HVAC INTEGRATED CONTROL FOR ENERGY SAVING AND COMFORT ENHANCEMENT

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ABSTRACT: The overall attainable reduction in energy consumption and enhancement of human comfort of Heating, Ventilating, and Air Conditioning (HVAC) systems are dependant on thermodynamic behavior of buildings as well as performance of HVAC components and device control strategies. In this paper by refining the models of HVAC components, the influence of integrated control of shading blinds and natural ventilation on HVAC system performance is discussed in terms of energy savings and human comfort. An actual central cooling plant of a commercial building in the hot and dry climate condition is used for experimental data collection, modeling and strategy testing. Subject to comfort constraints, interactions between the building's transient hourly load and system performance are considered to show how the system energy consumption varies at different control strategies. For validation, a holistic approach is proposed to integrate dynamic operations of shading devices with direct and indirect ventilation of a commercial building equipped with a central cooling plant. Simulation results are provided to show possibility of significant energy saving and comfort enhancement by implementing proper control strategies.

Keywords: *Comfort Enhancement, Energy Saving, HVAC System, Integrated Control*

1. INTRODUCTION

The continuous increase in the global electricity consumption is constantly demanding energy saving strategies. The energy consumption of the Heating, Ventilating, and Air-Conditioning (HVAC) systems is about 50-70% of the building energy usage for maintenance of thermal comfort in buildings [1]. The operation of chillers and cooling towers leads to the peak electricity demand and accounts for about half of electricity consumption for air conditioning [2]. The energy consumption of an HVAC system depends not only on its performance and operational parameters, but also on the characteristics of the heating and cooling demand and thermodynamic behavior of the building. The most important factors that contribute to HVAC energy usage reduction is via proper control of the building heating and cooling demand. Integrated control of the building cooling load components such as solar radiation, lighting and required fresh air can result in significant energy savings of a cooling plant.

There are many studies on how the different control strategies can reduce the HVAC energy consumption but most of them focus either on HVAC control or on building control approaches segregately but less effort has been paid to the integrated control of both of them. Mathews and Botha [3] investigated into the use of integrated simulations as a viable option to help improve thermal building management. They showed that by accurately simulating the thermal response and indoor air conditions in the building due to changes in the HVAC system, it is possible for a building manager to enhance the operation and maintenance of the building. Sun et al. [4] proposed a methodology to get a near-optimal strategy for controlling the shading blinds, natural ventilation, lights and HVAC system jointly but they did not consider the real monitored data for HVAC system to survey the influence of their proposed integrated control on the HVAC energy saving potential. Guillemin and Morel [5] presented an innovative and self-adaptive integrated control system for building energy and comfort management. The result showed a saving of 19 percent of the total energy consumption, while maintaining visual comfort in the space. This control rule is effective in energy saving but excluding the HVAC consumption. Kim et al. [7] investigated the influence of manual and automated blinds on the both cooling energy consumption and thermal comfort. Their study showed that in terms of cooling energy usage, automated blinds reduce the required cooling demand compared to manual blinds which are fully opened while the automated blinds can block the solar radiation according to the ambient conditions. However, no work has been mentioned on the combined simulation of building dynamic behavior with a detailed operational data of a real tested central HVAC system.

The objective of this paper is to address the reduction of the energy consumption of a central cooling plant (CCP) by using integrated control strategies of shading devices, direct and indirect natural ventilation and cooling system components while satisfying human comfort and system dynamics. For this purpose, a real-world commercial building, located in a hot and dry climate region, together with its central cooling plant is used for experimentation and data collection. In order to take into account the nonlinear, time varying and building-dependent dynamics of the HVAC system, a transient simulation software package, TRNSYS 16 [14], is used to predict the HVAC energy usage. The existing central cooling plant was tested continuously to obtain the operation parameters of system components under different conditions. On the basis of the TRNSYS codes and using the real test data, a simulation module for the central cooling plant is developed and embedded in the software. In this model, a commercial building is equipped with the water-cooled chiller, the open circuit cooling tower, the air handling unit, the chilled water pump and the condenser's cooling water pump and thus dynamic simulation of all main equipment in the whole system can be performed simultaneously.

