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SIMULATION OF BUILDING THERMAL PERFORMANCE IN AN INSTITUTIONAL BUILDING IN SUBTROPICAL CLIMATE

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ABSTRACT

Simulation of building thermal performance is important in predicting comfort of the occupants in buildings. An analysis and prediction of thermal comfort using DesignBuilder based on EnergyPlus, state of the art building performance simulation software, is presented in this study for an air conditioned multi-storied building in Rockhampton city of Central Queensland, Australia. Rockhampton is located in a hot humid region; therefore, indoor thermal comfort is strongly affected by the outdoor climate. The actual thermal condition of the Information Technology Division (ITD) Building at Central Queensland University during winter and summer seasons is evaluated and the possibilities of energy conservation without compromising thermal comfort of the occupants are explored. The Fanger comfort model, Pierce two-node model and KSU two-node model were used to predict thermal performance of the building. A sophisticated building analysis tool was integrated with thermal comfort models which allow for the determination of appropriate cooling technologies for the occupants to be thermally comfortable with sufficient energy savings. This study will also compare predicted mean vote (PMV) and thermal sensation vote (TSV) on a seven point thermal sensation scale calculated using the effective temperature, relative humidity, discomfort hours for alternative cooling and ventilation techniques.

INTRODUCTION

Many comfort studies have been carried out in different countries with different climate zones and geographical locations. The impact of the thermal environment on occupants' comfort in hot-humid climates and in a cold climate has been studied by different research projects of ASHRAE [1,2]. These studies have shown that thermal dissatisfaction was associated for higher air movement with respect to ASHRAE standard 55 [1,2]. Dissatisfaction with the actual thermal environment is expected during building operation due to the personal behaviour of occupants and difficulty in maintaining comfort conditions at all times. In Australia, thermal comfort studies have been carried out by Auliciems [3], de Dear and Auliciems [4], Ballianger et al [5], Cena et al [6] and Rowe et al [7].

Low energy opportunities offer building occupants to remain comfortable in a period of changing environmental conditions. In general, radiant cooling systems can be combined with other low energy strategies and adaptive opportunities in order to save both energy and carbon emissions. The equivalent measurements and survey results in old traditional buildings indicated that although the PMV, based on measurements, ISO 7730 [8] and implied discomfort (hot), the occupants expressed their thermal satisfaction with the indoor comfort conditions. The literature results suggested that people have an overall impression of a higher standard of thermal comfort in old buildings than in new buildings [9]. A study on thermal comfort in order to understand the possibility of energy conservation suggested that the indoor thermal comfort is strongly affected by the outdoor climate in non-heating usages zone [10]. In another study, the impacts of climate change on heating and cooling energy demands were investigated by means of transient building energy simulation and showed that night ventilation strategies were capable of keeping indoor air temperatures within an acceptable comfort range. Thermal comfort and occupants' steps to achieve and maintain a comfortable status had been assessed through another simulation study which had introduced a methodology by which the effects of controls and human behaviour could be incorporated into an existing simulation program. A multiphase and solution oriented approach to assess thermal comfort problems in buildings had been treated by a systematic way without utilizing unnecessary resources in another study which suggested to address thermal comfort problems as soon as they arise because dissatisfaction with the thermal environment was likely to trigger an immediate impact on the comfort and productivity of the occupants [11]. Next, a quantitative analysis was carried out to provide an overview of thermal comfort in homes and offices and thermostat uses were examined [12]. Therefore literature suggested that through the combined approach it is possible to compute the range of environments in a building, to predict the comfort and discomfort of occupants, the effects of occupants' behaviour on the energy use of buildings, to model the internal environment in occupied buildings and the actions to restore their comfort [13].

