An Overview of Cool Storage Technologies for Commercial Buildings

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Introduction

Thermal storage can significantly reduce the costs of providing cooling in commercial buildings by shifting a portion of the daytime cooling requirements to nighttime hours. This concept is depicted in Figure 1. At any time, the combination of the primary cooling system and storage must meet the building cooling requirements. During the night when commercial buildings are unoccupied and do not require cooling, the primary cooling equipment can be used solely to cool the thermal storage medium for use the next day.

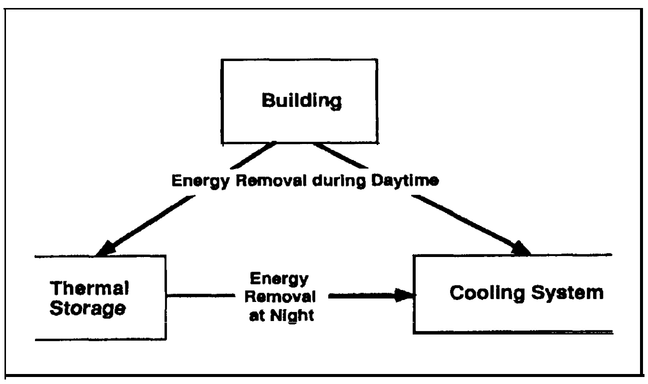

Figure 1. Thermal Storage to Reduce Daytime Cooling System Requirements

The term "charging" is often used to describe the cooling of storage, while "discharging" describes the use of storage to provide cooling. Conventional or industrial-grade chillers are typically used to charge storage tanks during off-peak hours. The storage is discharged by circulating a working fluid from storage to the building's cooling coils or to a secondary heat exchanger.

Cool storage was first used commercially in the 1940's for buildings that required cooling for short periods of time, such as theaters and churches. The goal was to reduce the size and cost of the primary cooling equipment. Today, the application of cool storage is based upon both down-sizing equipment and reducing utility costs.

Utility Costs: The utilities view thermal storage as an effective means of leveling their electrical demand. Many utilities provide incentives for the use of thermal storage by offering low cost energy during off-peak periods and by levying a demand charge that is based upon the peak power consumption (e.g., $/kW) during on-peak hours for the billing period (i.e., a month). Thermal storage can reduce both demand and energy charges by shifting primary cooling system operation from on-peak to off-peak hours. In many cases, the use of thermal storage can also result in a reduction in overall energy usage. These savings result from improved cooling plant efficiency due to increased operation at more favorable part-load and ambient conditions.

Capital Costs: Without thermal storage, equipment must be sized in order to meet the peak cooling requirement of a building. Given that commercial buildings are unoccupied at night and on weekends, then the overall building cooling requirements are a small fraction of the potential of the system to provide cooling. Appropriate sizing of thermal storage can result in significantly smaller primary and auxiliary equipment. In many situations, savings associated with downsizing of equipment can more than offset the cost of the storage medium.

When considering thermal storage systems, the lowest capital costs generally result for load-leveling partial storage systems. In this case, the storage and equipment are sized so that the primary cooling equipment operates at peak capacity over the entire day associated with the peak cooling requirement. Conversely, a full storage system is sized so that the primary cooling equipment never needs to operate during the on-peak period. Full storage systems have lower operating costs, but greater initial costs than partial storage systems.

Figure 2 illustrates the potential for load shifting and equipment downsizing associated with the use of partial and full thermal storage systems. The cooling requirement of the primary equipment is depicted as a function of time for each system on the design day. Without thermal storage, the equipment must be sized to meet the peak building cooling requirement occurring at about 3 pm. With a full storage system, all of the cooling requirements of the primary equipment are shifted to off-peak periods, thereby giving the maximum reduction in on-peak energy and demand costs. The primary cooling equipment can also be smaller than for the system without storage, since the equipment can operate at full capacity during the entire unoccupied period to "charge" (i.e., cool) storage for use the next day. With load-leveling partial storage, the goal is to size the equipment so that it operates continuously at full capacity throughout the entire design day. Compared with full storage, this results in a significant reduction in the capacity requirements of the primary equipment and thermal storage. However, the system shifts only a portion of the building cooling load to the off-peak periods and therefore has greater on-peak energy and demand costs than the full storage system.