As presented in this paper, detailed transient simulation results of the building, HVAC equipment and their control system indicate a promising potential of reduction in cooling energy usage for a typical commercial building via the integrated building and HVAC control system implementation. To show the effect of each proposed control strategy, the comfort condition index, predicted mean vote (PMV), is studied. Results show that between 3% to 12.8% power saving can be obtained by this approach while maintaining PMV between -0.5 to +1 for most of the summer time.

2. MATHEMATICAL DESCRIPTION

The schematic of the central cooling system is shown in Fig. 1. Among a variety of simulation components for central cooling plant, those of the chiller and cooling coil are most important. Therefore, in this section the details of these components are presented in order to truly simulate the effects of these operating variables and parameters.

2.1 Water-Cooled Chiller

A model derived from real-world test data is employed for water-cooled chiller to describe how the capacity ratio of the chiller and its COP ratio vary with operation conditions as well as the chiller's fraction of full load power varies with part load ratio. Therefore, two external data files are required to determine the chiller performance: (1) the normalized of coefficient of performance (COP) and capacity (CAP) values with respect to their rated values (2) the electric input part-load ratio in terms of cooling part load ratio. These data were obtained using field tests and implemented in TRNSYS. The mathematical expressions to determine these variables are summarized in equations (1)-(5) below:

$$CAP = CAP_{rated} \times CAP_{norm}, \tag{1}$$

$$COP = COP_{rated} \times COP_{norm}, \tag{2}$$

where CAP , CAP_{norm} and CAP_{rated} are current, normalized and rated chiller capacity respectively, and COP , COP_{norm} and COP_{rated} are respectively the coefficient of performance at current, normalized and rated chiller capacity. The chiller load is calculated by

$$Q_{load} = m_w C_{pw} \left(T_{chw,out} - T_{chw,in}\right) , \tag{3}$$

where m_w is the entering water flow rate, C_{pw} is the specific heat of the water entering the chiller and $T_{chw,in}$ and $T_{chw,out}$ are the temperatures of water entering and leaving the chiller respectively. The part load ratio(PLR) of the chiller is therefore:

$$PLR = \frac{Q_{load}}{CAP} . \tag{4}$$

Finally, the power consumption of the chiller can be determined as:

$$P_{chiller} = \frac{CAP}{COP} \times F_{flp}, \tag{5}$$

where F_{flp} is fraction of full load power.

2. 2Air-Handling Unit

The main part of an air-handling unit (AHU) is cooling coil. The performance of coils, which is embedded through their heat transfer properties, directly influences the performance of HVAC systems [6]. The cooling coil and supply fan used in this work are modeled from dynamic operation data and also included in TRNSYS. Three external data files are required to determine the total and sensible cooling energy transferred from the air stream. The first data file describes how the total and sensible cooling ratio of the cooling coil varies with the entering water temperature of the coil. The second data file contains correction factors to the performance due to variations of the wet-bulb and dry-bulb temperatures of the air entering the cooling coil. The third data file provides, correction factors to the performance due to changing the normalized air flow rate. Upon reading these data files, the TRNSYS is able to interpolate the dependent variable values in multiple dimensions. Consequently, TRNSYS calculates the cooling coil performance according to the following equations:

$$Q_{total} = Q_{total,rated} F_{tcr,1} F_{tcr,2} F_{tcr,3}, \tag{6}$$

$$Q_{sen} = Q_{sen,rated} F_{scr,1} F_{scr,2} F_{scr,3}, \tag{7}$$

where $F_{tcr,n}$ denotes the total cooling ratio returned by one of the three data files and $F_{scr,n}$ denotes the sensible cooling ratio returned by one of the three data files. In order to estimate these values, a large number of data points are required, often more than those given in typical product catalogs [8] and should be determined by real-world tests, which are performed in this study.

