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How Much Ice?

Simple Idea

Conceptually, ice storage systems are quite simple. The basic idea is to build a supply of ice when the energy rates are lowest and use the same ice supply when the rates are high. There is nothing terribly complicated about this idea.

Complexity erupts when we attempt to make all the engineering decisions needed to design a refrigeration system to accomplish this simple purpose. One such decision responds to the questions "How much ice should I plan to store?"

The answer, as usual, is "That depends." Mostly, it depends on the detailed objectives of the system. Given that the primary goal of an ice storage system is to save money, we have a starting point. Complexity and possible confusion occur when this goal is not kept foremost in our minds during the engineering process.

Complex Solution

The strategies of ice storage systems aim to save operating expenses with a system that probably is going to cost more to build. Thus, in deciding "how much ice," we need to understand the economics of various options as well as their technical characteristics. Starting from ground zero, a gigantic spreadsheet of all the possibilities would be desirable. But, we are not starting from ground zero on every project. A considerable body of knowledge, based on experience, is in place. We can use this knowledge to trim the number of possibilities.

For example, we know that partial storage systems usually provide a better return on invested capital than full storage systems. Since capital is limited on most projects, partial storage is most often preferred by owners. . . more bang for the buck. "How much ice" for full storage? The answer is the entire ton-hours peak daily cooling load. For partial storage, "how much ice?" could decrease to as little as one third to one quarter of the daily cooling load. A significant difference in cost.

Partial storage systems strike an apparent optimum when the required on-peak chiller capacity and the nominal capacity required to refreeze the ice tanks are matched. This allows the minimum installed chiller capacity. While this appears to be a simple matter of "numbers matching," the various kinds of available chillers impact the designers ability to achieve perfect balance. Consequently, there is often false savings associated with using only this method to minimize chiller capacity. In addition, the chiller has the lowest cost per ton of any primary component in the thermal storage system. Thus, its size does not necessarily control system cost.

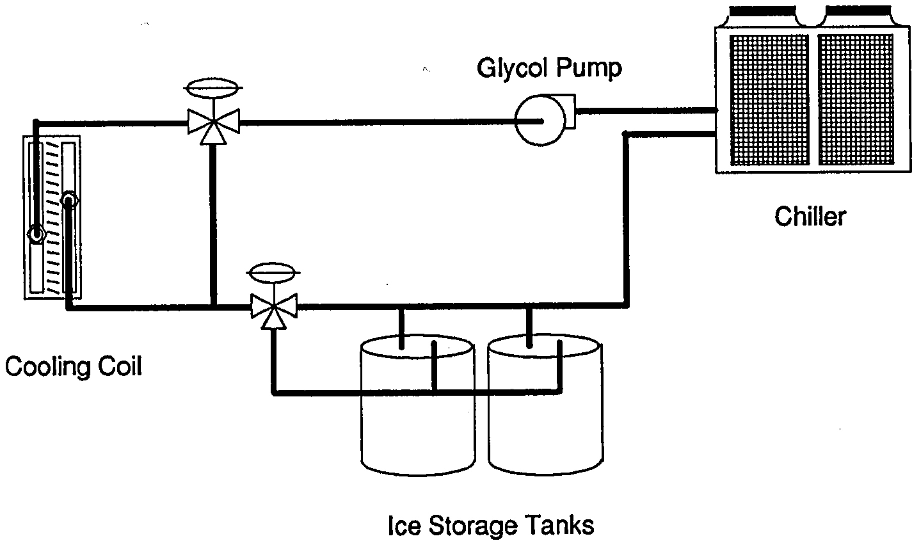

Figure 1: Ice Storage System

In addition to the **economic** balance of ice storage and cost, there must exist **system** balance between the ice and other components of the storage system. Systems that fail to achieve system balance also fail to maximize the economic returns and may also suffer control and operational problems.

The Basics

A comfort cooling system that employs ice storage is comprised of four basic components: air handling unit (cooling coil), packaged chiller, ice storage tanks and heat transport system (glycol loop), Figure 1. The glycol loop is used to transport cooling from the chiller (producer) to the cooling coil (consumer). The ice storage tanks are both consumers and producers. They are producers when ice is melted (discharging) and they become consumers when ice is produced (charging).

System performance is determined by the balance point of these components. Specifically, with ice storage systems, the balance point is critically affected by the performance of the heat transfer surfaces within the ice storage tanks.

