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ABSTRACT

Integrated Thermal Energy Storage (ITES) is a novel concept in improving cooling performance of air-conditioning systems at peak-load conditions. In contrast to conventional chilled-water or ice storage, it uses stored chilled water to subcool condenser refrigerant liquid instead of supplying cooling directly to a cooling load. For typical R-134a and R-410A systems, subcooling increases capacity by approximately .5 to .7%/°F (~.9 to 1.3 %/K) without increasing compressor input power. Even larger performance improvements are possible with transcritical carbon dioxide systems. The subcooler is preferably a high-effectiveness, counterflow heat exchanger with approximately equal temperature change on both the water and refrigerant sides. This configuration allows warm water to return to the tank at a temperature that approaches the entering refrigerant liquid temperature. For air-cooled systems the water temperature change can be 60 to 80°F (33 to 44 K) or even greater. The large temperature change greatly reduces the required tank size compared to conventional chilled-water storage, which is typically limited to a temperature change of about 10 to 20°F (5 to 11 K). The high temperatures of warm water in the tank combined with lower nighttime air temperatures reduce energy required to cool the tank and improve overall system efficiency in addition to providing a large reduction in peak electric demand. Laboratory demonstration with a nominal 30-ton (105 kW) air-cooled scroll chiller confirmed large performance improvements during subcooler operation. At an ambient temperature of 115°F (46°C), the measured cooling capacity increased almost 50% with a slight reduction in compressor input power.

1. BACKGROUND

1.1 Chilled Water Storage Systems

Thermal energy storage offers the ability to store cooling at night in the form of ice or cold water. Conventional cold water storage is relatively straight-forward but requires very large tanks because of the low energy density. These systems have seen limited use in large district cooling plants, but the size and cost of the tank has discouraged more general use.

1.2 Ice Storage Systems

Ice has the advantage of high energy density, but making ice requires evaporating temperatures that are ~20°F (11 K) lower than those typically used for air-conditioning, which greatly reduces chiller capacity during ice-making operation. In addition, ice storage normally requires use of glycol in the building loop, which can create a substantial performance penalty for the chiller, pumps, coils, etc. even during daytime operation. Additional information about current thermal energy storage systems appears in the ASHRAE Handbook (ASHRAE 2012).

1.3 Economizer and Intercooler Cycles

In addition to acting to provide thermal energy storage, the ITES system reduces losses associated with flash gas. Commonly used conventional approaches to achieve a similar goal include economizers, multistage compressors with intercooling, etc. These systems cool refrigerant liquid in discrete steps that limit the available performance improvement. In addition, conventional economizers used with screw compressors and other positive displacement compressors use expansion of economizer gas into a compression chamber, which inherently introduces losses.

1.4 Other Cycles

Numerous variations of cycles have been suggested and appear in the literature (Minh *et al*., 2006). An interesting approach is the Granryd cycle and similar variations (Minh *et al*., 2006), which cool refrigerant liquid in a batch process. This approach allows the cycle to approximate an infinite number of economizer steps as the liquid temperature changes over time. On the other hand, the Granryd cycle requires rapid cycling between two modes of operation and/or extremely large charge quantities, which can cause operational issues and can increase system cost.

2. DESCRIPTION OF ITES

2.1 Example System

Figure 1 shows a schematic diagram of an example system (Kopko *et al.*, 2014). The basic idea is to use stored chilled water to subcool condenser refrigerant liquid instead of supplying cooling directly to a cooling load. The subcooler is located in the chiller refrigerant circuit between the condenser and the expansion valve and is connected in a water loop with a water tank and a subcooler pump. The subcooler is preferably a high-effectiveness, counterflow heat exchanger with approximately equal fluid temperature change on both the water and refrigerant sides. Typical construction is a brazed-plate heat exchanger. This configuration allows warm water to return to the tank at a temperature that approaches the entering refrigerant liquid temperature. For air-cooled systems the water temperature change can be 60 to 80°F (33 to 44 K) or even greater, which is several times the available temperature change for conventional chilled-water storage systems. Valves allow chilled water from the chiller to cool the tank at night or during other low-load conditions. The high temperatures of warm water in the tank combined with lower nighttime air temperatures reduce energy required to cool the tank and improve overall system efficiency in addition to shifting electric load.