Building simulation allows the concurrent solution of thermal and mass flow paths within buildings and quantifies the environment to which occupants are exposed during the design phase. Thermal comfort is determined through personal (activity level and thermal resistance of clothing) and environmental (air and mean radiant temperatures) factors. In this study the comfort level has been assessed through simulation and alternative cooling technologies have been investigated for the ITD Building of Central Queensland University, Australia. This building, among 82 buildings in the campus, has been selected for modelling and simulation of thermal performance because it is likely to have the highest cooling load and has drawn attention of the facilities manager. Design Builder [14], commercially available software, was used for the prediction of thermal comfort considering all possible sources and uses of internal gain in the modelling and simulation of the building. Rockhampton climate is classified as Subtropical. The city is situated on the Tropic of Capricorn and lies within the southeast trade wind belt, too far south to experience regular northwest monsoonal influence, and too far north to gain much benefit from higher latitude cold fronts. Generally, summer is from December to February and winter is from June to August. For the simulation, an extreme hot summer period was selected from January 27 to February 2 and the nearest maximum summer temperature was taken at 40°C. In a typical summer week, the nearest average temperature is 26.38°C. An extreme cold winter week was selected from June 8 to June 14 and the nearest minimum temperature for winter was 5.00°C. In a typical winter week the nearest average temperature was 16.99°C.

NOMENCLATURE

L	kWh	Heat load acting on the human body
M	kWh/m^2	Metabolism heat producing rate
PPD		Predicted percent dissatisfied
PMV		Predicted mean vote

THERMAL COMFORT INDECIES AND STANDARDS

Based on human thermal balance, the average temperature comfortable to human skin and optimal sweat exhausting rate, Professor Fanger developed a thermal comfort heat balance equation and an index called PMV which shows the thermal sensational index produced by a combination of environmental parameters [15]. Fanger's proposition was that except for the four physical variables (air temperature, radiant temperatures, relative humility and air velocity) and personal variables (activity and clothing), all factors such as geographical location, age, sex, body build, menstrual cycle, ethnic difference, food, circadiam rhythm, thermal transients, adaptation, colour, crowding, etc have no significant effects on the state of thermal comfort. For the comfort equation, PMV and percentage of people dissatisfied (PPD) are the only means of expressing the state of thermal comfort condition anywhere for anybody within a moderate thermal environment. Using Fanger's comfort equation, all possible combinations of the climatic parameters, personal parameters and comfort condition can be included in a prediction. Fanger's thermal comfort index based on static lumped parameters requires time averaged parameters (including speed, humidity, temperature and the standard deviation of speed etc).The formula of Fanger's PMV and PPD are:

$$PMV = 3.155[0.303 \cdot e^{-0.114M} + 0.028]L$$

$$PPD = 100 - 95e^{\left[-\left(0.03353PMV^4 + 0..2179PMV^2\right)\right]}$$

Thermal comfort predicted by ASHRAE's model and Fanger's model is based on steady state conditions. In many situations, transient conditions may prevail. To predict comfort under transient conditions the two node model has been developed for low and moderate activity levels in cool to very hot environments [16]. Comfort indices for design and evaluation of the indoor thermal environment have been developed over the years [17]. The main idea behind the indices is to predict thermal comfort. With given personal factors and environmental parameters, the indices may predict whether the indoor thermal environment is acceptable or not for the occupants. For normal daily conditions the indices most used are the PMV-PPD indices developed by Fanger [15], and the Standard Effective Temperature (SET) and Effective Temperature (ET) index developed by Gagge et al. [18]. The indices are based on results from experiments with large numbers of subjects and have been validated over the years. The PMV-PPD indices are included in the ISO standard 7730 [8], which has recently been approved as the European standard, EN ISO 27730 [19] and ET index used by ASHRAE [1,17,19]. The PMV index predicts the average thermal sensation of a large group of people. A PMV=0 is equivalent to thermal neutrality. The quality of the thermal environment may be expressed by the PPD index which is related to the PMV value. For PMV=0, PPD is equal to 5%, i.e. 5% of the occupants is dissatisfied with the thermal environment. A PMV=±0.5 will correspond to 10% dissatisfied.

ASHRAE Standard 55-1992 [1] defines thermal comfort as satisfaction with the thermal environment by which 90% of the occupants would be thermally comfortable. The ASHRAE Standard defines the comfort environment in terms of operative temperature. The International Standards Organisation (ISO 7730) defines thermal comfort as the state that people are satisfied with thermal environment where they live. ISO 7730-1994 recommended 10% dissatisfaction as the boundary of the comfort environment. To meet this requirement, PMV has been recommended within -0.5 to +0.5. This is more mathematically and physically oriented compared to ASHRAE [1]. ASHRAE Standard 55-2004 [2] classifies an environment as thermally acceptable when 80% of the occupants are satisfied. This means that an environment with -1 to +1 thermal sensation vote is thermally acceptable [2].

