment and components and updates the zone-air conditions.

A specific on-off control strategy is followed to model pre-cooling the building and economiser system in the simulation. The radiant cooling models are an expansion of the conduction transfer function and incorporate thermal comfort calculations. Here, the system circulates cold fluid through tubes embedded in a ceiling or in a panel. Energy is thus removed from the space, and zone occupants are conditioned by radiation exchange with the system and convection from the surrounding air. EnergyPlus uses a time series solution for transient heat conduction. The basic time series solution is the response factor equation, which relates the flux at one surface of an element to an infinite series of temperature histories. The basic form of a conduction transfer function is given by:

$$q''_{i,t} = \sum_{m=1}^{M} X_m T_{i,t-m+1} - \sum_{m=1}^{M} Y_m T_{o,t-m+1} + \sum_{m=1}^{k} F_m q''_{i,t-m} \qquad (3.4)$$

Where q'' (W/m^2) is heat flux, T (^{o}C) is temperature, k (W/m^{2}K) is the order of the conduction transfer functions, M is a finite number defined by the order of the conduction transfer functions, and X, Y, and F are the conduction transfer functions, i signifies the inside of the building element, o signifies the outside of the building element, and t represents the current time step.

For a radiant cooling system, the known quantity is not heat, rather the temperature of the water being sent to the building element. Using heat exchanger relationships, an equation is formulated to obtain the heat delivered to the slab based on the inlet fluid temperature. As the inlet fluid temperature, the system geometry, and the solid temperature are known, then the outlet temperature and thus the heat transfer to the building element can be computed. For one dimensional conduction heat transfer, the solid temperature is the temperature of the building element at the depth and is given by

$$T_{s,t} = \sum_{m=1}^{M} x_{k,m} T_{i,t-m+1} - \sum_{m=1}^{M} y_{k,m} T_{o,t-m+1} + \sum_{m=1}^{k} f_m T_{s,t-m} + \sum_{m=1}^{M} w_m q_{source,t-m+1} \qquad (3.5)$$

The radiant system model is fully integrated into the heat balance. In EnergyPlus, the heat balance is simulated first, then, the system and plant heat balance are simulated at multiple time steps. The radiant system is allowed to operate as per the controls specified.

Mathematical models have been integrated into the thermal analysis tool, EnergyPlus, for predicting thermal comfort. Thermal comfort models ensure the environmental control strategies are thermally comfortable for the occupants. Many researchers developed mathematical models to simulate thermal comfort ability of the occupants under different environment. The most prominent models include Fanger comfort model (Fanger Predicted Mean Vote, PMV), Pierce two-node model (Pierce Predicted Mean Vote, PMV) and Kansas State University two-node model (KSU Thermal Sensational Vote, TSV).

Fanger developed a mathematical model, which considers the four physical variables (air temperature, radiant temperatures, relative humidity and air velocity), and personal variables (activity and clothing), to predict the thermal comfortability. The formula of Fanger's PMV is given by

$$PMV = (0.303 \times e^{-0.036M} + 0.028)(H - L) \tag{3.6}$$

Where, M (W/m^2) denotes metabolic rate per unit area, L (W/m^2) accounts all modes of energy loss from body and H (W/m^2) represents internal heat production rate of an occupant per unit area.

The KSU two-node model is based on the changes that occur in the thermal conductance between the core and the skin temperatures in cold environments, and in warm environments it is based on changes in the skin wettedness. TSV are calculated based on the formula derived through experiments in all temperature range and are given by

$$TSV \ (in\ warm\ environment) = \left(5 - 6.56 \times \left(Relative\ Humidity - 0.5\right)\right) \times Skin\ Wettedness\ factor \tag{3.7}$$

Pierce two-node model considers the same formula as proposed by Fanger to predict thermal comfort ability with an exception that Pierce models converts the actual environment into a standard environment at a standard effective temperature (SET) and in an environment at an effective temperature (ET).

IV. SIMULATION APPROACH

In the present simulation approach, the building is considered as enclosed surfaces facing the air and divided into window surfaces, wall surfaces, and chilled ceiling surfaces. The passive chilled ceiling cools room air through a natural convection current created by the temperature difference and hence the density difference between room air and the air near the beam. CC generally operates with the water temperatures between 14^{o}C-18^{o}C. The cooling output for passive cooling is 20-40 W/mK. 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. Defining the surfaces and analysing the dynamic behaviours, for instance, energy consumption, is a realistic approach to thermal comfort. The modelling uses an air system and includes standard system efficiencies to estimate the likely energy consumption of CC systems. This is done by scheduling the flow rate and temperature of the chilled water supplied to the ceiling systems. Therefore, the total energy consumption is the sum of the energy consumed by the ceiling panels.

