OPTIMIZATION OF ICE THERMAL STORAGE SYSTEM DESIGN FOR HVAC SYSTEMS

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ABSTRACT

Ice thermal storage is promising technology to reduce energy costs by shifting the cooling cost from on-peak to off-peak periods. The paper discusses the optimal design of ice thermal storage and its impact on energy consumption, demand, and total energy cost. A tool for optimal ice storage design is developed, considering the charging and discharge times and optimal sizing of ice thermal storage system. Detailed simulation studies using real office building located near Orlando, FL including utility rate structure are presented. The study considers the effect of the ice thermal storage on the chiller performance and the associated energy cost and demonstrates the cost saving achieved from optimal ice storage design. A whole building energy simulation model is used to generate the hourly cooling load for both design day and entire year. Other collected variables such as condenser entering water temperature, chilled water leaving temperature, outdoor air dry bulb and wet bulb temperatures are used as inputs to a chiller model based on DOE-2 chiller model to determine the associated cooling energy use. The results show a significant cost energy saving can be obtained by optimal ice storage design through using the tool proposed in this paper.

INTRODUCTION

Thermal energy storage includes a number of technologies that store thermal energy in energy storage tanks for later use. These applications include the production of ice, chilled water, or eutectic solution at night which is then used to cool the building during the day. The ice thermal storage (ITS) is one of thermal energy storage technology that is widely used in many countries to reduce electrical power or energy costs by moving the cost of cooling buildings from expensive “on-peak” periods to cheaper “off-peak” periods (Sebzali and Rubini 2007; Solberg and Harshaw 2007; and Montgomery 1998). The cool-energy is usually stored in the form of ice during the nighttime and used in the daytime. Many studies demonstrate the benefits of ice storage and how the thermal storage can shift the cost of electricity from on-peak to off-peak periods, thus reducing demand and energy charges (Nassif at al. 2013; Yau and Rismanshi 2012; Zhou et al. 2005; MacCracken 2004 and 2003; Silvetti 2002; Dincer 2002). Unfortunately, thermal storage may not provide the expected load shifting or the cost saving if not designed or operated properly. The paper discusses the optimal design of ice thermal storage and its impact on energy consumption, demand, and total energy cost. A tool for optimal design of ice storage is developed, considering variables such as chiller and ice storage sizes and charging and discharge times. The tool requires the hourly cooling load that can obtained from any available energy simulation software. It also requires an optimization algorithm to solve the optimization process. Although there may be many optimization methods that could be used for solving the optimization problem, the genetic algorithm (GA) inspired by natural evolution (Goldberg 1989, Deb 2001) is used. The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution. The GA is successfully applied to a wide range of applications including HVAC system control and design (Nassif 2012; Kusiak et al. 2011; Xu et al. 2009; Mossolly et al. 2009; Nassif et al. 2005).

Detailed simulation studies using real office building located near Orlando, FL including utility rate structure are presented. The study considers the effect of the ice thermal storage on the chiller performance and the associated energy cost and demonstrates the cost saving achieved from optimal ice storage design. A whole building energy simulation model eQuest is used to generate the hourly cooling load for both design day and entire year. Other collected variables such as condenser entering water temperature, chilled water leaving temperature, outdoor air dry bulb and wet bulb temperatures are used as inputs to a chiller model based on DOE-2 chiller model to determine the associated cooling energy use. As the main objective of the ice thermal storage is to shift the energy use from on-peak period to off-peak period, it is very important to examine the local utility cost structure to identify if the ice storage is cost effective. A particular utility structure is used as descripted later in this paper.

METHODOLOGY

To size the chiller, cooling load analysis is generally performed. Traditionally without ice storage, a factor of safety is added to the calculated load. The safety factor could be up to 20% and it is acceptable per ASHRAE Standard 90.1-2004 to oversize the chiller to 115% of load as a factor of safety (ANSI/ASHRAE/IESNA Standard 90.1-2004). As an alternative, rather than adding the factor of safety, it can be added as ice-storage capacity. In fact, the chiller can size 20 to 25% less than the cooling analysis when ice storage is installed (Solberg and Harshaw 2004). Optimal design of chiller and ice storage is then necessary to achieve the optimal performance. In addition, the optimal discharging and charging times are other important factors to achieve optimal performance. The optimization tool is then developed as shown in Figure 1 to find the optimal chiller and ice storage sizes and discharging and charging periods. The inputs required are the hourly cooling loads, utility cost structure, and outdoor air conditions. The cooling load and the outdoor air conditions could be generated by any energy simulation software and exported to be used as input. The cost structure should obtain from the local utility company that should include the cost of kWh and per peak demand kW during the peak and off peak periods.