EXISTING SYSTEMS OF CASE STUDY BUILDING

The modelled 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 modelled building view is illustrated in Figure 1. The input data were building constructional records, local climate data, occupancy, internal load, HVAC and lighting component data, equipment data etc. Far too often inputs were assumed according to the Building Code of Australia for class 5 building. The modelled building operates from 8:00 to 18:00, 5 days a week. The 3 storied northeast oriented rectangular shaped building has an entrance on the ground floor. The occupancy and outside air rate are 1 person per 10m^2 and 10L/s/person respectively.

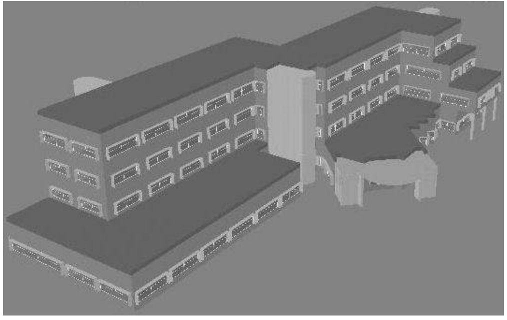

Figure 1 Model view of the ITD Building

The four levels of the building are air conditioned from a number of separate and independent air handling systems. The typical floor plan view is shown in Figure 2. Each air handling unit consists of a chilled water-cooling coil, disposable media air filter bank and centrifugal supply air fan. Conditioned supply air and return air is ducted to the respective areas in insulated sheet metal ducting. Ceiling diffusers are provided with sidewall registers. Fresh air is ducted to each air-handling unit from a wall louvre. Dampers are provided to each unit and these have been set at the time of commissioning to the required air quality. Cooling is provided by a central chilled water system through two equally sized, reciprocating, air-cooled chiller sets.

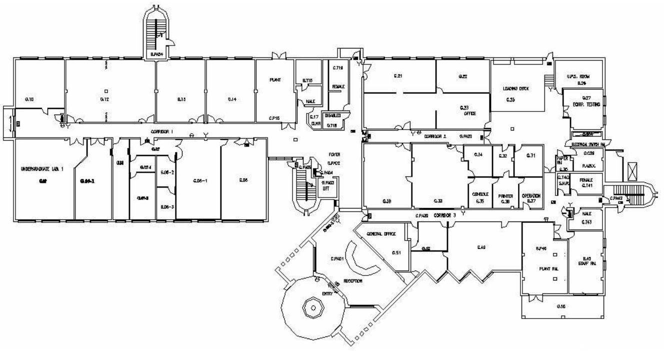

Figure 2 Typical Floor Plan Layout of the ITD Building

SIMULATED RESULTS AND DISCUSSION

A detailed investigation of space thermal parameters and HVAC system parameters are required in the simulation. Due to non-uniformity of space condition thermal comfort status is measured at different thermal zones of the building. Measurement was carried out for different time intervals to account for variation with time. Current space physical layout and separation of the building thermal zones are obtained from as-built drawings and building management systems. Although the process is time-consuming and resource demanding yet planned action helped to determine space thermal zoning, calculation of cooling load and air conditioning parameters for different redefined control strategies. Finally a thermal comfort profile was established for better investigation of the indoor environment. The key parameters and assumption are determined to represent a thermally worst case in terms of cooling and heating.

Indoor Temperature and Humidity

The relation between the indoor and outdoor temperatures in summer and winter days are shown in the Figure 3. The difference between indoor and outdoor temperatures is relatively small in winter. It is not necessary to use heating in Rockhampton due to the geographic situations. The average indoor temperatures are stable at about 23^{o}C. The outdoor and indoor air temperatures for the base case and other passive cooling strategies are shown in Figures 4 and 5.