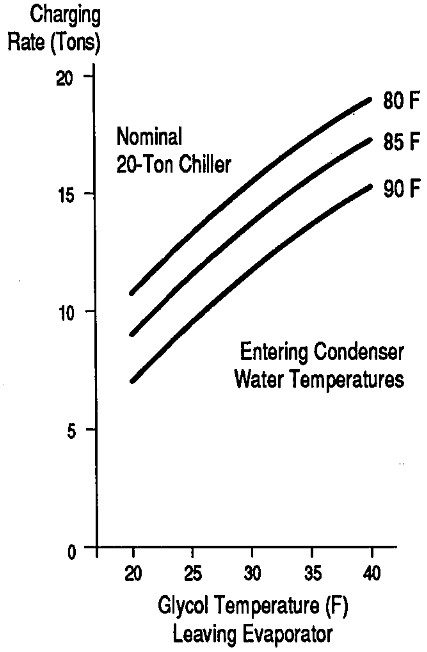

Figure 2: Chiller Capacity

The performance of chillers using positive displacement compressors (reciprocating, scroll, helirotor) bear similarities to each other. Figure 2 shows a typical performance curve, plotting capacity versus supply glycol temperature. Notice the "family" of curves at various condenser water supply temperatures. Within normal operating parameters, these types of chillers will always produce some capacity, regardless of the condenser water supply temperature; even at very low leaving glycol temperatures.

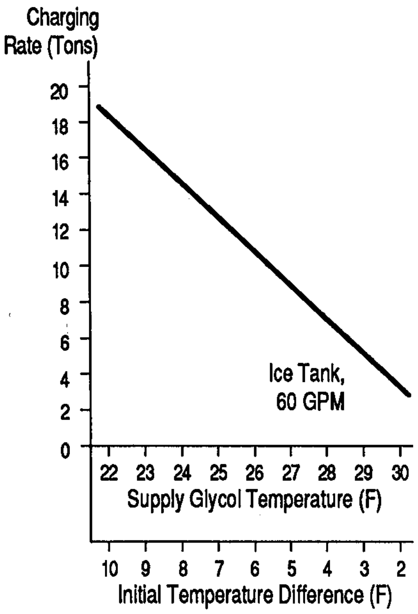

Figure 3: Tank Capacity

Figure 3 illustrates the influence of entering glycol temperature on ice storage tank charge rate. Notice that the charge rate is directly proportional to the **initial temperature difference.** The initial temperature difference or ITD of an ice storage tank is the freezing point of water (32 F) minus the tank inlet temperature during the charging cycle.

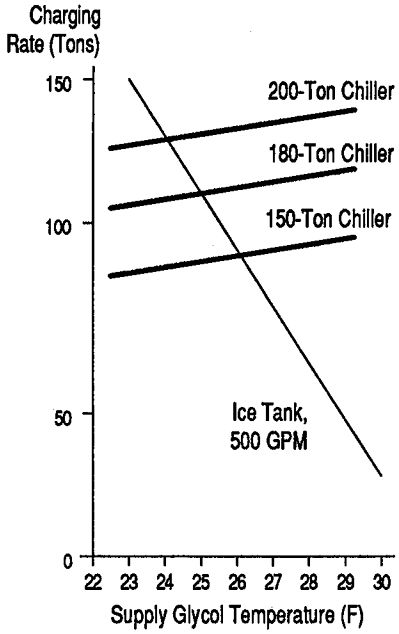

Figure 4: Matched Capacity

Figure 4 illustrates the influence of leaving evaporator fluid temperature on chiller capacity for nominal 150 ton, 180 ton and 200 ton air-cooled chillers employing reciprocating compressors. This figure also details the capacity of a 500 gpm ice storage vessel as a function of leaving evaporator fluid temperature. Notice that heat transfer at the ice storage tanks has increased to match the capacity of each chiller without an increase in surface area or an increase in glycol mass flow rate. This is accomplished by increasing the log mean temperature difference at the ice storage tank heat exchanger.

Heat transfer in the ice storage tank is defined by the equation $Q = U\,A\,DT_{lm}$.

Q = heat transfer rate (Btuh)
A = heat transfer surface area (ft^2)
U = "U" value (Btu/hr ft^2 °F)
DT_{lm} = log mean temperature difference (°F)
= $(DT2 - DT1)/Ln(DT2/DT1)$
$DT2$ = 32 - tank inlet temperature
$DT1$ = 32 - tank outlet temperature

Any increase in the heat transfer rate must be obtained by increasing one or more of the components on the right side of the equation. One way to increase heat transfer is to increase the surface area of the ice storage by adding ice storage trays or spheres in bulk storage systems, or by increasing the number of storage tanks in modular storage systems. An obvious disadvantage of this approach is cost. If the surface area required for balance with the chiller exceeds the quantity of ice storage that can be economically justified, the ice storage system fails economically.