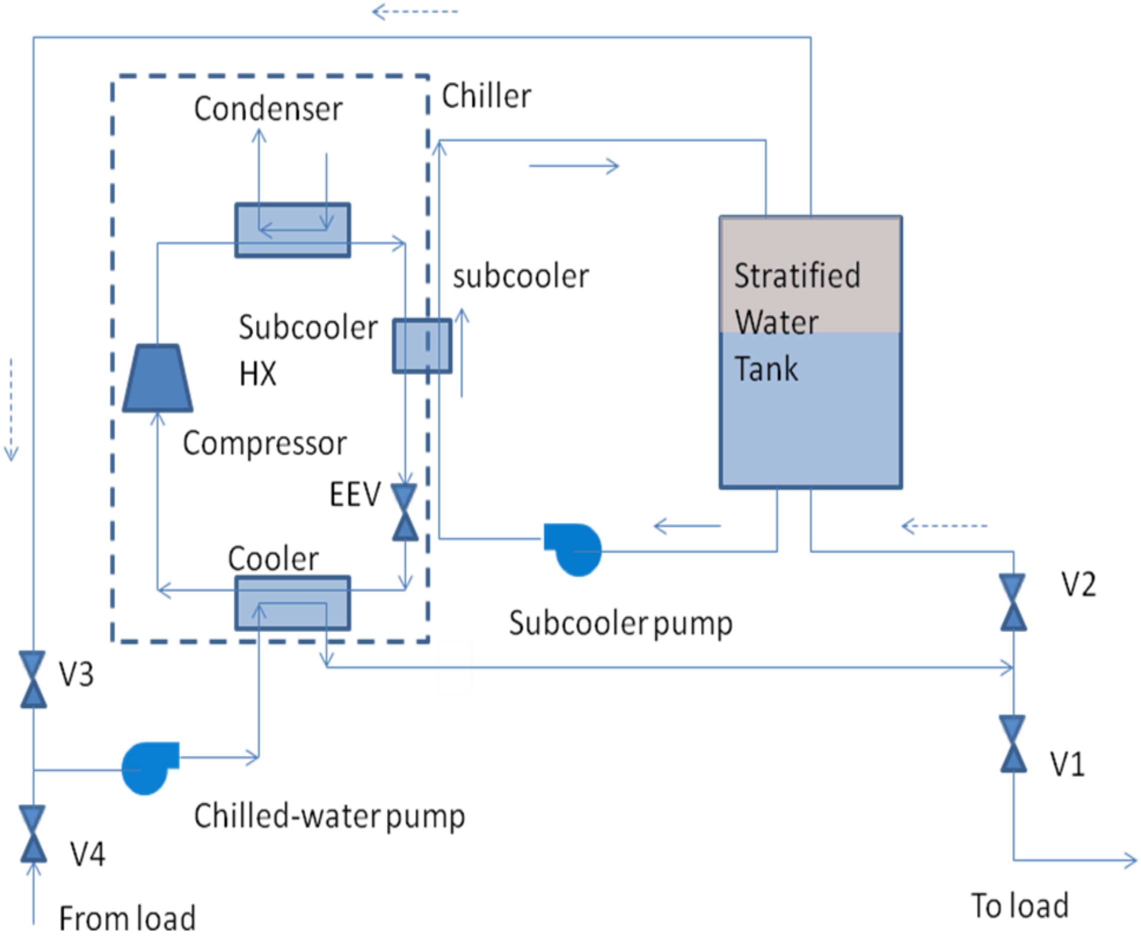

Figure 1: Example ITES configuration

2.2 Subcooling Mode of Operation

In subcooling mode (solid arrows in Figure 1), valves V1 and V4 are open and valves V2 and V3 are closed so that the chilled-water pump circulates water through the cooler to the building load. At the same time, the subcooler pump moves water from the bottom of the stratified tank through the subcooler and returns it to the top of the tank. This mode of operation allows for increased capacity and reduced electric demand during afternoon or other times of high load and/or high electric cost.