An "optimal" thermal storage design would minimize the overall costs of owning and operating the system over its useful life. The economics and design of thermal storage systems depend upon several factors including the utility rates, the profile of building cooling requirements, the storage medium, and whether it's a new or retrofit building. For new systems, the economics often favor the application of partial storage systems. This is particularly true in commercial buildings where the occupied and unoccupied periods are of similar duration. However, full

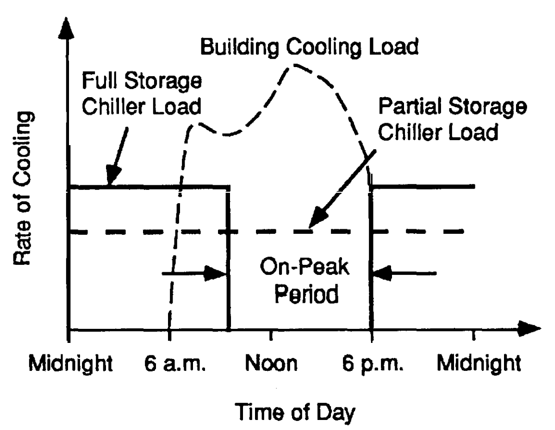

Figure 2. Chiller Cooling Requirements for Partial and Full Storage

storage systems can be appropriate for new buildings where the load occurs over a short duration, such as a sports facility, theater, or church. In this situation, a relatively small cooling plant can be used to meet a large peak cooling requirement. Full storage systems may also be economical as retrofits in typical commercial buildings, Since there is no opportunity to downsize primary cooling equipment, cost savings are only associated with utility charges.

For a particular thermal storage system, the operating costs are sensitive to the method used to control the energy state of storage over time. Control methods can be categorized as either "chiller-priority" or "storage priority." With a "chiller-priority" control method, the chiller provides as much cooling as possible to meet the on-peak building requirements and the ice storage medium provides the rest. This strategy is extremely easy to implement and ensures that sufficient cooling capacity will be available throughout the day. However, both the energy and demand costs are greater than what is possible through a better control method. Storage-priority control methods, on the other hand, attempt to maximize the use of storage during the on-peak periods of each day. There are many different ways to implement storage-priority strategies, but in general, they require the use of forecasting and result in lower operating costs.

Some of the important criteria that have driven the development and application of thermal storage devices are

1. **Storage Material and Enclosure Costs:** There can be a tradeoff between storage material and enclosure costs. A material with a higher energy storage density may cost more per unit volume, but requires a smaller volume.

2. **Storage Heat Exchanger Requirements:** Initial storage costs depend upon the requirements for a heat exchanger used to remove or add energy to thermal storage. Heat exchanger requirements depend upon the storage media and overall system design.

3. **Storage Efficiency:** Storage efficiency is the ratio of cooling that can be provided by storage to the cooling that was done in charging the storage tank. External energy gains from the environment reduce a storage device's potential to provide cooling, resulting in a storage efficiency less than 100%.

4. **Cooling System Requirements and Efficiency:** The choice of storage media can impact the requirements and efficiency of the cooling system utilized. In particular, the storage operating temperature is important in terms of the rate at which cooling can be provided by storage and the requirements of the

cooling equipment during the times when storage is being cooled. The size and associated auxiliary energy use for heat exchangers, pumps, and fans necessary to meet the building's cooling load typically increases with operating temperature. However, the size and energy use of the primary cooling equipment increases with decreasing storage operating temperature. Thus, the operating temperature is a critical factor in both initial and operating costs for thermal storage systems.

5. **Control Requirements:** Operating costs for thermal storage systems are also affected by the method used to control charging and discharging. The requirements for control are strongly dependent upon the type of storage.

The above criteria will be used in this paper as a basis for a qualitative discussion and comparison of alternative storage methods. Although several different types of storage media have been considered for use in commercial cooling, the three most commonly applied are 1) ice, 2) chilled water, and 3) building thermal mass. This paper gives an overview of the development, application, and control of these three types of storage. Each will be discussed and compared in terms of their advantages and disadvantages.

Ice Storage

Thermal energy can be stored as a result of the phase change between water and ice. Water has the highest heat of fusion among common materials and is the least expensive. Thus, ice storage systems can be relatively compact, low cost, and can have a high storage efficiency when properly insulated. In addition, a phase change temperature of 32°F provides a good operating temperature for removing heat from a building. As a result of these positive attributes, ice is the most commonly used storage medium for commercial cooling systems.

However, there are some negative aspects to the use of ice storage that have affected its development and application. First of all, specialized heat exchanger equipment is necessary to handle ice making and melting. Many different approaches have evolved to accomplish efficient heat transfer with the goal of low initial cost. The most common designs will be discussed in this section. Secondly, the low storage operating temperature necessitates the use of more expensive primary cooling equipment that operates with a lower efficiency as compared with conventional systems. To counteract this trend, the design of systems that incorporate ice storage have evolved to take advantage of the greater cooling capacity associated with low operating temperatures. These trends will also be discussed.

Storage Heat Exchanger Requirements

An ice storage tank must have the means to transfer heat from storage to a cool fluid supplied by the primary cooling equipment during ice making and to storage from a warm fluid returning from the building during ice melting. The most common methods can be categorized as 1) internal melt, ice-on-coil, 2) external melt, ice-on-coil, 3) containerized ice, and 4) ice harvesters. ASHRAE (1991) provides an overview of ice storage heat exchange methods that forms the basis of the presentation to follow.