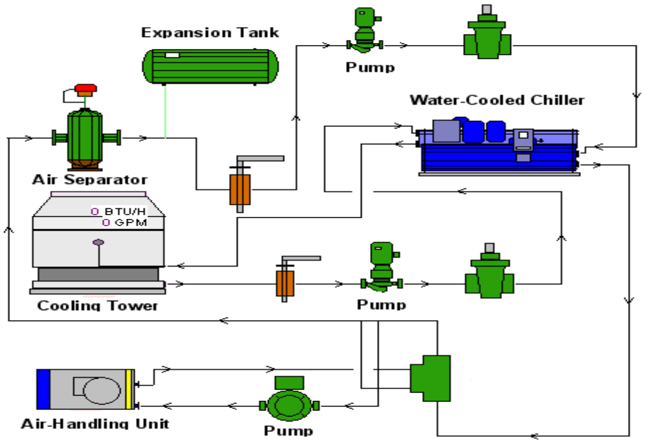

Fig. 1 Schematic diagram of the central cooling plant

3. CONTROL STRATEGIES

A real-world commercial building equipped with its existing central cooling plant is modeled to predict the performance of integrated control of shading blinds and direct and indirect natural ventilation by using the transient simulation tool. Each system component has a mathematical model, usually programmed in FORTRAN. Different control strategies designed and implemented on TRNSYS are used to determine the CCP power consumption and predict the building thermal comfort conditions. An hourly energy consumption formulation for CCP equipment is used for this study as follows:

$$E_{total} = \sum_{i=1}^{N} E_{total,i} , \tag{8}$$

where $N = 2170\,H\,(5 \times 31 \times 14)$ for May, June, July, August and September (based on 14-h daily operation) and E_{total} is the summer energy consumption of the CCP including energy usage of the chiller $E_{ch,i}$, the AHU variable air volume (VAV) fan $E_{ahu,i}$, the cooling tower fan $E_{ctf,i}$, the chilled water pump $E_{chp,i}$, the cooling tower pump $E_{cwp,i}$, the heat exchanger fan (for indirect ventilation) $E_{hx,i}$ and the economizer fan (for direct ventilation) $E_{econ,i}$, and is written as:

$$\begin{aligned} E_{total,i} = {} & E_{ch,i} + E_{ahu,i} + E_{ctf,i} + E_{chp,i} + \\ & E_{cwp,i} + E_{econ,i} + E_{hx,i} . \end{aligned} \tag{9}$$

3.1 Shading Control Strategy

In this paper three control strategies are analyzed by using the developed TRNSYS model. This operational hysteresis can be used to promote stability. It avoids shading devices to keep going up and down all the time as soon as the control value varies a little bit.

The first control strategy is based on the solar radiation level only. In this case, the internal shading devices are pulled down as soon as the solar radiation exceeds a chosen set point. Shading devices are opened back when the radiation lowers under the set point. The second strategy is based on inside temperature level only. In this case, shading devices are pulled down as soon as the inside temperature reaches a determined temperature but not rolled up until the temperature comes down above set point. The third strategy is a combination of both strategies. Shading blinds will be pulled down when both conditions are filled, otherwise they will be opened. The choice of the set point value will mostly affect the comfort and energy demand. However, the set point combination of 23°C for the inside temperature and $250\frac{\mathrm{W}}{\mathrm{m}^2}$ for the solar radiation is quite efficient [9] especially in hot and dry climate.

3.2 Ventilation Control Strategy

This section presents a holistic approach of integration direct and indirect ventilation to reduce building cooling load and thus HVAC energy consumption. Thermal comfort in a building cooled with natural ventilation, depends on the external weather conditions. For natural ventilation control, most important variables are the ambient dry-bulb temperature and enthalpy of outside air [15]. The outside air enthalpy can be lower than the indoor air enthalpy when the ambient humidity is higher than the indoor air humidity also, ambient dry-bulb temperature is much lower than the indoor dry-bulb temperature. Therefore, the control strategy based on the difference between indoor and outdoor enthalpy can lead to a reduction of the total cooling and dehumidifying load. In this paper Direct ventilation is used when the outside air temperature is lower than the inside air temperature and outside enthalpy is lower than inside enthalpy. In this case, the outside air comes inside the building through an economizer without any heat exchange. Moreover indirect ventilation is used when the outside air temperature is lower than the inside air temperature and outside enthalpy is higher or equal to inside enthalpy. In this case, outside and inside air will pass through exterior and interior chamber of the air-to-air heat exchanger respectively. By that way, the proposed ventilation control strategy is an integration of direct and indirect ventilation, triggered of logic functions.