2.3 Tank-Recharge Mode

In tank-recharge mode (dashed arrows in Figure 1), the valves V1 and V4 are closed and valves V2 and V3 are open to direct water from the cooler to the water tank. The flow is many times higher than that for subcooling mode, and the water in the tank flows through the cooler several times as it is gradually cooled down. This mode allows the chiller to cool the water in the tank at night or other times of reduced load and/or low electric cost. Systems with multiple chillers are also possible and allow for simultaneous tank recharge and building cooling.

2.4 Conventional Cooling Without Subcooler

It is also possible to run the system to cool the load without operating the subcooler. In this case the valves are positioned to direct flow to the building. The subcooler pump is not operating, and the refrigerant flows through the subcooler with little or no cooling. This mode is suitable for operation in the morning or other times of moderate cooling load and/or moderate electric cost.

2.5 Tank Sizing

The tank size is greatly reduced compared to that required for conventional chilled water energy storage systems. For a tank sized for five hours of full-load operation with R-134a or R-410A, the required tank capacity is approximately 40 gallons per ton (40 liters/kW) of total design cooling capacity including the benefit of subcooler operation. While the tank is physically large compared to the size of a chiller, the ability to use a single large tank to service multiple chillers and/or the ability to locate the tank underground can provide a smaller overall footprint, especially in the case of large systems using dry towers or radiators at high ambient temperatures.

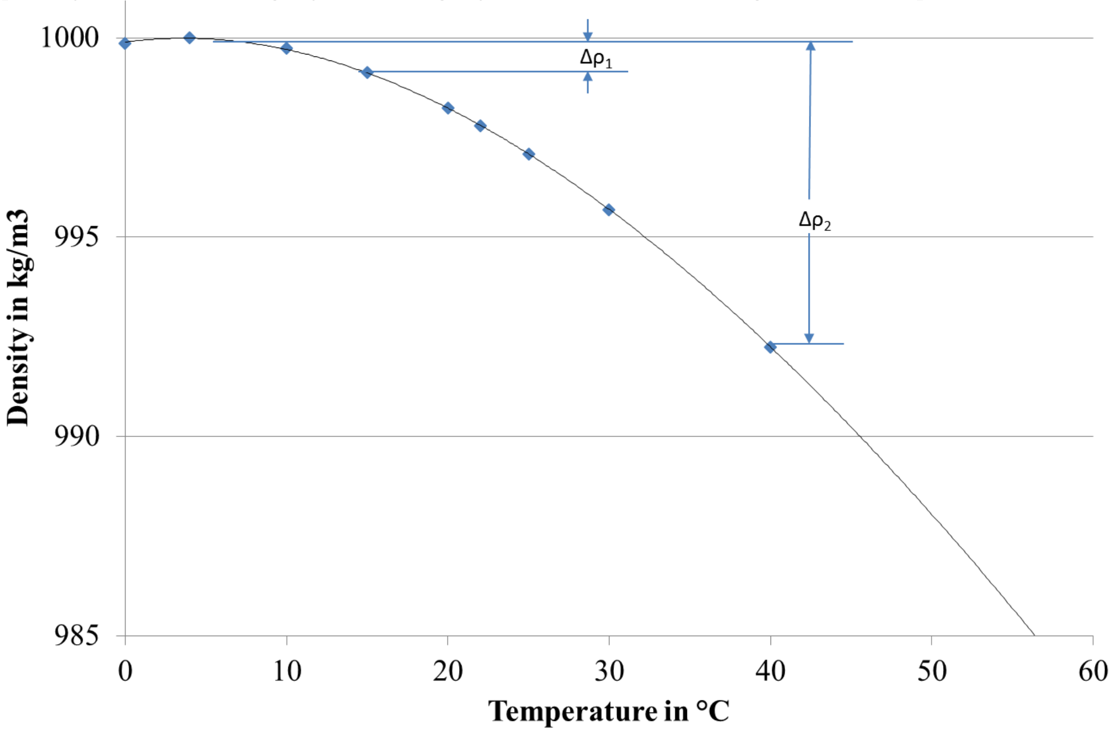

Figure 2: Water density change for ITES compared to conventional chilled-water storage

2.6 Tank Stratification

Stratification during subcooling operation is simplified because of the large density difference between the warm water entering the tank and cold water in the tank as shown in Figure 2. In conventional chilled-water storage, the density difference, $\Delta\rho_1$, is very small because of the smaller temperature difference and because the density of water changes little with temperature near the maximum density condition. On the other hand, ITES has a much higher entering tank temperature during subcooling operation, which gives a much larger density difference, $\Delta\rho_2$. While stratification is important during subcooler operation, perfect stratification during tank recharge mode is not vital since the much larger flows reduce the theoretical benefit.