The majority of ice storage tanks incorporate ice-on-coil heat exchangers in which a coil of tubing is in a tank of water. With an internal melt, ice-on-coil, a brine solution flows inside the tubing to either freeze or melt the ice. In the ice making or charging mode, cold brine (e.g., 22°F) from the chiller flows through the tubes causing the formation of ice on the outside of the tubes. As the ice thickness grows, conduction through the ice reduces the heat transfer effectiveness. In some designs, the tubes are placed close together so that the ice thermal resistance is small. However, once the ice formations intersect, then the surface area in contact with the freezing water is dramatically reduced and the heat transfer effectiveness drops. This type of ice-on-coil storage device is termed area constrained. As a result of the very large heat exchange areas required for area-constrained storage tanks, plastic tubing is typically employed. The tubing is usually spaced so that between 80 and 90% of the maximum ice build occurs when the ice formations intersect.

Figure 3 shows a cross-sectional view of one common geometry for an internal melt, area-constrained, ice-on-coil storage tank. Brine supply and return headers are oriented vertically within the tank and connected to spirally-wound rows of tubing. Two separate circuits are arranged to feed brine to both the perimeter and center of each row of tubing in the tank. This arrangement promotes uniform ice building and melting. A large length of low cost plastic tubing is used to give good overall heat transfer between the water/ice and the brine. Charging and discharging of the storage is determined by the temperature of brine supplied, which is controlled through valves and the chiller operation.

External melt, ice-on-coil storage tanks use separate circuits for making and melting ice. In many cases, the in-tank coil is the evaporator for a chiller. In the ice making mode, cold refrigerant flows inside the tubing to make ice on the outside of the tubes. Ice melting is accomplished by circulating water from the tank to an external heat exchanger that directly or indirectly removes heat from the building. Figure 4 schematically depicts the external melt, ice-on-coil concept. It is also common to replace the in-tank evaporator with a secondary brine heat exchange loop between the chiller evaporator and the in-tank coil.

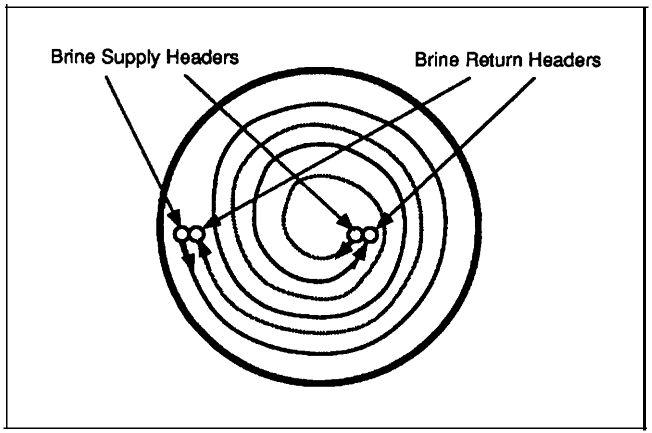

Figure 3. Spirally Wound, Area-Constrained, Ice-on-Coil Storage

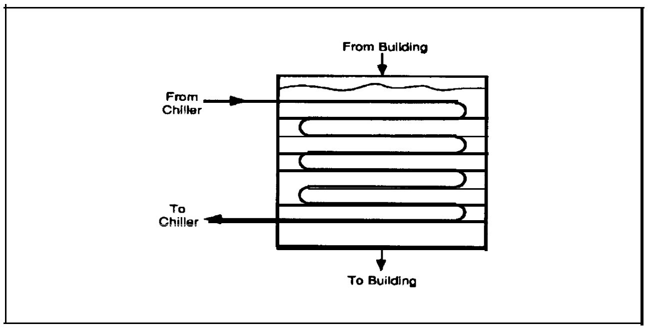

Figure 4. External Melt, Ice-on-Coil Storage

There are tradeoffs between the internal and external melt ice-on-coil concepts. The external melt with an in-tank evaporator has the advantage of lower heat transfer resistances. However, there are added construction costs necessary to reduce the possibility of refrigerant leaks. Most of the new ice storage installations use internal melt, area-constrained, ice-on-coil designs that utilize plastic tubing for the heat exchanger.

Containerized ice storage tanks are conceptually similar to internal melt, ice-on-coil tanks. A cold or warm brine solution flows through the tank to form or melt ice that is held within many small plastic rectangular or spherical containers. The containers are heat exchangers that form a packed bed within the tank as depicted in Figure 5. Potentially, this is a relatively simple and low cost method for ice storage. However, depending upon the size of the containers, the heat transfer resistance associated with the ice formation can be significant. Containerized ice storage is a relatively new concept that has not been widely applied.

