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Tank size and operating strategy optimization of a stratified chilled water storage system

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ABSTRACT

In the downtown area of Austin, Texas, United States, it is planned to build a new naturally stratified chilled water storage tank and share it among four separated chilled water plants in order to reduce the utility billing cost. Each plant is charged with a typical time-of-use utility rate including energy charge and demand charge. This paper presents the method of determining the optimal tank size as well as corresponding optimal operating strategies for this project. A simplified thermal energy storage plus four plants model is built based on some assumptions. Three conventional control strategies (full storage, chiller priority, and storage priority) with limitations on the maximum number of chillers running during the off-peak and on-peak periods are simulated. The results show that a 3.5 million gallon (13,249 m^3) tank has the shortest simple payback time and the projected total capital cost is within the budget. Full storage strategy is selected for the summer months and storage-priority strategy is selected for the winter months. The annual billing cost savings are estimated at $907,231 and the simple payback time is 12.5 years.

1. Introduction

Thermal Energy Storage (TES) technology is often used to reduce the operating costs by shifting cooling production from higher cost periods to low cost periods. The electricity energy savings can also be achieved by shifting the cooling load from less efficient chillers (CHLR) to more efficient chillers (such as new electric centrifugal chillers) or loading chillers at the optimal Part Load Ratio (PLA). In an energy retrofit project, a chilled water (ChW) storage system is often preferred to ice storage since existing equipment can be kept and the least system changes to the original system configuration have to be made. In the preliminary study phase, the available information is limited, but the determination of an optimal tank size as well as the energy and cost savings estimation will be critical for the success of the project. Although the concept is very simple, the various operation modes together with complicated rate structures enhance the difficulties and complexities of determining the optimal tank size and operating strategies. In this phase, hand calculations or typical day simulations are often used but its accuracy and reliability is questionable. Therefore, a simple method is needed to help designers select an optimal tank size, determine optimal operating strategies, and estimate the savings potential based on limited information and assumptions. It should be performed within a reasonable time with reasonable efforts, while yield accurate and reliable results.

An in-depth literature search and study shows that the studies on ChW storage systems are mainly concentrated on field experiment testing of the tank performance. Tran et al. [1] tested six chilled water storage systems and found that well-designed storage tanks had a Figure-of-Merit (FOM) of 90% or higher for daily complete charge and discharge cycles and between 80% and 90% for partial charge and discharge cycles. Bahnfleth and Musser [2] found that the lost capacity was roughly 2% of the theoretical capacity available when a minimum outlet temperature limit was applied while as much as 6% could be lost for discharge processes performed at the same flow rate for typical limiting temperatures. Discharge cycle lost capacity was significantly decreased by reducing the inlet flow rate. In a dynamic mode of operation, the effects of mixing overtook the influence of other parameters but the effect of wall materials could not be neglected when the tank was in an idle status [3]. Caldwell and Bahnfleth [4] found that mixing was localized near the inlet diffuser and directly related to flow rate. Nelson et al. [5] proposed the definition of the mixing coefficient, which was expressed as a function of Reynolds number (Re) and Richardson number (Ri).

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Other researchers built dynamic or static simulation models to study the thermal performance of a stratified ChW storage tank. Gretarsson et al. [6] derived a fundamental energy balance model based on a one-dimensional plug-type flow approach. Studies showed that the thermocline thickness could be 3–7% of the water height. Homan et al. [7] grouped the capacity loss into heat transfer through the tank walls, conduction across the thermocline, and the flow dynamics of the charge and discharge process and found that the flow dynamics were generally orders of magnitude more important than the other factors. Published data showed current storage tanks generally operated at efficiencies of 50–80%.

These studies indicate that considerable capacity loss may occur when a minimum outlet temperature limitation is applied, especially during a discharge cycle at higher flow rates. The tank discharge rate should be controlled to minimize the mixing effect near the inlet diffuser. These findings could place some constraints on the operations of the TES system and also provide insights to simply quantify the tank performance.