4. MODEL VERIFICATION AND RESULTS

The simulation object is a real-world commercial building. The walls, windows, floor and roof are modeled according to the ASHRAE transfer function approach [10] for calculating cooling loads. Building information is compliant with the requirements of the ANSI/ASHRAE Standard 140-2001[11]. The CCP models are developed in TRNSYS. Then real test measured data were input to the HVAC models. The integrated simulation tool was validated by comparing predicted and measured power consumption of the chiller for the first day of July during which the chiller operated continuously from 8 a.m. to 10 p.m. As shown in Fig. 2 the model predicts quite well the variation in the chiller electric demand over the operating periods.

The TRNSYS model is run to obtain component-wise energy analysis and the indoor comfort conditions throughout the summer.

4.1 Energy Analysis

Eight control scenarios are designed for the afore-mentioned building:

Scenario 1. Estimation of the CCP energy consumption without any control strategy.

Scenario 2. Determination of the CCP energy consumption with internal shading blinds control based on the solar radiation level.

Scenario 3. Determination of the CCP energy consumption with internal shading blinds control based on the inside temperature level.

Scenario 4. Determination of the CCP energy consumption with internal shading blinds control based on a combination of both the solar radiation and inside temperature level.

Scenario 5. Determination of the CCP energy consumption with natural ventilation control.

Scenario 6. Determination of the CCP energy consumption based on a combination of both scenarios 2 and 5.

Scenario 7. Determination of the CCP energy consumption based on a combination of both scenarios 3 and 5.

Scenario 8. Determination of the CCP energy consumption based on a combination of both scenarios 4 and 5.

Results demonstrate that the profiles of energy consumption in May, June, July and August are similar for each control scenario but different in September. As shown in Fig. 3 in July a control mode based on solar radiation level causes an important decrease in energy usage for CCP while in September the control scenario based on a combination of natural ventilation and solar radiation control is most significant. This is due to the solar radiation has most influence on building cooling load during the hottest summer months while in September ambient temperature is quite low and not often higher than indoor temperature between 8 a.m to 9 a.m and 8 p.m to 10 p.m. Also the effect of building control via the solar radiation level on CCP energy reduction is more than blinds control using the inside temperature level approach. The natural ventilation control does not seem to have much influence during the July. As a result, it may then be said that the most important approach to reduce energy in a hot and dry climate for the building with large external windows is the solar radiation control compared with the control of other cooling load components. Natural ventilation appears as a secondary parameter and coupled natural ventilation and solar radiation control is not efficient in hot and dry conditions. However, the potential of energy saving for scenarios 2, 3, 4 and 5 in July are respectively 12.8%, 8.2%, 6.8% and 3% which are significant enough to consider.