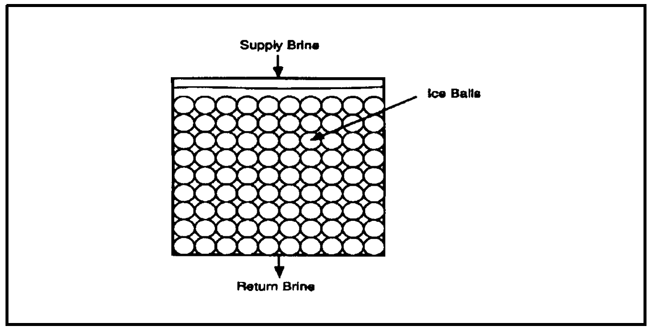

Figure 5. Containerized Ice Storage

Another popular type of ice storage is an ice harvester. Ice harvesters are conceptually similar to the external melt, ice-on-coil devices, in that separate circuits are used for making and melting ice. However, ice is formed on and harvested from flat plate evaporators as liquid water flows over the surface. Figure 6 shows a schematic of an ice harvester. Typically, the ice is harvested into a large tank at regular intervals (e.g., 15 minutes) using a hot gas defrost cycle. Since the thickness of the ice is limited for this system, the heat transfer effectiveness is good. However, there is a significant penalty associated with the energy required for defrost. There is ongoing research into surface treatments that can eliminate the adhesion of ice to the evaporator surface, thus eliminating the need for defrost.

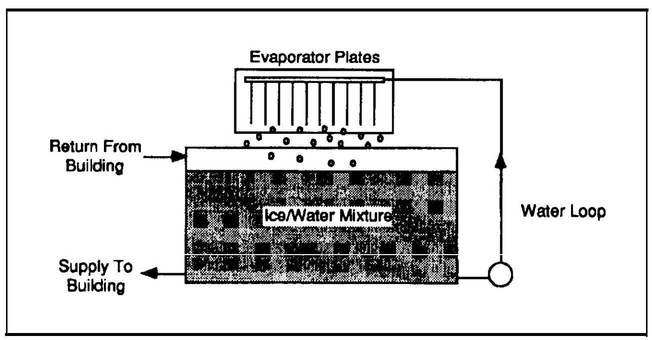

Figure 6. Ice Harvester

Cooling System Requirements and Efficiencies

In conventional chilled water cooling systems, the chiller supplies water to the building cooling coils at about 45°F. For an ice storage system, the chiller must be capable of supplying brine (or refrigerant) at a temperature of about 22°F in order to effectively make ice. Both the efficiency and cooling capacity of any chiller are reduced as the evaporator operating temperature is lowered. Thus, initial and operating costs associated with the chiller are greater for ice storage temperatures than those that would result for storage at higher temperatures (e.g., 45°F). However, there are other benefits associated with low temperature storage that can counteract this effect if the system is properly designed.

Low temperatures associated with ice storage allow the use of cold air distribution systems. In conventional systems with chilled water supply of about 45°F, the coiling coils provide cool air to the building at around 55°F. Ice storage systems can easily provide cool air at about 45°F. The use of cold air supply can reduce both the initial and operating costs associated with the air distribution system.

Colder supply air to the building means that less air needs to be circulated to meet the same cooling requirement. As a result, smaller ducts and fans are required to transport the air to the zones, reducing both the initial and fan energy costs. In many cases, the savings can compensate for the increased chiller energy use and cost. A recent study by Bhansali and Hittle (1990) evaluated cold air distribution systems. They compared conventional HVAC systems delivering air at 55°F with conventional systems delivering air at 43°F, and with full storage systems delivering air at 55°F and 43°F, respectively. With the low temperature system, the fan power for the air handling units was cut in half. Since air handling units run during the on-peak period even with a storage system, the on-peak energy and demand charges were significantly reduced. Overall, the storage system with cold air distribution was the most cost effective option.

There are other benefits associated with cold air distribution. In many commercial buildings, supply and return ducts are located in a space above the ceiling. Reducing the duct size allows this space to be reduced on the order of one foot. In a ten story building, a saving of one foot per floor is equivalent to adding another floor at little added cost. Cold air distribution systems also provide considerably drier air that can improve comfort conditions in many locations. However, care must be taken in the design of air diffusers for the building zones in order to ensure adequate uniformity of environmental conditions (Kirkpatrick & Hassani (1992).

Another opportunity for reducing the initial cost of cold air distribution systems that has not yet been exploited is the redesign of cooling coils. Currently, no manufacturer offers a cooling coil that has been "optimized" for low temperature systems. Instead, conventional coil designs are being specified for these applications. Cooling coil designs for conventional chilled water systems have evolved over time to provide a good balance between initial and operating costs. Since the flow rates are much lower for cold air distribution systems, this balance changes significantly. Mirth (1993) showed that the performance of conventional chilled water coil designs applied to low temperature applications could be improved by as much as 90% through relatively simple design changes. Overall, the economics of ice storage systems could be improved through optimal design of cooling coils for this application.

Control Requirements

A full storage system is relatively easy to control. Sufficient ice must be made during the off-peak period in order to fully meet the load during the next on-peak period. A conservative strategy would be to always fully charge the storage. If there are significant energy penalties associated with fully charging storage, then a forecaster could be used to estimate the required on-peak cooling.

For partial storage systems, chiller priority is the most commonly applied control method. On the design day, it's the only control method that will meet the building load requirements. On off-design days, there could be significant opportunities to improve on chiller priority with control methods that favor the use of storage (storage-priority). However, since it doesn't require forecasting, chiller priority is extremely easy to implement and is very robust in terms of meeting the building cooling requirements.