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 is 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 were floated upward and the cooling stores in the building mass were discharged. The pre-cooling and occupied set points were chosen properly so the zone conditions remain within the comfort region throughout the occupied period with the capacity limit in place.

Economiser control strategies based on return air temperature was simulated using the compact MVAC option of EnergyPlus. This was done by limiting the upper temperature limit for economiser operation. The options for economiser control strategies is that if the outside air temperature is above the upper temperature limit (23^{o}C), the outside air flow rate will be set to a minimum. No input in this field means that there is no outside air temperature high limit control.

V. MODEL DESCRIPTIONS

DB models were structured in order of site, building, block, zone, and 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 similar to building a physical model using bricks. Component blocks are added to the building to create non air-conditioned spaces, visual and shading structures that 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.

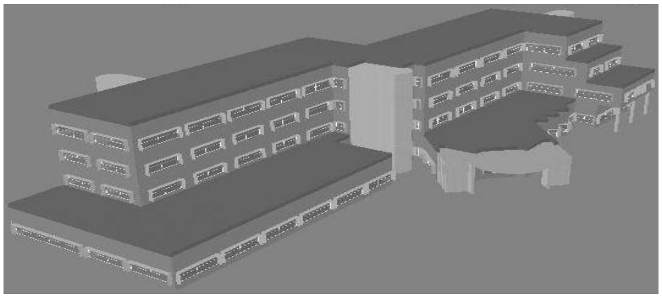

Fig. 1. Geometric representation of the building

The reference building, located in Rockhampton, Central Queenslands, Australia consists of four levels and has a complete air-conditioned floor area. Rockhampton climate is classified as Subtropical. Generally, summer is from December to February and winter is from June to August. For the simulation, the extreme hot summer period was selected from January 27 to February 2 and nearest maximum summer temperature was taken as 39°C. In a typical summer week, the nearest average temperature is 26.4°C. Extreme cold winter week was selected from June 8 to June 14 and nearest minimum temperature for winter is 5.00°C. In a typical winter week, the nearest average temperature is 17°C. 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 boundary conditions used for the simulation are listed in Table 1.

Table 1. The boundary conditions used for the simulation

Description	Value
Building Size	3 storied, nearly rectangular shaped plans with entrance on the ground floor
Front Orientation	NE
Width, Length and Height	34 m, 74 m and 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 and Height	1.5 m and 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

In the simulation, heating and cooling design calculations use simple worst-case winter and summer design data from ASHRAE respectively. The calculations are carried out to determine the size of the heating and cooling equipment required to meet the coldest and hottest winter and summer condition. Heating and cooling design calculations are done by putting a sin curve through maximum daytime and corresponding night-time summertime design temperatures. By default, EnergyPlus assumes that air temperature within a zone is uniform (i.e. the air is fully mixed). The weather data used in winter design calculations were minimum outside dry bulb temperature (design outside air temperature), co-incident wind speed and direction. The weather data used in summer design calculation were maximum outside dry bulb temperature (maximum dry bulb air temperature over the day), minimum outside dry bulb temperature (minimum dry bulb air temperature, night-time), and wet bulb temperature at the time of the maximum dry bulb temperature.

The types of internal gain considered in the simulations are 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 are also specified. DB is 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 in the morning when the cooling requirement is relatively higher. The cooling requirement is almost one third in winter, compared to summer. Internal heat gain after hours and in the early morning is almost negligible.

VI. RESULTS AND ANALYSIS

The whole building energy simulation is performed for a reference office building based on the data from the nearest available hourly weather station. Performance of the building for summer and winter is simulated to check whether the building is performing as expected. The simulation of the building helps to study the building operation strategies due to seasonal variation.