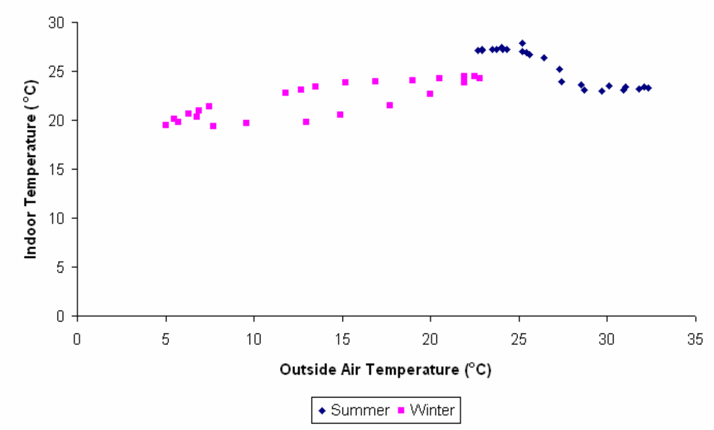

Figure 3 Indoor and outdoor temperature profile

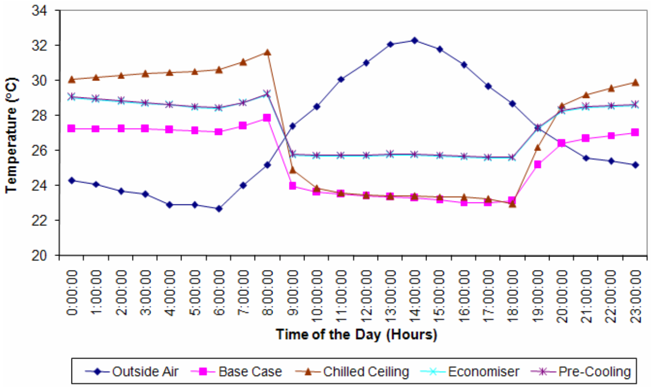

Figure 4 Simulated temperature profile in a typical summer

It can be seen from Figures 4 and 5 that the majority of values fall during office hours within the acceptable temperature range of 20-27^{o}C as stated in the ASHRAE Standard 55-1992 [1] in summer and winter. Singapore Standard Code of Practice 13 requires the comfort temperature to be within 23-25 °C while ENV Guidelines recommend the temperature range between 22.5 and 25.5 °C for acceptable indoor air quality [20]. According to the Australian Building Code Board (ABCB), the average room temperatures for all control strategies are satisfactory (within 20-24°C) except temperature readings for economisers on summer days [21]. Those readings are a little bit higher than the rest of the simulated values and similar outcomes are observed during working hours because simulated values are based on the conventional complete mixing system. It is seen from the values of the base case and using a chilled ceiling at the levels set out by the respective standards mentioned above that temperatures satisfy the requirements of thermal comfort.

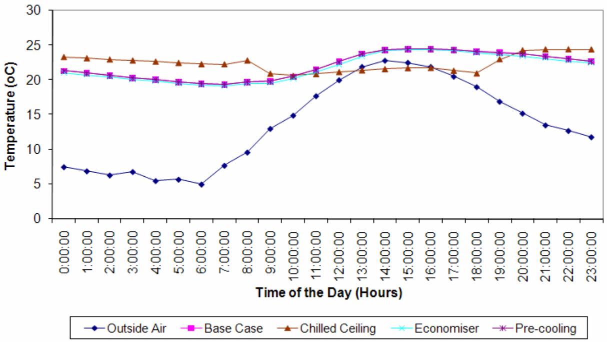

Figure 5 Simulated temperature profile in a typical winter

Relative humidity levels in the base case and using other control strategies are shown in the Figures 6 and 7 for summer and winter respectively. In all cases the humidity level is within the acceptable range of 30-45% in winter and 45-55% in summer except for the chilled ceiling during summer.