"Storage-priority" control strategies have been presented in the literature for ice-storage systems (Rawlings 1985; Braun 1992). In contrast to chiller priority, these methods require the use of forecasts for cooling requirements such as those presented by Forrester and Wepfer (1984), MacArthur et al. (1989), and Seem and Braun (1991). Although these generic control strategies are improvements over chiller priority control, none approach optimal performance for all systems and conditions.

In order to utilize storage-priority control methods, an on-line measurement of "state of charge" is required. This is a difficult measurement for ice storage tanks. One approach to measuring the energy state is to equate the change in internal energy to the integrated enthalpy change of the fluid that is transferring heat to or from the storage. This neglects any heat gain to storage from the surroundings; a good assumption for an insulated tank. For an ice-on-coil brine system, temperature differences during charging are only about 5 - 10°F. Thus, in order to have good accuracy with the energy balance method, very accurate temperature measurements are required. Expensive temperature sensors, such as platinum RTD's, should be used. Although the accuracy of flow measurements is not as critical, only certain types of flow measuring devices provide good accuracy for brine solutions. Rotary or paddle type meters will typically read high if not calibrated for the brine solution. Magnetic flow meters give good accuracy, but are expensive.

A common way to measure the energy state of an ice storage tank is to keep track of the amount of ice in the tank. One method involves measuring the change in volume occupied by the water and ice mixture in the tank that results from the phase change. The amount of ice is calibrated with a measurement of the level of an unfrozen layer of water at the top of the tank. As water freezes on the coils, the water level rises. Another ice inventory method for ice-on-coil tanks involves the use of "ice thickness" sensors. Thermistors located at different distances from the outside of the tube sense the growing ice thickness. Ice inventory methods do not account for sensible cooling of ice or warming of water that can occur at the outside tube interface during freezing or melting. The energy associated with these local sensible effects can be significant for large temperature differences between the brine and ice/water mixture. This is particularly the case during tank discharge when the temperature differences between the brine and storage are greatest.

Chilled Water Storage

Chilled water tanks are a natural alternative to ice storage systems, particularly for retrofits. Water is often circulated in large systems and it is relatively simple to add tanks to the existing network to store chilled water. Since the storage operating temperatures are above 40°F, conventional chillers can be used and the initial and operating costs associated with the chiller are lower than those for ice storage. However, the tank volume required is on the order of 5 to 10 times larger with water than ice, and weight may be a problem.

Storage Heat Exchanger Requirements

Heat exchangers are not necessary to transfer heat to or from a chilled water storage tank. However, thermal stratification is used to enhance the rate at which energy can be added or removed from storage. Since water density decreases with increasing temperature above 40°F, a tank will naturally stratify with colder temperatures near the bottom and warmer temperatures near the top. To promote stratification of storage, chilled water is added at the bottom during charging and removed from the bottom during discharging. A perfectly stratified tank would separate the warm and cold sections of the tank.

Figure 7 depicts an ideally stratified chilled water tank. During charging, cold water from the chiller is introduced into the bottom of the tank, displacing the location of the thermocline upwards. In the discharge mode, warm return water from the load is added at the top, pushing the position of the thermocline downward. The rate at which energy can be removed from storage during charging or added to storage during discharging increases with increasing temperature difference between the warm and cold sections of the tank. Both conduction and mixing tend to reduce this temperature difference. Flow distribution devices are employed to lower the flow velocities entering the tank and reduce mixing. Internal baffles are often employed to reduce the tendency of the inlet flow to short circuit the tank and flow directly to the outlet.

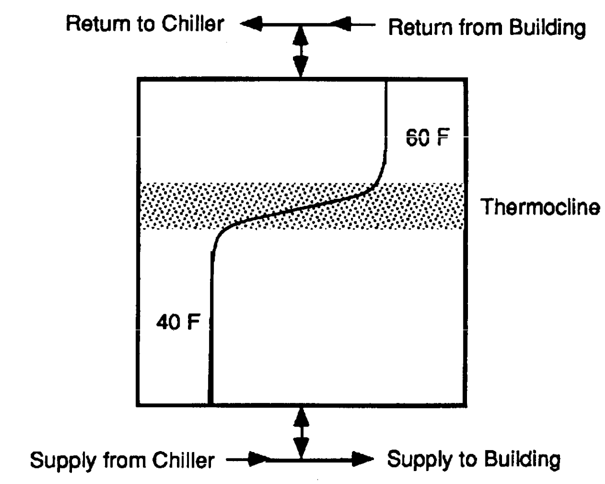

Figure 7. Stratified Chilled Water Storage

Multiple small tanks are an alternative to a single tank and provide better "stratification" in that each tank can be completely charged or discharged. One extra empty tank is always needed to accommodate the flow from, or to, the tank that is being discharged, or charged, respectively.