A. Base-case Results

The DB simulates extensive data on environmental conditions within the building and occupants’ comfort level. Through the simulation, the current indoor environmental control strategies were checked and thermal comfort ability of the building was determined. Fig 2 provides air temperature, humidity, discomfort hours and thermal comfort index for a typical week. The temperature and humidity level are consistent and maintained considerably within the comfort level as per standard value. The discomfort hours are almost negligible. Thermal comfort index (Fanger PMV, Pierce PMV and Kansas TSV) has also been simulated on seven point thermal sensational scale and results are found within acceptable range ±1 (where +1 stands for slightly warm and -1 stands for slightly cool) as per ASHRAE Standard 55 [27] during the occupied hours of the day.

Fig. 3 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 exceed 0.6 kWh/m^2/day in summer which has good agreement with previous published data [28].

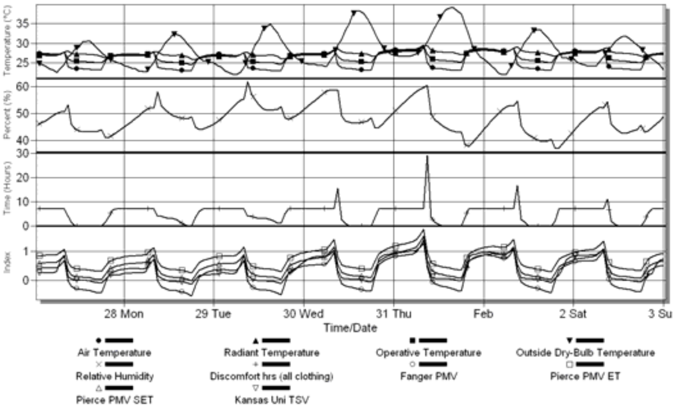

Fig. 2. Thermal comfort profile in a typical week

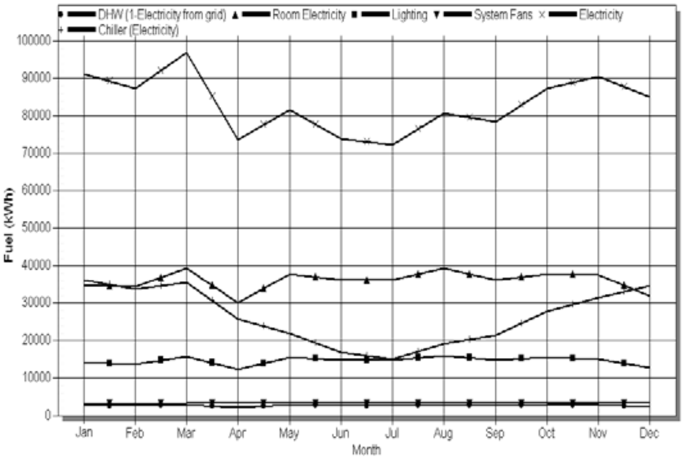

Fig. 3. Consumption breakdown of the base model

B. *Validation of the Base Model*

For validating 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. 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 [29]. Most recent studies showed that EnergyPlus results generally agrees within 1.1% of the analytical results except for the mean zone humidity ratio. These results agree within 2.7% for high sensible heat ratio cases and within 0.65% for low sensible heat ratio cases [30]. In the base-case simulation, 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. 4). 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. 5). 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. 6).

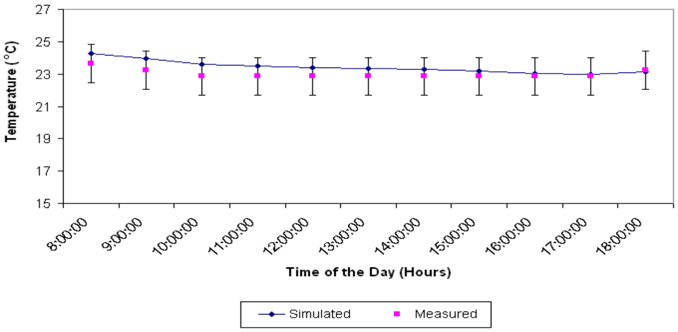

Fig. 4. Comparison of simulated and measured temperature profile in a typical day

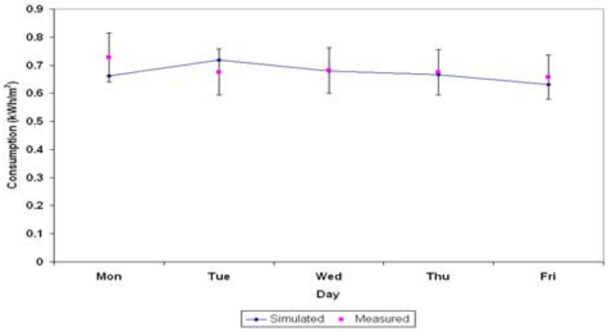

Fig.5. Comparison of simulated and measured air conditioning electricity consumption