4.2 Thermal Comfort

Thermal comfort is all about human satisfaction with a thermal environment. The design and calculation of air conditioning systems to control the thermal environment to achieve standard air quality and health inside a building should comply with the ASHRAE standard 55-2004 [12]. To predict the thermal comfort condition, an index called predicted mean vote (PMV) which indicates mean thermal sensation vote on a standard scale for a large group of people is used in this paper. PMV is defined by six thermal variables from human condition and indoor air, namely air temperature, air humidity, air velocity, mean radiant temperature, clothing insulation and human activity. The PMV index predicts the mean value of the votes on the seven point thermal sensation scale +3: hot, +2: warm, +1: slightly warm, 0: neutral, -1: slightly cool, -2: cool, -3: cold. According to ISO 7730 standard [13] the values of PMV between -1 and 1 are in the range that 75% people are satisfied while between -0.5 and 0.5 is the range that 90% people will be satisfied. It is of interest to see how the resulting PMV appears with each control scenarios. The resulting PMV fluctuates between -0.6 to 0.8 for hottest day in July for scenario 2 and 6 as most effective scenarios discussed in the last section. It is changed between 0.9 and 0.67 for those scenarios for hottest day in September as shown in Fig. 4. Therefore, all PMV responses lie in the acceptable range, i.e. -1< PMV <+1. Also according to the results, 78% of the votes are for PMV < 0.5 and 100% of the votes for PMV < 0.8 which means both control strategies 2 and 6 are able to save energy significantly while can maintain PMV values in a standard range.

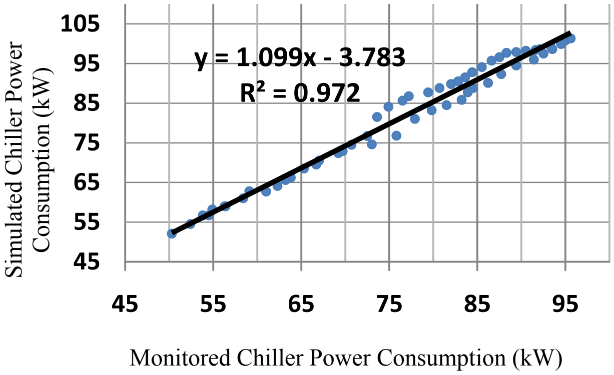

Fig. 2 Comparison of measured and simulated chiller power

5. CONCLUSION

This paper has presented integrated strategies encompassing CCP thermodynamics, natural ventilation and shading control for a commercial building in hot and dry climate to address issues of energy savings and human comfort. Simulation has been carried out to investigate the impact of internal shading control and natural ventilation on energy demand and comfort conditions. The simulation modules were developed by using monitored data which were collected experimentally from the existing central cooling plant of the building. Results show that up to 12.8% energy saving is possible via the integrated control of building cooling load components owing to coupling the effects of different parameters on energy usage and comfort conditions.

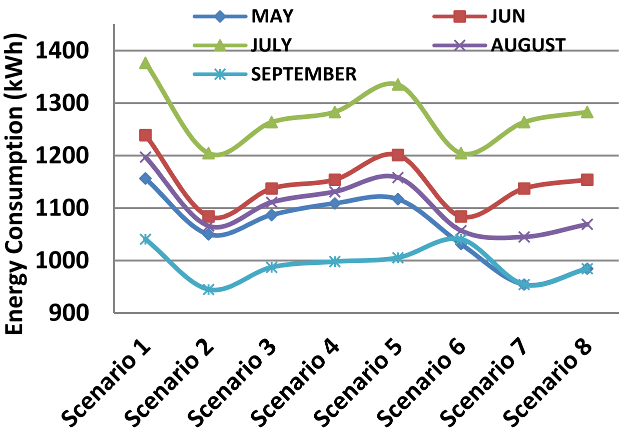

Fig. 3 CCP energy consumption via different scenarios

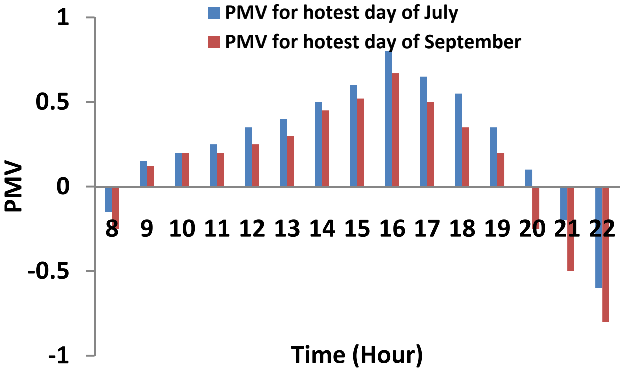

Fig. 4 PMV comparison for July and September

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