COMPUTER SIMULATION AND EXPERIMENTAL VALIDATION OF A MODERN HOTEL ON BUILDING ENERGY CONSERVATION

K.H. Yang and S.C. Wu
Mechanical Engineering Department, National Sun Yat-Sen University, Kaohsiung, Taiwan 80424

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ABSTRACT

The annual power consumption of a five-star hotel was analyzed with computer simulation, followed by full-scale experiment for validation. Comparative result of the two indicates that significant energy savings, up to 15.4% annually, can be expected in this high-rise building if the chiller plant, especially the chilled water distribution system can be renovated with variable speed driven pumps. The validation process provides an useful method in achieving a more energy-efficient building and is discussed in detail in this paper.

1. INTRODUCTION

The LD hotel is a high-rise building with forty-one floors above ground and is one of the landmarks in Kaohsiung city of southern Taiwan. Fig. 1 gives a view of the hotel. It consists of 373 guest rooms, and with 5 restaurants and a 500-people conference ballroom. The total floor area of the hotel amounts to 42,956 m² and is equipped with a 2,040 tons of refrigeration (RT) chiller plant to provide cooling. It consists of 3 centrifugal chillers of 400 RT each, a 440 RT absorption chiller and with primary-secondary pumps for chilled water distribution as shown in Fig. 2. During the design stage, concerns were raised about the appropriate zoning of chilled water distribution loop in considering its significant height which was believed to take up a huge portion of the total power consumption.

On the other hand, the efficiency of the chiller plant also plays a key role in the building’s total power consumption, and thus the operation cost. After five years of operation, the owner decided to perform a thorough energy auditing of the hotel, so that energy conservation strategies can be developed and implemented. We have proposed to proceed through computer simulation and followed by full-scale experimental investigation as the following.

2. COMPUTER SIMULATION

In order to simulate the dynamic cooling load and annual power consumption of the hotel, the DOE2.1 program has been used as the simulation tool [1]. The simulation process calculates the hourly cooling load based on Transfer Function method as recommended by ASHRAE after the building AutoCad file and design parameters, such as the occupancy and lighting density, and operation scheduling, were inputted. The second phase of calculation gave the annual power consumption when chiller plant capacity and efficiency were inputted. Lastly, economic evaluation can be performed after local power tariff and the initial cost of the equipment were inputted.

The LD hotel simulation was performed on a personal computer with a Pentium 4 processor efficiently. The simulated annual power consumption of the hotel is shown in Fig. 3. A pie chart indicating the consumption of each subsystem can be plotted in Fig. 4 on annual basis.
3. EXPERIMENTAL VALIDATION

In order to perform annual energy auditing of the building, data loggers were installed within the power supply panels for a year-long data recording, including chillers, fan and pumps, and lighting systems. The logger allows a real-time on-line access through internet, or data can be downloaded periodically, say a month in this case. Fig. 5 shows the measured result in a pie chart consisting of the three major portions of the energy use in the hotel in May, namely 34% by chillers, 35% by fans, pumps and miscellaneous equipment, and 31% by lighting system.

4. RESULTS AND DISCUSSIONS

A comparison between the simulated and measured result of the annual power consumption of the hotel can be plotted in Fig. 6. Fig. 7 further indicated the deviation between the two. The deviation ranges from 5% to 10% most time of the year, while the maximum deviation of over 15% occurs in December. The variation is seasonal that the occupancy of guestrooms fluctuates significantly in this hotel. It reaches its peak in the summer where families go for a vacation to the national park further down south of the island always staying overnight here since this is the city with the most
convenient direct flights from the north. Numerous sightseeing groups checked in on a packaged tour where airline tickets and hotel accommodation were included at a fairly low price. So summer is definitely a booming season for the LD hotel. The simulation result underestimated its impact on the total cooling load. On the other hand, being in hot and humid climate, people refrain from travelling during the winter unless it is a business trip and is definitely necessary. Therefore, the occupancy went down significantly in December. Again, the simulation result underestimated its impact.