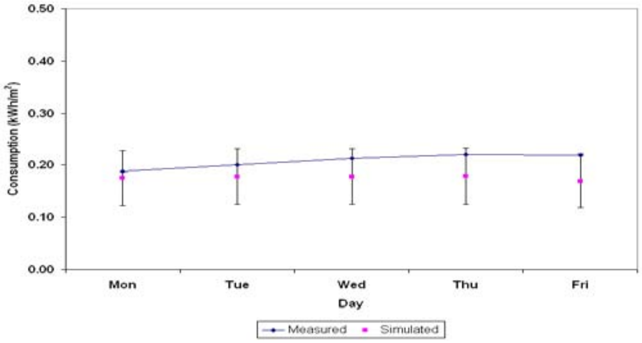

Fig. 6. Comparison of simulated and measured chiller electricity consumption

C. *Comparison of Low Energy Cooling Technologies*

To minimize the high cooling load and to reduce the use of air conditioning, the application of passive cooling retrofitting measures are considered. The current indoor environmental control strategies have been checked and thermal comfortability of the building has been determined using the above passive cooling technologies. The results of the Fanger Predicted Mean Vote (PMV) simulation are plotted in Fig. 7

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) during office hours in 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 [31].

Simulation results have shown that the cooling requirement throughout the day remains approximately the same. Using pre-cooling, the cooling energy demand is quite low during the start of the day. For other options, the requirement is similar to the base case demand. The peak energy demand is almost similar for all the cooling control options except pre-cooling of the building thermal mass, which reduces 28% peak energy demand of the base load at the start of the day (Fig. 8). Pre-cooling strategies resulted in a reduction in cooling requirement throughout the occupied period varying from 28% to 9%, being highest in the early morning. Although the on-peak total cooling demand is reduced significantly, the peak cooling requirement is marginally reduced because this strategy tends to discharge the mass relatively early during the peak period. The strategy does not utilise the entire comfort range during the occupied period, which can further reduce energy and demand costs. Fig. 8 shows that the cooling load under a constant temperature control decrease through the pre-cooling period to a low value just prior occupancy.

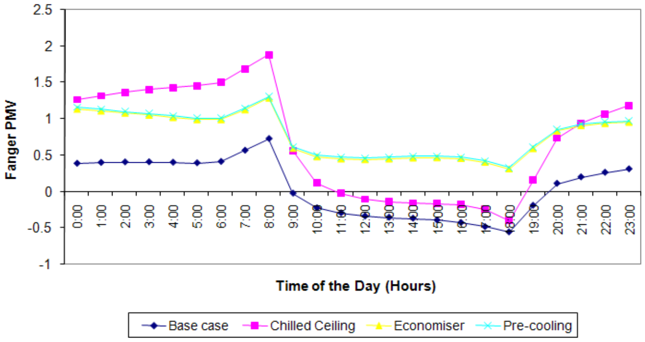

Fig. 7. Comparison of thermal performance index in a typical day

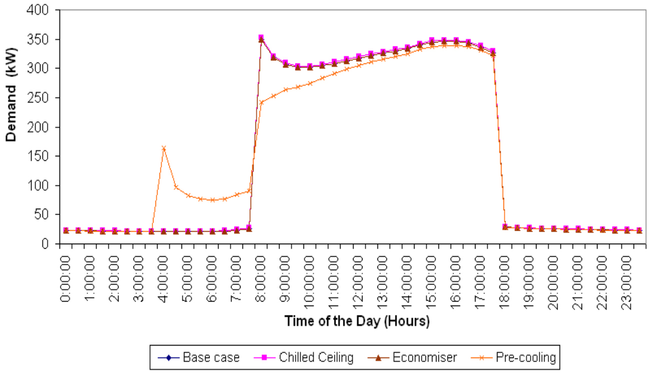

Fig. 8. Cooling energy demand under different control strategies

In the reference building, 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. Simulation results of base case chiller energy depict that total chiller energy demand varies from 10-11 kW/m^2/month during the high load period (December to February) and 4-5 kW/m^2/month during the low peak period (June to August). Under the low energy cooling, chiller peak energy varies from 7-8 kW/m^2/month during summer and 2-3 kW/m^2/month during winter through the application of chilled ceiling and pre-cooling. On the other hand, chiller energy varies from 5-6 kW/m^2/month in summer and 1-2 kW/m^2/month in winter through the application of an economiser system. As a result, simulated results indicate that up to 2 kW/m^2/month (using economiser usages), 4 kW/m^2/month (using pre-cooling), and 5 kW/m^2/month (using chilled ceiling) chiller energy can be saved (Fig. 9).