Alternately, the heat transfer rate can be increased by increasing the mass flow rate of glycol. Increasing glycol velocity in the ice storage vessel provides two immediate benefits. First, the increased velocity improves heat transfer by reducing fouling on the glycol side of the heat transfer surface. Second, increasing the gpm reduces the fluid delta-T. A lower glycol delta-T allows a lower glycol temperature leaving the ice storage vessel. This increases the DT_{lm} and increases heat transfer proportionately. However, this increased heat transfer comes at the expense of greatly increased pumping horsepower. Not only is the mass flow rate increased, but resistances to flow increases as the square of velocity.

Perhaps the simplest method of increasing heat transfer rate of the ice storage vessel is to increase DT_{lm} directly by increasing the ITD. This requires lower leaving glycol temperatures from the chiller. The DT_{lm} is a function of tank inlet and outlet temperatures and the freezing point of water (32F). Table 1 summarizes the balance obtained by the ice storage system and each of the three chillers.

Table 1

Chiller nominal capacity	150	180	200	tons
Tank inlet temperature	26	25	24 F	
Glycol gpm	500	500	500	gpm
Charge rate	98	115	131	tons
Charge time	16.8	14.4	12.6	hours
Temperature rise	5.00	5.84	6.68	F
gpm/ton	5.1	4.3	3.8	gpm
gpm/nominal ton	3.3	2.8	2.5	gpm

Notice that lower charge temperatures not only increase charge rate and shorten charge time, but match system flow to a more normal flow rate for chillers. System balance. While reducing charge temperature increased tank heat transfer by over a third, chiller capacity is diminished by only two percent, Figure 4. Clearly system balance favors lower charge temperatures.

Up The Ante

System balance may be a little more difficult to achieve when centrifugal chillers are used. Unlike scroll, reciprocating or helirotor compressors, centrifugals are not positive displacement compressors. Centrifugal compressors are constant head, **variable volume** compressors. The mass flow rate in a centrifugal chiller is not guaranteed by the compressor, but determined by the rate of refrigerant evaporation in the evaporator. The refrigerant mass flow rate in a centrifugal chiller must be of sufficient quantity to support the head. Deficient mass flow can lead to surge. The problem is further compounded by refrigerant density. A cubic foot of refrigerant weighs 0.184 pounds at 40 F but weighs only 0.105 pounds at 15 F. Because refrigerant vapor leaving the evaporator of a chiller producing ice is less dense, the same volume of refrigerant presents less mass to the centrifugal compressor. Selection of the correct centrifugal compressor is key to the success of the ice storage system.

Fortunately, the system designer has a greater degree of latitude in the selection of centrifugal chillers. This is due to the ability to mix-match compressors and evaporators within a chiller line. There are also a number of heat transfer tube types and pass arrangements to choose from. The number of choices can be overwhelming. Again we can draw from previous experience.

Centrifugal chillers employed in ice storage systems tend to have larger evaporators. The increased heat transfer surface compensates for the lower heat transfer coefficients associated with glycol solutions. The best chiller selections maintain relatively high tube velocities to exploit higher heat transfer coefficients.

Balance of heat transfer and compressor capacity within the chiller is only part of the task. The heat transport rate between the chiller and ice storage tanks as well as heat transfer within the ice storage tank itself play key roles in the balance equation. There are many ways to increase the heat transfer rate in the ice storage tank to achieve system balance. These include increasing the mass flow rate, increasing the heat transfer area or increasing the log mean temperature difference. Almost without exception, the **affordable** route is to increase the log mean temperature difference by lowering the charge temperature.

As noted earlier, dropping the charge temperature by two degrees can increase the charge rate by over 30 percent while diminishing chiller capacity by only two percent. Any chiller employing a positive displacement compressor can trade that two percent capacity for lower leaving chilled fluid temperatures. Centrifugal chillers can also produce lower leaving fluid temperatures, but only if they are **selected** for lower temperatures.

The Solution

We can see that ice storage systems are more than "tinker toys," using simple combinations of conventional pieces of equipment. Instead, they are systems of interrelated heat transfer and refrigeration components. They are **engineered systems.**

Is it necessary to custom engineer every ice storage project? Probably not, if the designer is willing to think carefully about the objective of the system. Once this objective is defined, system engineering becomes more narrow and focused. Specific combinations of pre-engineered components are known to meet defined ice storage system goals. As we have seen, the pre-engineering process involves the same sort of thought process that manufacturers use to design chillers. A fairly wide variety of "packages" is available to meet different ice storage system performance goals.

The question: "How much ice?" The answer: "It depends."