Some researchers performed studies on the operations of chilled water storage systems. Henze et al. [8] described the investigation of the economic and qualitative benefits of adding a chilled water thermal energy storage system to a group of large buildings in the pharmaceutical industry in Southern Germany. It is found that the adoption of a chilled water thermal energy storage system is expected to provide economic benefits as measured in energy cost savings, as well as qualitative merits such as the avoidance of numerous safety measures necessary for a chilled water plant without storage (e.g., always operating at least two chillers), and a cost effective addition of supplemental chilled water plant cooling capacity. Moreover, the overall system reliability and availability will be significantly improved through the addition of a thermal energy storage system. The near-optimal heuristics suitable for implementation in the actual pharmaceutical buildings is an ongoing task. Zhou et al. [9] developed a chiller start–stop optimization program and implemented it into the energy management and control system to determine the number of chillers that need to be brought on line and the start and stop times for each chiller every day, based on the prediction of the campus cooling load within the next 24 h. Wei et al. [10] developed control strategies for both on-peak and off-peak months to minimize demand charges for a 7000 ton-hour (24,618 kW_t-hour) chilled water storage system serving a hospital. By optimizing the operation of the building air handling units, chilled water pumps, chiller plant and the thermal storage system, the storage tank is better charged while chiller run time is reduced. Both on-peak and off-peak electrical demands are expected to be reduced significantly. All these studies are on a case-by-case base and the effect of loop chilled water supply and return temperature degradation is not considered. However, in practice, low delta-*T* is common for an aged chiller plant, and it can be expected to fall to about one-half to two-thirds of design at low loads [11]. This will reduce the tank capacity proportionally. In addition, the tank state and state change are described with refrigeration tonnage and ton-hour, respectively, which will lead to inconsistency for a chilled water storage tank when the loop delta-*T* fluctuates.

The electricity rate is the main driving force and the economic incentive for the application of a TES system. There are various kinds of rate structures but a Time-of-Use (TOU) rate structure is most popular for a TES system in United States. A TOU rate defines the cost of energy during specific times of the day and encourages customers to defer energy use until costs are lower. It is fixed in advance usually at the time of signing the contract, and is not subject to variations during the contracted period. Sometimes, the calculation of monthly billed demand can be very complicated if a demand ratchet is defined [12].

This paper introduces a simple method to select an optimal tank size under a typical TOU rate structure for a retrofit project. Hourly simulations are performed month by month to determine the corresponding optimal operating strategies. The effects of chiller performance, loop ChW delta-*T*, tank performance, and cooling load profile are all considered. This method is illustrated with a practial project and annual cost savings as well as simple payback are calculated.

2. Method

2.1. Searching flow chart

This method is based on a direct search of all possible operating strategies, which consist of control strategy type and the maximum number of chillers running during the off-peak and on-peak periods. For each daily cycle, normally 24 h, it is divided into off-peak period and on-peak period. Fig. 1 shows the flow chart of the search procedure. Within the search loop, all possible combinations are explored. The hourly tank water level and system total power are simulated with a model called system model. A minimum tank level set point is used to filter the combinations that lead to premature depletion. For all acceptable combinations, an electricity rate model is used to calculate the monthly billing cost. The scenario with the lowest monthly billing cost will be chosen as the optimal operating strategy for the current month.

The maximal numbers of chillers that can be staged on should be no less than zero and no higher than the number of installed chillers in the plant. The limitation on the number of chillers running is a kind of demand limiting because, for a multi-chiller plant, the ChW-related power is approximately proportional to the number of chillers running. Each control strategy consists of a series of control logic, which is used to calculate the plant total ChW flow rate and the number of chillers staged on for each time step. The control strategies used include three conventional strategies, which are elaborated in other sections. In addition, the scenario without TES is also simulated as a baseline when calculating the energy and cost savings.

For this method, input parameters include cooling load, tank performance, loop delta-*T*, etc. In practice, it is impractical to accurately predict these variables. Conservative estimations could result in a conservative strategy and a lower saving potential, while aggressive estimations could force the plant to stage on more chillers during the peak demand period and achieve less cost savings. To minimize the negative impacts of prediction uncertainties on the tank size and operating strategy projection, it is possible to perform multiple simulations under scenarios with various inputs, such as high or low cooling load, good or poor tank performance, constant or variable loop delta-*T*, etc. Based on the simulation results, designers can balance the risks and benefits and make best decisions. Comparison of the results can also provide an insight into the sensitivity of the estimated cost savings or simple payback time on these parameters.

2.2. System model

The flow chart of a system model is shown in Fig. 2. It is used to calculate the hourly tank water level and system total power. This model includes three sub-models and each of them will be introduced in the following sections. The advantage of such a system model is that each sub-model is independent and its function is explicitly specified. It also clearly describes the relationships among plant, loop, and TES tank. For different applications, the user may replace them with self-built sub-models or make minor changes on