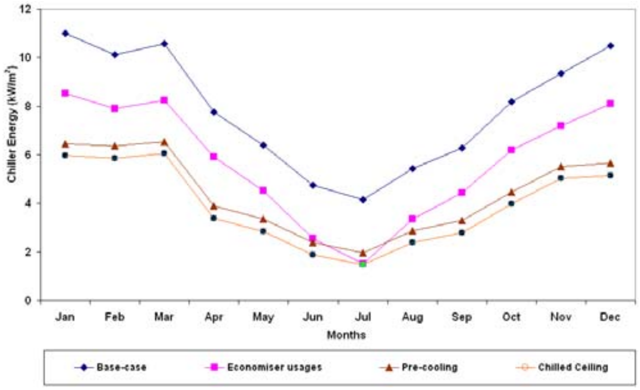

Fig. 9. Comparison of monthly chiller energy breakdown with different cooling technologies

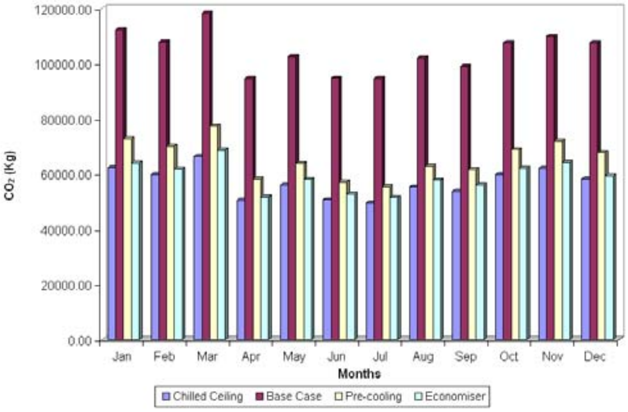

Fig. 10. Comparison of greenhouse gas emission

Based on emissions factor, CO_2 emissions (the major component of the greenhouse gas emissions) is accounted. The energy performance calculated by the simulation is converted into a mass or volume of pollutants emitted. From a baseline building performance simulation, alternative energy and pollution saving strategies can be explored, and the energy savings and pollution reduction can be calculated. To calculate the mass or volume of each pollutant, consumption is multiplied by an emissions factor for electricity. Fig. 10 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 low energy cooling technologies compared to current practice and it produces 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. By calculating environmental impact, alternative technologies are compared not only in terms of their energy performance but also in terms of their environmental performance for a more sustainable environment.

VII. CONCLUSION

Reduction of the energy consumption and maintaining a comfortable indoor thermal environment are the criteria used to identify the effect of low energy cooling technologies. As a passive cooling alternative, chilled ceiling has higher potential for energy savings of around 35% compared to the base case, and pre-cooling provides a peak energy demand reduction of 28% compared to the base case. The savings are accounted based on the current inefficient practice in a 15 years old reference building. Simulations depict that the applications of chilled ceiling and pre-cooling to subtropical regions are much more necessary. It is found that the use of low energy cooling techniques can have an important role to play in reducing dependency on mechanical cooling systems in an office building. Moreover, the study reveals that low energy cooling measures can be successfully applied to buildings located in warmer climates, which require high-energy use of an air conditioning system.

REFERENCES

[1] ASHRAE, *ASHRAE Handbook of HVAC Applications.* Atlanta, GA: American Society of Heating, Refrigeration and Air Conditioning Engineers Inc., 1999.

[2] M. Deru, and P. Torcellini, “Source Energy and Emissions Factors for Energy Use in Buildings,” Battelle: National Renewable Energy Laboratory, U.S. Department of Energy, 2007.

[3] C. Thormark, "A Low Energy Building in a Life Cycle - Its Embodied Energy, Energy Need for Operation and Recycling Potential," *Building and Environment,* vol. 37, pp. 429 – 435, 2002.