Storage Efficiency

Large chilled water storage tanks are often built on site from concrete. Poor storage efficiencies can result from improper insulation and location of storage. Mixing in the tank can also reduce storage efficiency by reducing stratification. Merten et al. (1989) reported storage efficiencies above 90% for well-designed chilled water tanks that were charged and discharged daily. Low storage efficiencies of between 45% and 70% were also reported for poorly designed systems.

Cooling System Requirements and Efficiencies

The operating temperatures for chilled water storage must be above 40°F in order to promote proper stratification. At about 39.4°F, the density of water decreases with decreasing temperature causing cold water to rise to the top of the tank. As a result of this restriction, the operating temperatures are similar to those for conventional chilled water systems. Thus, conventional chillers are used and the initial and operating costs associated with the chiller are lower than those for ice storage.

Control Requirements

The methods for controlling chilled water storage are similar to those for ice storage. For full storage, sufficient water must be cooled during the off-peak period in order to fully meet the load during the next on-peak period. There is little penalty associated with always fully charging the storage. For partial storage systems, the same chiller priority or storage priority strategies used for ice storage systems can be applied.

In order to utilize storage-priority control methods, an on-line measurement of "state of charge" is required. For chilled water systems, this is an easier measurement than for ice storage tanks. Again, the energy state can be determined from an integrated energy balance on the tank. This method requires measurements of flow rate and temperature difference between tank entering and leaving water. The temperature sensor requirements are not as stringent as for ice storage, since the temperature differences are more than twice as large (e.g., 20°F). Another method for monitoring energy state within the tank would be to utilize an array of temperature sensors at various vertical positions.

Building Thermal Storage

The contents and structural components of a modern office building represent a potential for energy storage that is largely ignored within current control practices. However, it is possible to shift a significant portion of a building's on-peak cooling requirements to off-peak periods through precooking of its thermal mass. In addition, adjustment of building temperatures within the comfort region during on-peak periods can limit peak power demand. Whether load shifting and demand limiting results in significant operating cost savings depends upon both the method of control and the specific application.

Figure 8 shows an example of how the building temperature might vary throughout a day when using building thermal mass for storage as compared with conventional night setback control. At the onset of occupancy (or high electric rates), the zone temperature is at or near the lower limit of the comfort zone due to precooking throughout the previous night and morning. Over the course of the occupied period, the space temperature setpoint is adjusted upward to reach the upper comfort limit prior to the end of occupancy. At the end of the occupied cycle, the equipment turns off and the zone temperature floats above the upper comfort limit. At some point during the night (depending on ambient conditions, plant characteristics, and utility rate structure), the equipment (either mechanical or "free" cooling) turns on to precool the building. Conversely, with a conventional night setback control strategy, the zone temperature is commonly maintained at the upper limit of the comfort zone during the occupied period and floats freely with the equipment off during unoccupied times until the last possible time when the equipment can bring the zone to the upper setpoint at occupancy.

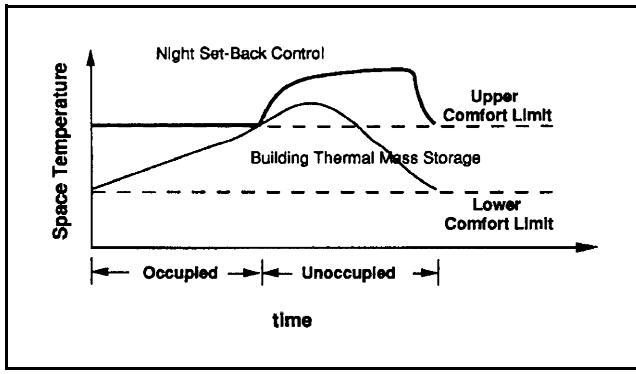

Figure 8. Example Control of Building Thermal Mass Storage

The potential for storing thermal energy within the structure and furnishings of conventional commercial buildings is large compared to the load requirements. A ten-degree change in temperature for a concrete floor in a typical commercial building represents approximately one-half of the cooling energy requirements for the design day. Typically, concrete floors represent about 60% of the available storage in a commercial building.

A recent study by Braun (1990) showed that cooling system operating costs can be reduced by as much as 40% through optimal control of the intrinsic thermal storage within building structures. Other simulation studies by Snyder and Newell (1990) and Andresen and Brandemuehl (1992) have shown similar results. The opportunities for load shifting and peak reduction were also demonstrated through experiments performed by Morris and Braun (1994) at a test facility located at the National Institute of Standards and Technology (NIST). In all of these studies, no special provisions were taken to enhance the heat transfer between the air and thermal mass.

There are both advantages and disadvantages in the use of building thermal storage as compared with ice or chilled water. One of the primary advantages is that many existing buildings would not require major capital retrofits in order to realize savings. Even in the absence of time-of-day or demand charges, effective use of building thermal mass can reduce energy costs. In many situations, the mechanical cooling requirements of a building can be reduced by the use of cool nighttime air for ventilation precooking. This is particularly true for clear, dry climates that have large diurnal temperature variations.