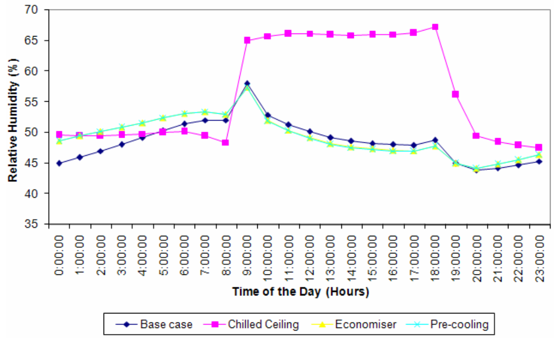

Figure 6 Simulated humidity level in a typical summer

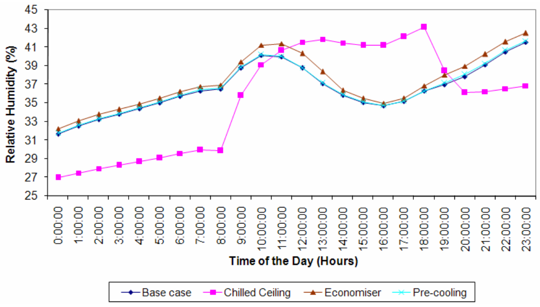

Figure 7 Simulated humidity level in a typical winter

Fanger PMV

The level of thermal comfort was determined through the Fanger PMV method for different cooling strategies and compared with the base case in summer and winter seasons. As the operation of HVAC system is based on the occupancy and there is not that much after hours activities except in a few zones, the thermal comfort prediction was based on weekday working hours. The results of the Fanger PMV simulation are plotted in Figures 8 and 9 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 [8] during office hours in summer and winter days. In all instances, simulated PMV with chilled ceiling was much closer to neutral/comfortable (0.0) in both summer and winter seasons than other two cooling options; i.e. economizer and pre-cooling control strategies.

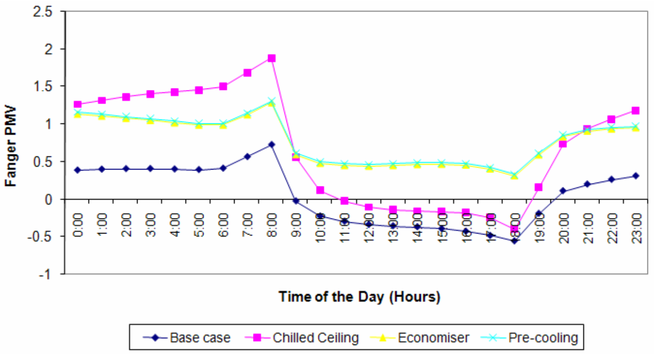

Figure 8 Simulated Fanger PMV index in a typical summer

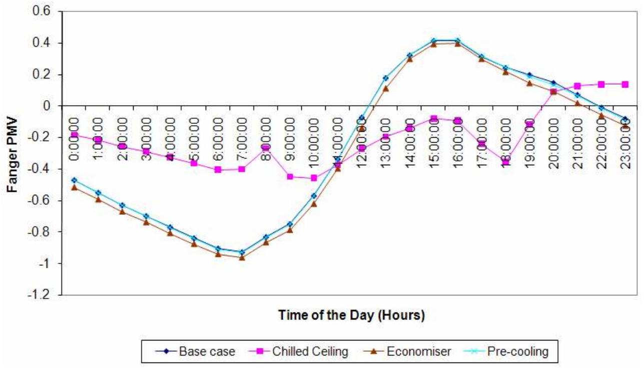

Figure 9 Simulated Fanger PMV index in a typical winter

Pierce PMV

The Pierce model converts the actual environment into a standard environment at a Standard Effective Temperature, SET. SET is the dry-bulb temperature of a hypothetical environment at 50% relative humidity for subjects wearing clothing that would be standard for the given activity in the real environment. The Pierce model also converts the actual environment into an environment at an Effective Temperature, ET, that is the dry-bulb temperature of a hypothetical environment at 50% relative humidity and uniform temperature (Ta = MRT) where the subjects would experience the same physiological strain as in the real environment. The simulated results of the Pierce PMV based on Effective temperature are presented in Figures 10 and 11 for base case and different control strategies. The simulated PMV for all other control strategies are not so close to the Neutral (0.0) point like Fanger PMV on summer days. Pierce PMV based on Effective Temperature predicted slightly warm environments during working hours on summer days; yet chilled ceiling offers the best PMV and much closer to base case and the neutral (0.0) point. In winter, the Pierce PMV for all control strategies are much better than summer days and the consistency in thermal condition is maintained by the control strategies. Here, PMV is computed using effective temperature as well since relative humidity of the environment changes in a wide range during day time in summer and winter. Both summer and winter day thermal comfort indices are within the acceptable range from -1 to +1 as per ASHRAE Standard 55-2004 [2] during office hours.