[4] I. Sartori, and A. G. Hestnes, "Energy Use in the Life Cycle of Conventional and Low-Energy Buildings:A Review Article," *Energy and Buildings,* vol. 39, pp. 249-257, 2007.

[5] J. N. Holst, "Using whole building simulation model and optimising procedures to optimise building envelop design with respect to energy consumption and indoor environment," In *Proc. Eighth International IBPSA Conference.* Eindhoven, Netherlands: International Building Performance Simulation Association (IBPSA), 2003, pp. 507-514.

[6] J. Haarhoff, and E. H. Mathews, "A Monte Carlo method for thermal building simulation," *Energy and Buildings,* vol. 38, pp. 1395-1399, 2003.

[7] P. Tavares, and A. Martins, "Energy efficient building design using sensitivity analysis - A case study," *Energy and Buildings,* vol. 39, pp. 23-31, 2006.

[8] A. Yezioro, B. Dong, and F. Leite, "An applied artificial intelligence approach towards assessing building performance simulation tools," *Energy and Buildings,* vol. 40, pp. 612-620, 2008:.

[9] R. J. Fuller, and M. B. Luther, "Thermal Simulation of an Australian University Building." *Building Research & Information,* vol 30, pp. 255-263, 2002.

[10] K. W. Mui, L. T. Wong, and L. Y. Law, "An energy benchmarking model for ventilation systems of air-conditioned offices in subtropical climates." *Applied Energy,* vol. 84, pp. 89-98, 2007.

[11] J. E. Braun, K. W. Montgomery, and N. Chaturvedi, "Evaluating the performance of building thermal mass control strategies." *HVAC&R,* vol. 7, pp. 403-427, 2007.

[12] E. Dascalaki, and M. Santamouris, "On the potential of retrofitting scenarios for offices." *Building and Environment,* vol. 34, pp. 557-567, 2002.

[13] A. Novoselac, and J. Srebric, "A critical review on the performance and design of combined cooled ceiling and displacement ventilation systems." *Energy and Buildings,* vol. 34, (2002): 497-509.

[14] F. Sodec, "Economic Viability of Cooling Ceiling System." *Energy and Buildings,* vol. 30, pp. 195-201, 1999.

[15] C. L. Conroy, and S. A. Mumma, "Ceiling Radiant Cooling Panels as a Viable Distributed Parallel Sensible Cooling technology Integrated with Didecated Outdoor Air Systems." *ASHRAE Transections,* vol. 107, pp. 177-193, 2005.

[16] M. Ayoub, N. Ghaddar, and K. Ghali, "Simplified thermla model of spaces cooled with combined chilled ceiling and displacement ventilation system." *ASHRAE International Journal of HVAC&R Reseach,* vol. 12, pp. 57-83, 2006.

[17] K. Ghali, N. Ghaddar, and M. Ayoub, "Chilled ceiling and displacement ventilation system for energy savings : A case study." *International Journal of Energy Research,* vol. 31, pp. 743-759, 2007.

[18] P. Xu, "Evaluation of Demand Shifting Strategies with Thermal Mass in Two Large Commercial Buildings." *SimBuild 2006,* in *Proc. Conference on Building Sustainability and Performance Through Simulation.* Cambridge, MA: International Building Performance Simulation Association (IBPSA) - USA, 2006.

[19] R. Becker, and M. Paciuk, "Inter-related Effects of Cooling Strategies and Building Features on Energy Performance of Office Buildings." *Energy and Buildings,* vol. 34, pp.25-31, 2002.

[20] P. Xu, H. Philip, P. Mary-Ann, J., “Braun Peak demand reduction from pre-cooling with zone temperature reset of MVAC in an office,” in *Proc. ACEEE summer study on energy efficiency in buildings*, Pacific Grove, 2006.

[21] S. Morgan, and M. Krarti, "Impact of electricity rate structures on energy cost savings of pre-cooling controls for office buildings." *Building and Environment,* vol. 42, pp. 2810–2818, 2007.

[22] E. H. Mathews, and E. V. Heerden, “A User-Friendly Tool For The Integrated Simulation of Building MVAC Control Performance,” Department of Mechanical Engineering, University of Pretoria, 2002.