3. THEORY OF OPERATION

3.1 Cycle Benefit from Subcooling

Figure 3 is a cycle diagram showing the benefit from subcooler operation. Subcooling increases the refrigeration effect by an amount equal to the change in refrigerant enthalpy, Δh, through the subcooler. The increased refrigeration effect gives a corresponding benefit in both cooling capacity and efficiency for given evaporating and condensing temperatures without increasing compressor work. In addition, energy absorbed by the subcooler goes into the tank, not the condenser, which means that there is no increase in condenser loading. In real life, the increased evaporator load results in a somewhat lower evaporating temperature, which can slightly reduce cooling capacity, compressor input power, and condenser loading. As shown in Figure 3, subcooling to near the evaporating temperature can greatly reduce or eliminate flash gas entering the evaporator.

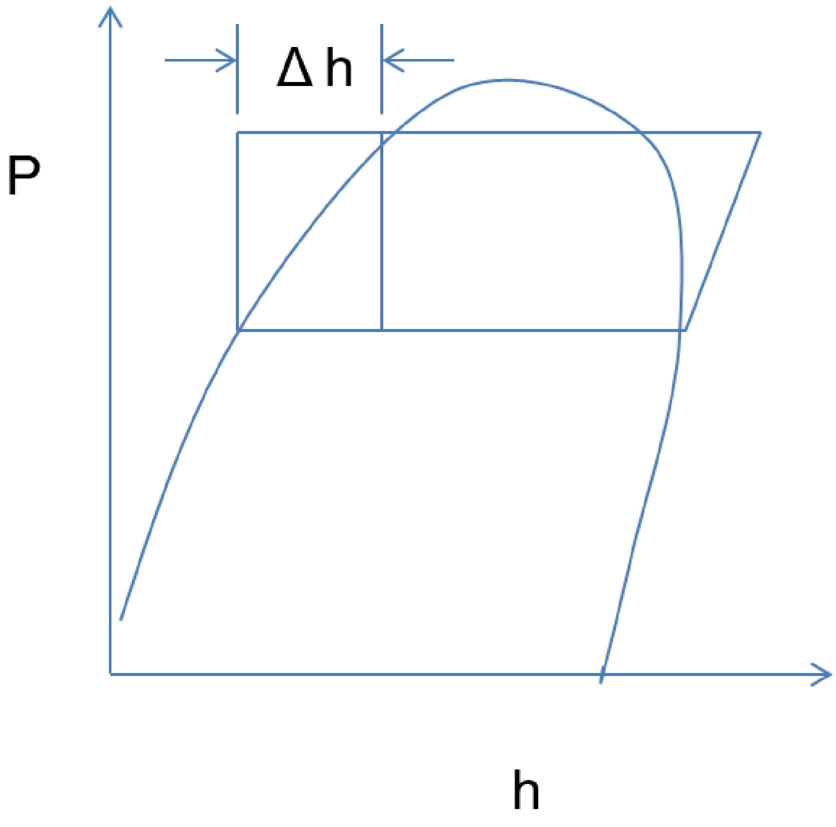

Figure 3: Cycle benefit from additional subcooling

3.2 Calculated Benefits of Subcooling

Figure 4 shows the cycle benefit from subcooling for R-134a, R-410A, and carbon dioxide (R-744) for various refrigerant liquid temperatures. The cycle calculations assume an evaporating temperature of 41°F (5°C) with no superheat at the compressor suction. The curve for carbon dioxide stops at the critical temperature, but similar or greater benefits should exist for transcritical operation. The refrigerant liquid temperature leaving the subcooler is assumed to be 50°F (10°C). Based on these assumptions, there is no change to the compressor work with subcooler operation, which means that the percentage improvements in efficiency and capacity if tank recharge is not considered.