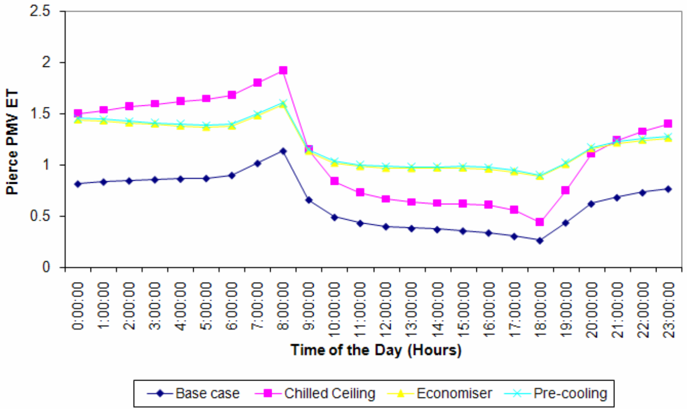

Figure 10 Simulated Pierce PMV base on effective temperature in a typical summer

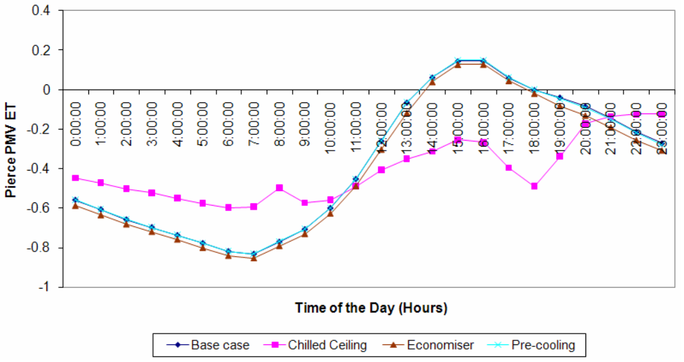

Figure 11 Simulated Pierce PMV base on effective temperature in a typical winter

The simulated results of the Pierce PMV based on standard environment are compared in Figures 12 and 13. The simulated PMV for all other control strategies are not so close to the Neutral (0.0) point like Fanger's PMV on summer and winter days. The Pierce PMV based on Standard Effective Temperature predicted a slightly warm environment during working hours in summer and winter; yet chilled ceiling offers the best PMV and much closer to the neutral/comfortable (0.0) point. In winter, the Pierce PMV using chilled ceiling offers the best comfort option as the mean votes are uniformly distributed around the comfort region. Both summer and winter day thermal comfort indices are within reasonable agreement from -1 to +1 as per ASHRAE Standard 55-2004 [2] during office hours.