Another simulation was conducted to take this factor into account yielding the modified simulation result as indicated in Fig. 8. It showed that the measured result correlated closely with that of simulation, with deviation ranging from 4% to 10%, within the engineering tolerance.

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**Fig. 4:** A pie chart indicating the power consumption of each subsystem on annual basis

**Fig. 5:** The measured energy use of LD Hotel in a typical summer
To Compare with the Benchmark of Typical Hotels’ Annual Energy Use across the Nation

It is an interesting point to ask, then, how do typical hotels perform thermally and what will be the average annual energy use of them, in units of kWh/m² air-conditioned space? The benchmarking of typical hotels across the nation will lead to the establishment of Energy Use Index (EUI) to be compiled into the building energy code, and providing valuable references to hotel owners so that energy conservation measures can be taken. The systematic study of EUI establishment was much more involved and will be covered in another paper. For clarity, the EUI result was given briefly here as a comparison basis. The result was originated from field measurement of more than thirty typical hotels with central cooling plant across the country located in the north, central, and south of the country. Hourly energy use data consumed by chillers, fan and pumps, and lighting system were recorded for a year as mentioned earlier. Through statistics, the EUI of hotels was thus established.

Fig. 9 indicated the pie chart of the annual energy use of a typical hotel where EUI is about 300 kWh/m² per annum. In comparison, the LD hotel with 323 kWh/m² per annual consumption presents potential for improvement on energy conservation designs, where Fig. 10 showed its corresponding pie chart.
**Pumping Power Savings**

Furthermore, the pie charts comparison of the two revealed that the LD hotel consumes more pumping power than average. It is obvious that, due to its height, chilled water zone pumps should be designed more strategically and carefully. A one-through type pumping loop will introduce heavy duty pumps with significant static head, not to mention the heavier gauge piping and fittings needed to hold the pressure. Vertical zoning of the pumping loop is essential in this case and would bring down power consumption significantly.

Furthermore, variable speed driven (VSD) pumps can be considered another option with energy-savings potential.

In other words, the LD hotel chilled water pumping performance can be greatly enhanced if three to four VSD pumps were utilized for the lower-level floors, and the other group of pumps to cover the higher level floors. During different cooling load conditions, the return water temperature variation can be picked up as a signal to trigger different pump groupings to compose a Variable Water Volume (VWV) system.
Following the law of energy conservation, the cooling capacity is determined by the chilled water flow rate in distributed through the pumps, multiplied by the temperature difference $\Delta T$ between the supply and return chilled water. By keeping the $\Delta T$ constant, a VSD pump reduces the $m$ to meet the decreasing cooling load, and thus running at a slower speed $N$ leading to a significant reduction of the pumping power according to the "fan law". Or in equation from,

$$Q = \dot{m} C_p \Delta T \quad (1)$$

where $Q$ is the cooling capacity, kW, $\dot{m}$ is the chilled water pumped to meet the cooling load, kgs$^{-1}$, $C_p$ is the specific heat of chilled water, kcalkg$^{-1}$C$^{-1}$, and $\Delta T$ is the temperature difference generated by the supply and return chilled water, °C.

As $\dot{m}$ is in direct proportion to the rotational speed $N$ of pumps, the pumping power $W$ is in cubic proportion to $\dot{m}$ or

$$\frac{W_2}{W_1} = \left(\frac{\dot{m}_2}{\dot{m}_1}\right)^3 = \left(\frac{N_2}{N_1}\right)^3 \quad (2)$$

The subscripts 1 and 2 represent the VSD and CSD pumping system respectively, yielding an estimation model for pumping energy savings.