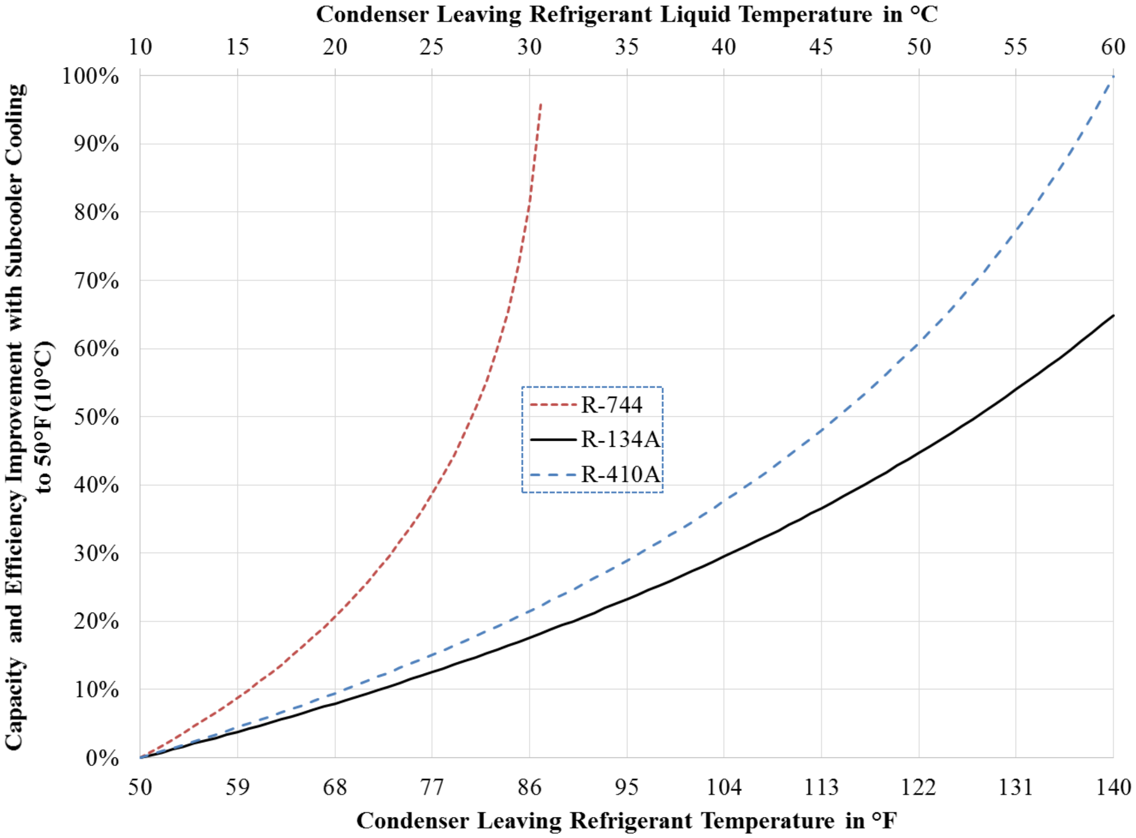

Figure 4: Capacity and Efficiency Benefit at Peak Conditions from Additional Subcooling

3.3 Tank-Recharge Cycle

Tank cooling effectively approximates an infinite number of stages of intercooling as the evaporating temperature drops gradually in response to lower tank temperatures. In this respect the tank cooling approximates the Granryd cycle without the need for a large refrigerant charge or refrigerant storage tanks. In addition, the cooling capacity during tank cooling can be substantially higher than the maximum capacity during conventional chilling. In cases where capacity during tank cooling is not important, limiting the capacity of the chiller can reduce energy use.

3.4 Calculated Tank-Cooling Performance

Tables 2 and 3 summarize the benefit for a water-cooled, variable-speed centrifugal chiller including the effect of tank recharge based on performance from chiller rating software. The assumed peak condition corresponds to AHRI design conditions. (Standard AHRI conditions are ambient air temperature = 95°F (35°C), entering water temperature = 54°F (12.2°C), and leaving chilled water temperature = 44°F (6.7°C).) The recharge assumes a fixed load of 150 tons (527 kW) with an entering condenser water temperature of 80°F (26.7°C). The assumed cooling capacity corresponds to an evaporator water temperature range of approximately 6°F (3.3 K). The tank temperature is assumed to start at a uniform value of 82°F (27.8°C) with a final tank temperature of 40°F (4.4°C). The entering evaporator water temperature is equal to the temperature at the top of a stratified tank, so the tabulated steps of 6°F (3.3°C) correspond to steps of equal cooling capacity. The equal step size means that the average RCOP (= 1/COP and expressed as kW/ton in English units) for the process is simply the average of the RCOP for each temperature step. The results show running the chiller to recharge the tank saves about 40% of the compressor energy compared to running the base chiller at peak conditions.