[23] E. H. Mathews, D. Arndt, and M. F. Geyser, "Reducing the Energy Consumption of A Conference Centre – A Case Study Using Software." *Building and Environment,* vol. 37, pp.467-444, 2002.

[24] *DesignBuilder User Manual, Version 1.2.* UK: DesignBuilder Software Limited, 2006.

[25] *EnergyPlus Manual, Version 2.0.* U.S. Department of Energy, 2007.

[26] E. L. Olsen and Q. Y. Chen, "Energy consumption and comfort analysis for different low-energy cooling systems in a mild climate." *Energy and Buildings,* vol. 35,pp.560-571, 2003.

[27] *Thermal Environmental Conditions for Human Occupancy,* ANSI/ASHRAE Standard 55-2004, American Society of Heating, Ventilation and Airconditioning Engineers Inc., 2004.

[28] A. A. Chowdhury, M. G. Rasul, and M. M. K. Khan, "Modeling and Simulation of Building Energy Consumption: A Case Study on an Institutional Building in Central Queensland, Australia." *Building Simulation 2007,* in *Proc. 10th IBPSA Conference and Exhibition.* International Building Performance Simulation Association, 2007.

[29] R. H. Henninger and M. J. Witte, "EnergyPlus Testing with HVAC Equipment Performance Tests E100 to E200 from ANSI/ASHRAE Standard 140-2004, EnergyPlus Version 1.4.0.025." *Energy Efficiency and Renewable Energy,*U.S. Department of Energy, 2006.

[30] M. J.Witte, R. H. Henninger, J. Glazer, and D. B. Crawley, "Testing and validation of a new building energy simulation program," in *Proc. Seventh International IBPSA Conference,* International Building Performance Simulation Association, pp. 353-359, 2001.

[31] A. A. Chowdhury, M. G. Rasul, and M. M. K. Khan, "Simulation of Building Thermal Performance in an Institutional Building in Subtropical Climate," in *Proc. HEFAT 2007,* University of Pretoria, South Africa, 2007.

Ashfaque Ahmed Chowdhury obtained Bachelor of Science in Mechanical Engineering at Islamic University of Technology (IUT) in 2003 and Master of Engineering (Research) at Central Queensland University in 2008.

Since 2004, he worked as a lecturer at Islamic University of Technology, Bangladesh and at Central Queensland University, Australia. His research area includes building energy simulation, energy conservation and management, low energy cooling technologies, manufacturing technologies, and computer numeric control manufacturing etc.

He is an author of several papers in refereed journals and conferences. He is an active member of the International Building Performance Simulation Association (IBPSA) – Australasia, the Modeling and Simulation Society of Australia and New Zealand (MSSANZ), the International Association of Engineers (IAENG) - UK, and the Australasian Association for Engineering Education (AAEE).

Mohammad G. Rasul graduated in Mechanical Engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh in 1987. He completed his Master of Engineering in Energy Technology from Asian Institute of Technology (AIT), Bangkok, Thailand, in 1990. He obtained PhD on Energy and Thermodynamics from The University of Queensland, Australia, in 1996.

Currently, he is working as a Senior Lecturer in Mechanical Engineering at College of Engineering and the Built Environment, Faculty of Sciences, Engineering and Health, Central Queensland University, Rockhampton, Queensland 4702, Australia. He is specialised and experienced, and interested in research, teaching and consultancy in the area of thermodynamics and energy, fluid mechanics, process industry’s energy and environmental pollution analysis and building energy analysis.

Dr Rasul is an author of more than 80 refereed journal and conference papers including few chapters in books. He is an active member of the Engineers Australia and the Australasian Association for Engineering Education

M. Masud K. Khan is an Associate Professor and Head of Department of Infrastructures in the Faculty of Sciences, Engineering and Health, Central Queensland University, Rockhampton, Queensland 4702, Australia. He received his MS (Mech) with 1st class Honours from Moscow Institute of Petrochemical and Gas Industry in 1982. Subsequently he worked with the oil industry for 2 years. He obtained his PhD in engineering from the University of Sydney in 1990.

His teaching, research and consulting activities are in the area of non-Newtonian fluid mechanics, thermofluid engineering and rheology of industrial fluids and polymeric materials.

He has authored more than 95 refereed journal, conference and technical papers. He is a member of American Society of Rheology, Australian Society of Rheology, Engineers Australia and the Australasian Association for Engineering Education (AAEE).