The simulation model calculates the hourly cooling power by the chiller model for the charging, discharging, and normal chiller operating periods, and then determines the monthly and whole year energy consumption and associated cost. An optimization algorithm is needed to solve the optimization problem. The problem variables as output of the recommended process are discharging period, charging period, chiller size, and ice thermal storage size. The objective function is the annual energy cost.

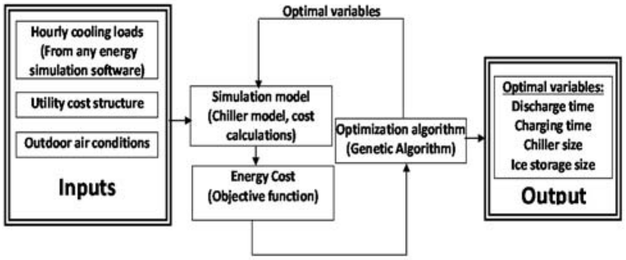

Figure 1 *Recommended optimization tool for optimal design of chiller and ice storage sizes, discharging and charging periods.*

The optimization seeks to determine the optimal ITS and chiller design to reduce the annual cooling energy cost. The problem variables are (1) chiller size, (2) ice thermal storage size, (3) discharging period, and (4) charging period. The objective function is the annual cooling energy cost. The constraints result from restrictions on the size and operation of the central plant. They cover the lower and upper limits of design variables, such as the maximum and minimum size of the chiller, and discharging and charging periods, e.g. discharging period starts only during the peak period, and charging period should start before the occupied period.

The genetic algorithm is used to solve the optimization problem. The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution. The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution. The GA starts with a random generation of the initial population (initial solution) and ends with the optimal solutions including the optimal variables. The problem variables represent an individual solution in the population. The performance or objective function of each individual of the first generation is estimated. The second generation is generated using operations on individuals such as selection, crossover, and mutation, in which individuals with higher performance (fitness) have a greater chance to survive. The performance of each new individual is again evaluated. The process is repeated until the maximum number of generations is reached. In this study, the GA algorithm from the optimization tool available in MATLAB® is used (MATLAB 2013).

To test the recommended procedure, an existing 40,000 ft^2 (3716 m^2) office building located near Orlando is selected. The building is occupied from 8 AM to 5 PM, and the HVAC system turns on at 7:00 AM and turns off at 6:00 PM. The space air is conditioned by typical variable air volume (VAV) systems with chilled water supplied by one screw chiller along with six ice thermal storages. The central plant piping configuration, including pumps, chiller, ice storage, and heat exchanger is illustrated in Figure 2. The building is served by a 150 ton (528 kW) chiller. A total of five pumps circulate either water or a glycol mixture. The piping configuration consists mainly of five water loops (1) primary loop, (2) secondary loop, (3) ice thermal storage ITS, (4) heat exchanger (HX) and (5) condenser water loop. In the primary, ITS, and HX loops, there are three pumps circulating glycol water solution through the chiller, ice storage, and heat exchanger, respectively. In the secondary loop, a pump equipped with variable speed drive circulates chilled water to the nine AHUs. In the condenser water loop (not shown in Figure 2), the pump operates at constant speed to circulate condenser water to the cooling tower when the chiller is operating. There are many operating strategies that could be applied to charging or discharging the storage. The operating strategies include partial or full storage. A full storage strategy is considered for the simulation as it is the one adapted in the existing system. Due to the utility structure considered, the peak period is from 12:00 PM to 5:00 PM so that the ITS is sized to cover this particular period. In this paper, the following cost structure is assumed. The energy cost if there is no ITS is $0.06 per kWh and $9 per peak demand kW. The cost with ITS is $0.08 per kWh plus $9 per peak demand kW during the peak period and $0.05 per kWh during off peak. The peak period is from 12:00 PM to 5:00 PM. It should be noted that different cost structures could be applied in other areas and readers need to check their local utility.

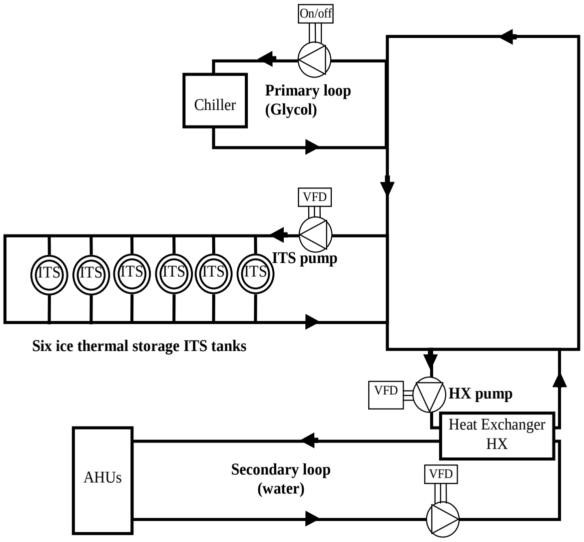

Figure 2 *Central plant piping configuration*

RESULTS

The energy simulation model eQUEST runs for the selected building to determine hourly cooling loads for the design cooling day and for the whole year. Using those cooling loads, the optimization process as shown in Figure 1 then runs to determine the optimal variables including the chiller and ice storage sizes and charging and discharge times.