To validate this calculation model, a full-scale experiment has been performed on another similar building equipped with VSD pumping system. As indicated in Fig. 11, the measured hourly pumping power consumption varies from 10 kW to 26 kW during the time of day when cooling load varies. In compared with the constant speed pumps, the power consumption would have been 35kw throughout the day, and the accumulated pumping energy savings is reaching 38%. This result is in good correlation with our calculation model to estimate the VSD pumping energy savings, with deviation of less than 3%. This calculation model is then applied to estimate the energy savings of the LD hotel, if VSD system were in place. The pumping power can be brought down from 11.6 kWh-m$^{-2}$-yr$^{-1}$ to around 7 kWh-m$^{-2}$-yr$^{-1}$, or a significant energy savings of around 40%.

\* Chiller Plant Performances and Energy Savings

A detailed field measurement on the chillers was conducted to evaluate the chiller thermal performances. The experiment included measuring the cooling capacity provided by chillers by measuring the supply and return water temperatures with k-type thermocouples, and the water flow rate with ultrasonic flow meter. Both were redundantly installed to compare with data generated from the existing control center. The performance test is also non-destructive in nature and without the necessity to interrupt the chiller plant normal operation which is important to the hotel manager. In addition, the partial load factor of a specific chiller was recorded as well as the power consumption, so that the coefficient of performance (COP) can be measured on site. Different from the chiller rating process which is following the ARI test conditions, the on-site cooling capacity testing has to cope with the existing operation conditions, and thus under a specific partial load condition. As recommended by the ASHRAE [2], the chiller performance can be further correlated by an experimental model as the following:
\[
Pe = 1905 - 440.61Tch + 25.0861Tch^2 - 110.85Tcd + 1.6092Tcd^2 + 25.6768Tch \cdot Tcd - 1.464Tch^2 \cdot Tcd - 0.373Tch \cdot Tcd^2 + 0.02129Tch^2 \cdot Tcd^2
\]  
(3)

where \( Pe \) is the power consumption per unit cooling capacity, kW \( \cdot \) RT\(^{-1} \), \( Tch \) is the leaving chilled water temperature, \(^\circ\)C, and \( Tcd \) is the entering condenser water temperature, \(^\circ\)C.

The experiment on chiller capacity carried out in the LD hotel results in an average power consumption per unit cooling capacity of 1.12 kW\( \cdot \)RT\(^{-1} \), equivalent to a COP of 3.13. It is clear if a more energy-efficient chiller plant with, say 0.55 kW\( \cdot \)RT\(^{-1} \), the energy savings can be significant. At this point, the LD hotel management is considering seriously about the feasibility of replacing some of the chillers. And again, the DOE 2.1 simulation provides valuable information to help make that decision.

As shown in Fig. 12, the pie chart of the new chiller plant can be estimated.

![Fig. 11: The comparison of the measured pumping power consumption of the VSD vs. CSD systems](image1)

![Fig. 12: The improved annual energy use index pie chart of the LD Hotel with new chiller plant](image2)
The average power consumption of the original chiller is 89.3 kWh m\(^{-2}\) yr\(^{-1}\). When replaced with new and more efficient chillers, the power consumption can be reduced to 43.8 kWh m\(^{-2}\) yr\(^{-1}\).

When adding to the pumping power savings as stated earlier, the EUI value of LD hotel could be brought down to 273 43.8 kWh m\(^{-2}\) yr\(^{-1}\), after energy conservation measures are applied. This would amounts to an energy saving of 15.4% of total energy consumption of the hotel.

5. CONCLUSIONS

Computer simulation has been used widely during the design stage, but can contribute significantly also as a prediction and evaluation tool for a renovation project. The experimental process performed in this study beginning with annual energy auditing of the building for diagnostics. The measured energy consumption of the building, when compared with the benchmark value of typical hotels in the nation, indicated that the LD hotel necessities further effort on energy conservation. The potential savings could be up to 15.4% annually when more energy efficient measures were brought into the existing chiller plant.

The simulation process, which has been experimentally validated with average deviation of less than 10% in this study, has become a useful tool to predict energy saving potentials. This information is important for the building management to make that decision whether the energy savings measures can be justified technically and economically. The successful implementation of this evaluation process on the LD hotel, both analytically and experimentally, has warranted its application in other engineering projects.

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