One of the main drawbacks of building precooking is that there is an increase in the total cooling requirement as compared with conventional control. With conventional night setback control and "optimal" start, the zone temperature is allowed to rise during unoccupied times. The goal is to minimize the overall cooling requirements. Precooking lowers the zone temperature during unoccupied periods, increasing the energy gains to the space. If the control strategy is not carefully chosen, overall operating costs can actually increase with precooking. Another factor to consider with precooking is the impact on human comfort.

Storage Heat Exchanger Requirements

For a conventional building, energy transfer to or from the building mass is accomplished by convection between the surfaces and air in the building. Although the temperature differences are small, the exposed surface area is very large. Even with carpeted surfaces, previous studies have demonstrated that the rate at which energy can be transferred is sufficient to allow significant load shifting and energy cost reductions.

For a new building, heat exchangers can be incorporated in the building floor to provide more effective precooking (Andersson et al. 1979; Marseille et al. 1989). Compared to a conventional building, the floor mass can be precooled to a lower temperature with less effect on the zone conditions. This results in lower total cooling requirements and less impact on human comfort.

Cooling System Requirements and Efficiencies

The operating temperature for building materials acting as a storage medium is between about 65 and 75°F. This is significantly higher than the operating temperatures for ice or chilled water. One of the advantages of the higher operating temperature is that it allows the use of cool outside air for "charging" thermal storage. Even with mechanical precooking, the efficiency of the mechanical cooling equipment is not penalized as a result of the storage operating temperature.

Storage Efficiency

Unlike ice or chilled water, storage efficiencies for building thermal storage can be significantly less than 100%. As previously discussed, building precooking causes an increase in the energy gains to the building. Thus, not all of the precooking energy reduces the on-peak cooling requirements. Although the operating temperature is relatively high, the surface area exposed to the environment can be very large. Depending upon the building and method of control, the storage efficiency could be as low as 50%. In particular, storage efficiency depends upon the timing of the charging and discharging. If most of the building precooking occurs just prior to the discharge (i.e., occupancy), then the storage efficiency can approach 100%. As the precooking period moves further away from the period when this cooling could be recovered, then the efficiency can drop dramatically. Storage efficiency also improves as the storage discharge period is moved closer to the charging period. This is accomplished by setting the thermostat to the upper comfort limit at the beginning of the on-peak period.

Control Requirements

It is difficult to control the charging and discharging of the thermal mass to ensure cost savings for a particular building. In fact, improper building precooking can result in significantly higher operating costs as compared with night setback control. Although there is ongoing research in the control of building thermal storage, no general control method currently exists.

In order to have an effective control method, the load shifting benefits must be balanced against the increase in total cooling requirement that occurs with precooking of the thermal mass. As a result of these tradeoffs, Braun (1990) found that the cost savings are very sensitive to both the control method and several design and operating characteristics, including utility rates, cooling system part-load characteristics, weather, occupancy schedule, and building construction. Even without time-of-day utility prices, this study showed a large benefit associated with effective utilization of building thermal storage for many situations.

One of the most important conclusions that can be drawn from previous simulation studies is that appropriate methods for controlling building thermal storage and the associated cost savings as compared with conventional control are very sensitive to the application and operating conditions. Some previously documented experimental studies in buildings did not include sufficient preliminary analysis to identify a) whether the system was a good candidate for effective utilization of building thermal mass and b) an effective method for control. As a result, the conclusions from these studies were not as positive as might have been expected.

Ruud et al. (1990) evaluated the effect of precooking on the on-peak cooling requirements for an existing building. The results showed only a 10% reduction in the cooling energy required during the occupied period with a substantial increase in the total cooling required and no reduction in the peak cooling requirement. The primary reasons for the poor results were attributed to the building not being a good candidate for effective utilization of building thermal mass. The building construction was such that there was a relatively small amount of thermal mass, a weak heat transfer coupling between the thermal mass and the internal air space, and a strong heat transfer coupling to the external ambient conditions. Furthermore, the control was not optimized for this application. However, the optimal control for this application may well have been conventional night setback control.

Conniff (1991) performed experiments using a laboratory test facility in which the structure was designed to represent a thermal zone within a multi-story building. External boundary conditions for the floor, ceiling, and walls could be controlled independently. The structure was of relatively lightweight construction, having a 2-inch concrete floor, suspended ceiling, and gypsum walls. The floor was carpeted and there were no special provisions for coupling to the thermal mass. The purpose of the study was to investigate the effect of alternative control procedures on the peak air conditioning load. The strategies that were investigated resulted in less than a 3% reduction in the peak cooling load. However, the strategies were not optimized for the facility.

Recently, Morris and Braun (1994) devised and performed a set of experiments at the same facility that Conniff utilized in order to demonstrate the potential for load shifting and load leveling when the control is optimized. In order to determine the control strategy to use in the experiments, optimization routines were applied to a simulation of the facility with the constraint that thermal comfort must be maintained during the occupied period. Control strategies determined in this manner were implemented in the facility and compared with night setback control.