The simulations without ITS and with near optimal and non-optimal designs are repeated for the whole year using typical weather conditions for Orlando, FL. Figure 3 and Figure 4 show the monthly energy consumption and associated energy cost without ITS and with near optimal and non-optimal ITS designs. Energy cost is determined by the cost structure introduced before.

By comparing the near optimal ITS design with when there is no ITS installed, it found that monthly energy consumption increases. For example, energy consumption rises by using optimal design ITS from 20,822 kWh to 23,899 kWh in July, an increase of 15%. The main reason for elevated energy consumption with ITS is because of the low chiller efficiency as it operates at lower chilled water-glycol temperature (25 °F vs. 45 °F) (-4 °C vs. 7 °C) to make ice. However, because most of the energy consumption occurred during the off-peak period when the cost of energy is low, the energy cost drops significantly. The energy cost drops from $2,329 to $1,367 in July, a saving of $962 (41%). By adding up the monthly energy use and associated cost, the annual cooling energy consumptions with/and without ITS are 108,590 kWh and 97,977 kWh and the annual cooling energy costs are $6,210 and $12,548, respectively. These results indicate that the annual energy consumption increases by 11% and the energy cost drops by 50% by using ITS.

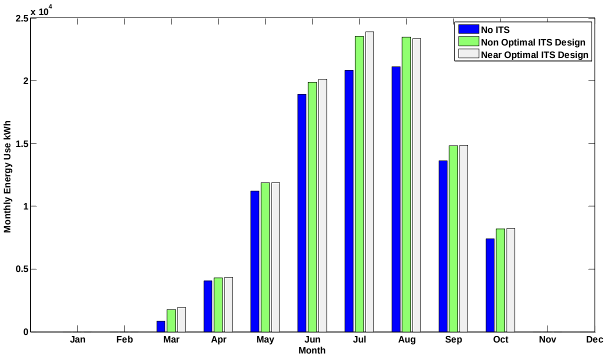

Figure 3. The monthly energy consumption with/without ice thermal storage ITS

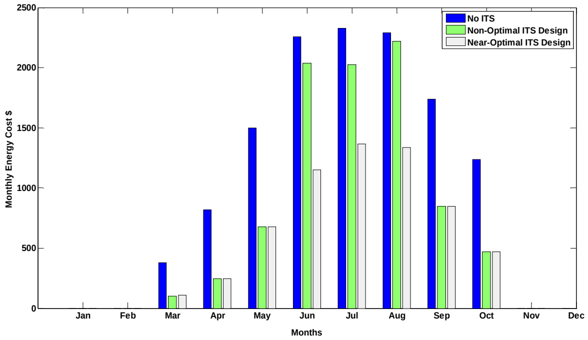

Figure 4. The monthly energy cost with/without ice thermal storage ITS

By comparing the near optimal ITS design with non-optimal design, it found that the energy cost drops in most of months and total energy cost drops from $8,630 to $6,210. The optimal design could provide saving up to 28% comparing to non-optimal design. It should be noted that this result is based on one location and a specific cost structure and the readers should not draw a general conclusion on the amount of the operating cost saving indicated in this paper. The saving varies from one location to other and strongly depends on local utility cost structure. However, the optimization process as shown in Figure 1 can be always a useful tool to achieve the optimal design as long as the utility cost structure, hourly cooling loads, and outdoor air conditions are correctly entered.

CONCLUSION

Ice thermal storage is promising technology to reduce energy costs by shifting the cooling cost from on-peak to off-peak periods. The ice thermal storage can have high impact on energy consumption, demand, and total energy cost. The paper introduces a tool for central plant optimal design including chiller and ice storage sizes and charging and discharge times. The building energy simulation model eQUEST® is used to generate the hourly cooling load, and the chiller model is used to determine the chiller power. A specific local utility cost structure and one location is used as example for energy cost analysis. The results demonstrated that although the energy consumption increases by using ice thermal storage, the energy cost drops significantly, mainly depending on the local utility rate structure. It showed a significant cost energy saving can be obtained by optimal ice storage design through using the tool proposed in this paper. The saving could be up to 28% comparing to non-optimal design of ITS. The results also indicated that that the annual energy consumption increased by 11% and the energy cost dropped by 50% compared to the case when no ITS is installed. This study focuses on a particular cost structure and climate, local utility cost structure needs to be checked in order to determine if the ice thermal storage is cost effective.

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