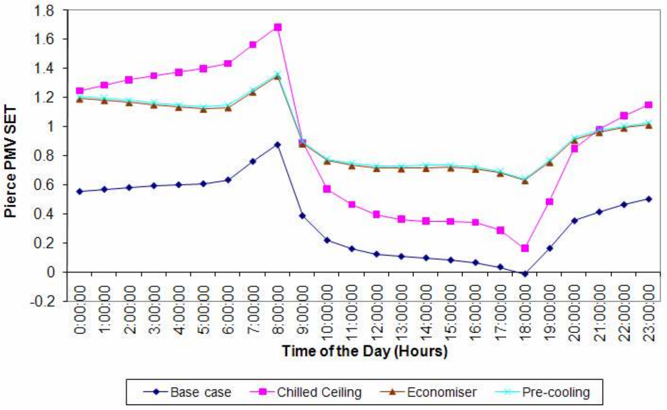

Figure 12 Simulated Pierce PMV based on standard temperature in a typical summer

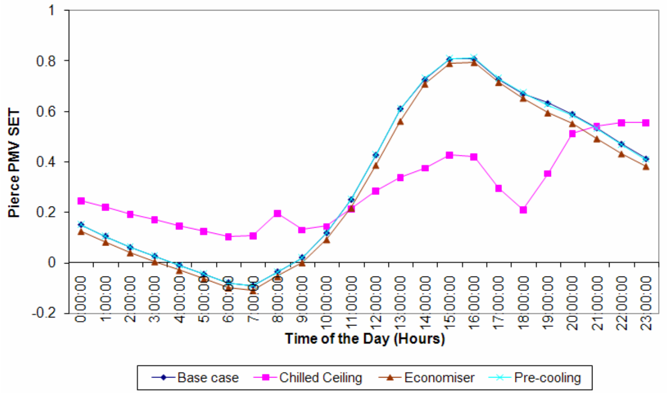

Figure 13 Simulated Pierce PMV based on standard temperature in a typical winter

Kansas PMV

The main difference between the Pierce model and Kansas model is that the KSU model predicts thermal sensation (TSV) differently for warm and cold environments. The KSU two-node model is based on the changes that occur in the thermal conductance between the core and the skin temperature in cold environments, and in warm environments it is based on changes in the skin wettedness. The results of the Kansas TSV simulation are plotted in Figures 14 and 15 for each of the control strategies and they are within the -1<TSV<+1 limits which are deemed thermally acceptable as per ASHRAE Standard 55-2004 [2] during office hours in summer and winter days. In all instances, simulated TSV with chilled ceiling was much closer to neutral/comfortable (0.0) both summer and winter seasons than the other two cooling options, economizer and pre-cooling control strategies.

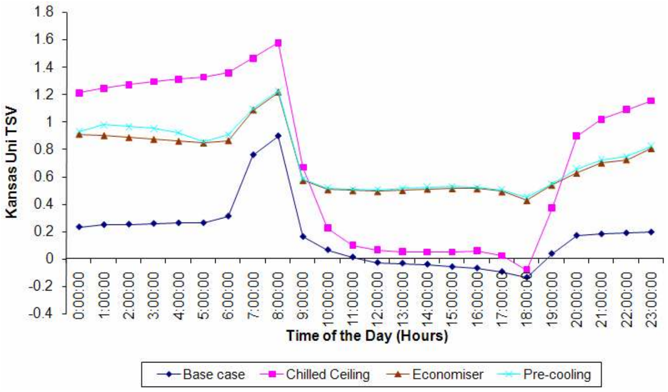

Figure 14 Simulated Kansas TSV in a typical summer

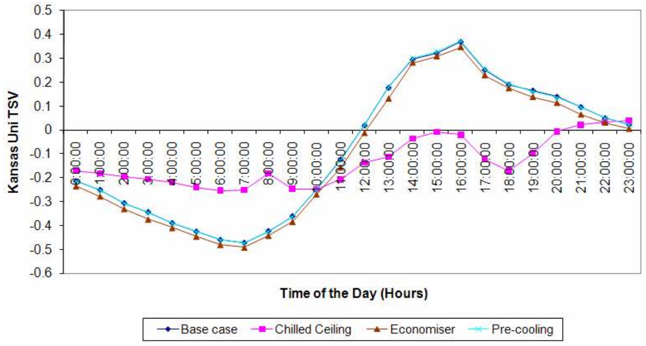

Figure 15 Simulated Kansas TSV in a typical winter

Discomfort Hours

The analysis of the thermal comfort of the ITD building indicates that the thermal discomfort hours are nearly zero for base case and chilled ceiling option during day time in summer and winter as illustrated in figures 16 and 17.