Table 2: Summary of ITES Benefits for a Variable-Speed Centrifugal Chiller

Base Unit:	
Design capacity	250 tons (879 kW)
RCOP	0.588 kW/ton (0.167)
COP	5.98
Unit with ITES:	
Design capacity	290 tons (1019 kW)
RCOP at peak	0.475 kW/ton (0.135)
RCOP with recharge	0.545 kW/ton (0.155)
COP at peak	7.40
COP with recharge	6.46

Table 3: Compressor Energy Required for Tank Cooling

Entering Evaporator Temperature	RCOP = 1/COP
82°F (27.8°C)	0.158 kW/ton (0.045)
76°F (24.4°C)	0.202 kW/ton (0.058)
70°F (21.1°C)	0.258 kW/ton (0.073)
64°F (17.8°C)	0.324 kW/ton (0.092)
58°F (14.4°C)	0.400 kW/ton (0.114)
52°F (11.1°C)	0.487 kW/ton (0.139)
46°F (7.8°C)	0.585 kW/ton (0.166)
Average RCOP	0.345 kW/ton (0.098)
Corresponding COP	10.20

3.5 Potential for Free Cooling

Free cooling is another option for cooling the tank, especially for high-ambient, air-cooled applications. In desert climates there can be an average daily temperature range of 30 to 40°F (17 to 22 K) or more, which creates the possibility of using nighttime free-cooling to provide a substantial portion of the required tank cooling.

3.6 Effect of Extreme Ambient Temperatures

ITES has a unique feature in that the performance benefit and stored cooling capacity actually increase during heat-wave conditions. Higher ambient temperatures result in higher condenser refrigerant-liquid temperatures, which increase the benefit from subcooling as shown in Figure 4. In addition, the higher refrigerant-liquid temperature raises the temperature of water leaving the subcooler, which increases the energy storage capacity of the tank. This feature may be especially valuable to utilities since extreme heat-wave conditions closely correspond to conditions that set peak summer electric demand.

4. LABORATORY DEMONSTRATION

4.1 System Description

Figure 5 is a photo of a demonstration setup for a nominal 30-ton (105 kW) single-circuit, R-410A, air-cooled scroll chiller with a York model designation of YCAL0033. A plate heat exchanger with a small circulating pump was added to serve as the subcooler. Two plastic water tanks were used to store chilled water. The water in the tanks and subcooler circuit is near atmospheric pressure, which allowed for the use of inexpensive plastic water piping.

Figure 5: Photo of Demonstration System

4.2 Test Results

Table 4 is a summary of the test results of operation at full-load conditions at 95 and 115°F (35 and 46°C) ambient temperature. The leaving evaporator water temperature was 44°F (6.7°C) for the tests. Water flow was adjusted to maintain an evaporator temperature difference of 10°F (5.6 K). Increased cooling capacity resulted in a somewhat lower evaporating temperature, which gave a small reduction in compressor input power. Testing confirmed stratification of the tanks using a conventional pipe connection and confirmed pressure isolation using the valve setup in Figure 1. The test results agree well with the theoretical cycle advantage shown in Figure 4.

Table 4: Summary of Test Results

	Base	ITES	Change	% Change
At 95°F (35°C) ambient temperature:				
Capacity	27.8 tons (97.8 kW)	35.6 tons (125.2 kW)	7.8 tons (27.4 kW)	**28%**
Power input	32 kW	31.4 kW	-0.6 kW	**-2%**
COP	3.06	3.99	0.93	**30%**
Calculated input power at ITES capacity	40.9 KW	31.4 kW	9.5 KW	**-23%**
At 115°F (46°C) ambient temperature:				
Capacity	23.5 tons (82.6 kW)	34.9 tons (122.7 kW)	11.4 tons (40.1 kW)	**49%**
Power input	38.4 kW	37.5 kW	-0.9 kW	**-2%**
COP	2.08	3.18	1.1	**53%**
Calculated input power at ITES capacity	59 kW	37.5 kW	21.5 kW	**-36%**

4.3 Peak Demand Reduction

The last row of Table 4 summarizes the potential electric demand reduction from ITES compared to a larger chiller running without ITES. The calculated base input power is simply the measured ITES capacity divided by the measured base COP. Subtracting the calculated base input power from the measured ITES input power gives the demand reduction at the ITES capacity.