Morris demonstrated that for a representative day approximately 40% of the daytime cooling requirement could be shifted from the occupied period to the unoccupied period. Depending upon the cooling system and utility rates, this could result in energy cost savings of up to 30%. In addition, Morris showed that the peak cooling demand could be reduced by about 40% through optimal control of building thermal storage. Comfort conditions were also monitored for the tests at NIST. Overall, the comfort conditions during the occupied period were well within acceptable comfort limits.

The contradictory results of Morris and Conniff for the same test facility emphasize the importance of developing a control strategy that is specific to the application. Coniff's results were not nearly as encouraging as those of Morris for the same test facility because the control was not optimized. There is a need to develop control methods and application guidelines for effective use of building thermal storage. Clearly, there is a great potential associated with effective use of the thermal storage in buildings. However, there is also potential for misuse of thermal mass that could lead to increased operating costs as compared with conventional night setback control.

One of the more effective methods for precooking a building involves the use of "free" cool night air to reduce cooling requirements for the next day. In reality, the use of outside air is not free, since energy is required to operate the air-handling fans. Precooking with outside air should only be considered if (1) heating is not required during the occupancy period, (2) the humidity of the ambient air is lower than an acceptable comfort limit, and (3) the cost of operating air-handling fans is less than the reduction in operating costs associated with mechanical cooling during the occupied period. Depending on the cooling requirements and equipment design, precooking with outside air is usually advantageous when the temperature difference between the zones and the ambient air is greater than about 10°F.

Summary

This paper has presented an overview of ice, chilled water, and building thermal mass for cool storage in commercial buildings. Several criteria have driven the development and application of these 3 storage types including:

1. **Storage Material and Enclosure Costs:** The costs of the storage material used for ice and chilled water storage are insignificant compared to other costs. This is also true for building thermal storage, if the choice of materials for the building is not altered to accommodate energy storage. Low material cost is the principal reason why ice, chilled water, and building thermal mass are most often considered for thermal storage over other possibilities. Ice storage requires a much smaller enclosure than chilled water storage due to its higher energy storage density. Smaller space requirements for ice storage is one of the principal advantages of ice over chilled water storage.

2. **Storage Heat Exchanger Requirements:** Ice storage systems require specialized heat exchanger equipment to handle ice making and melting. Concern over cost and reliability has driven the development of many different ice storage heat exchanger concepts. On the

other hand, chilled water storage tanks do not require any special heat exchangers. Energy transfer rates to and from storage are enhanced through thermal stratification. Care must be taken in the design of diffusers to avoid mixing. Heat transfer to or from building thermal mass can be accomplished through its natural coupling to the room air. At a greater initial cost, in-floor heat exchangers can be used to cool the thermal mass with chilled water or air as the working fluid.

3. **Storage Efficiency:** Well-insulated ice and chilled water storage tanks will have high storage efficiencies. Merten et al. (1989) reported storage efficiencies greater than 90% for tanks that were properly installed and operated. For building thermal storage, storage efficiencies can be significantly less because of the large area exposed to the external ambient. In fact, the extra energy gains associated with building pre-cooking can more than offset potential benefits if not properly controlled.

4. **Cooling System Requirements and Efficiency:** Chillers for ice storage systems operate at lower temperatures than those for chilled water or building thermal mass storage. This leads to more expensive chillers that operate with lower efficiencies. However, the use of cold air distribution allows downsizing of ducts and fans and reduces distribution energy requirements. In many cases, the savings can compensate for the increased chiller energy use and cost. Both chilled water and building thermal mass storage utilize conventional chillers whose performance is not penalized as a result of the operating temperature. Building thermal storage has the added advantage that nighttime ventilation can be used in many situations to reduce daytime chiller cooling requirements.

5. **Control Requirements:** “Chiller-Priority” control is a very straightforward method for controlling partial storage systems that incorporate ice or chilled water. However, both energy and demand costs can be reduced through the use of “storage-priority” control methods. Storage-priority methods require the use of a forecaster and a measure of the state of charge of storage. The added complexity and cost has discouraged widespread implementation of storage-priority control for ice and chilled water storage. The complexity of the control necessary for effective use of building thermal mass has not yet been established. It has been shown that simulations can be used to develop a site-specific control strategy for use of building thermal storage. However, this is probably not a practical approach for wide-spread implementation.

Each type of storage technique has advantages and disadvantages with respect to initial and operating costs. The fact that chilled water storage systems use conventional chiller equipment often make them a better choice than ice storage for retrofits. In new construction, chilled water storage may be more cost effective than ice storage in large buildings (e.g., greater than 500,000 square feet) as a result of economies of scale. For smaller buildings, ice storage is normally more cost effective due to lower tank and engineering costs.

If adequate control methods existed, then building thermal storage would be a natural retrofit for existing buildings. However, improper control of building thermal storage can actually increase operating costs over conventional control methods. More research and development is necessary before building thermal storage is a viable alternative to ice and chilled water.

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