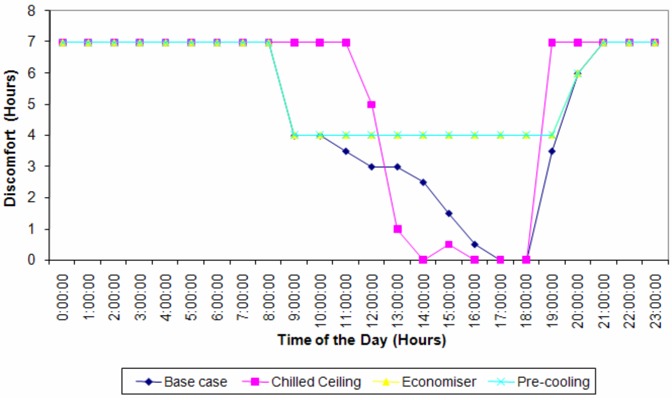

Figure 16 Simulated discomfort hours (for all clothing) in a typical summer

Economiser and pre-cooling options also provide relatively less discomfort hours during office hours in summer and winter and these discomfort hours are not more than current practice. Thermal discomfort due to excessive indoor temperature is not significant in all cases. The percentage of hours in the thermal comfort is high. Considering that warmer temperatures usually require the use of ventilation, the approximation of temperature and moisture patterns in and outside favour the estimation of discomfort hours for chilled ceiling.

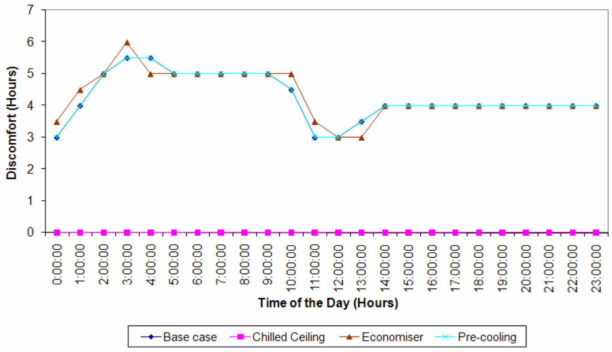

Figure 17 Simulated discomfort hours (for all clothing) in a typical winter day

VERIFICATION OF SIMULATED RESULTS

The output of the thermal comfort simulation consists of hourly values of the indoor temperature in the room being simulated. Two HOBO H8 family data loggers were used for the measurement of indoor temperatures in different zones of the building. The temperature and humidity were also calibrated through the Johnson control building management system (BMS). Measurement of temperature through BMS and HOBO loggers, found that on an average 23^{o}C temperature is maintained during the summer time in the ITD building. In the simulation using the existing system (base case) the 23^{o}C temperature is also maintained during the occupied period of the day as shown in Figure 18.

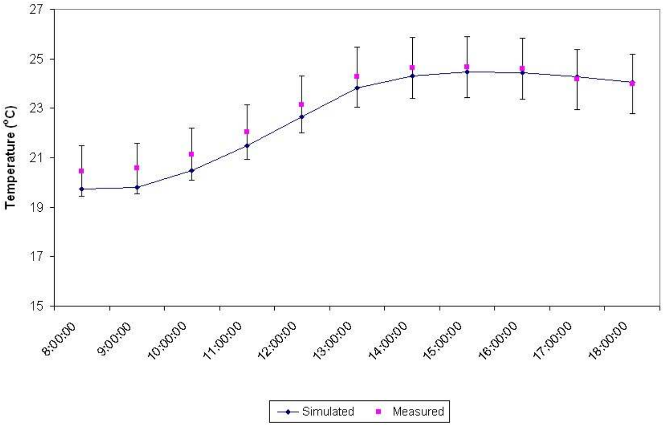

Figure 18 Comparison of simulated and measured temperature profile in a typical day

CONCLUSIONS

The thermal comfort simulated in this study considers the steady state condition and does not consider the thermal comfort environment when the parameters change dynamically. Cooling system comparison shows that systems using chilled ceiling offer the best thermal comfort for the occupants during summer and winter in a subtropical climate. Although economiser usages and pre-cooling offer less thermal comfort in summer using Pierce PMV, another comfort index predicts a better performance and satisfies the existing thermal comfort standard. The study exemplifies that by using the thermal comfort theory it is possible to identify low energy cooling technologies with acceptable temperature formulation in summer and winter months. The predicted overall comfort votes correlated best with mean internal and external temperatures respectively. The simulations strongly indicate that office building systems in a subtropical climate can be retrofitted with low energy cooling technologies for better thermal comfort. The simulation interface DesignBuilder is able to assess the influence of fabric, ventilation, solar gains etc on the internal thermal environment. The thermal performance of the existing building can be improved by introducing alternative low energy cooling systems.

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