5. ECONOMICS

5.1 Incentives for Demand Reduction

Utilities in the United States frequently offer incentives for thermal energy storage and other technologies that reduce summer peak electric demand. In California, several utilities are offering rebates up to 875 US$/kW (Southern California Edison, 2015) and Con Edison (2016) in New York has been offering rebates of up to 2600 US$/kW of demand reduction. For the California case, tested ITES system would qualify for a rebate of as much as $18800 for a design ambient of 115°F (46°C). Demand incentives usually include a cap based on some fraction of the installed cost (typically 50%), so the maximum incentive may not be available in some cases.

5.2 Value of Capacity Improvement

The value additional cooling capacity provided by ITES depends on the particular installation. For an existing installation, the value of extra capacity may be very low if additional cooling capacity is not needed. In new installations or in retrofits that require more cooling capacity, the value corresponds to the incremental cost of increasing the capacity of a base system, which is typically in the range of $500 to $1000/ton (150 to 300 US$/kW) or more including installation. For the 115°F (46°C) ambient condition, the ITES would amount to a value of $5700 to $11400 or more.

5.3 Energy Cost Savings

The ITES saves energy cost through reduced electric demand charges, shifting load to lower cost times of day, and reduced total energy use. In general, the benefits from reduced demand charges dominate the energy cost savings, but the saving related to time-of-day charges and lower overall energy use are also important. The energy savings and shift in electric demand can also provide environmental benefits that are not normally included in the cost of electricity.

5.4 Tanks and Piping Costs

Commercially available tanks have a retail price of approximately 1 US$/gallon (~.25 US$/liter). For the test unit the approximate tank size should be 1400 gallons (5300 liters) with a cost of about US$1400 or about 40 US$/ton (11 US$/kW) of the total chiller capacity during subcooler operation. The tank cost based on incremental capacity from ITES depends on the design conditions and ranges between $180 and $120/ton (50 to 35 US$/kW), which is much smaller than the cost of installing new chiller capacity. Additional components include the subcooler heat exchanger(s), subcooler pump(s), tank insulation, piping, etc., and have combined material cost that is comparable to that of the tank for smaller systems.

5.5 Overall Economics

Overall economics depend greatly on many factors which are beyond the scope of this paper, but the ITES should make economic sense in many applications. It may give lower installed cost than conventional systems without thermal energy storage in some cases, especially in high-ambient air-cooled applications and in cases where there are large utility incentives. A big variable is installation cost which is highly variable and depends on details for the particular location. For smaller systems, much of the system can be factory-assembled, which can greatly reduce field labor and engineering costs.

6. CONCLUSION

Integrated Thermal Energy Storage (ITES) appears to be a promising approach for reducing peak electric demand while improving overall system performance. ITES uses stored chilled water to provide subcooling to a refrigeration system. In contrast to conventional chilled-water storage systems, ITES has a much larger available water-temperature difference because warm water entering the tank can approach the refrigerant liquid temperature leaving the condenser. In addition, high tank temperatures also help to reduce energy required for tank cooling, help to promote tank stratification, and allow for increased system performance at extreme ambient temperatures.

NOMENCLATURE

h	Enthalpy	(Btu/lbm or kJ/kg)
Δh	Change in enthalpy	(Btu/lbm or kJ/kg)
P	Pressure	(psia or MPa)
COP	Coefficient of Performance	(dimensionless)
RCOP	Reciprocal COP = 1/COP	(kw/ton or dimensionless)
$\Delta\rho_1$	Density change of water for conventional chilled water storage	(kg/m^3)
$\Delta\rho_2$	Density change of water for ITES	(kg/m^3)

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