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Integrated Thermal Energy Storage for Cooling Applications

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Integrated Thermal Energy Storage for Cooling Applications

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ABSTRACT

Many commercial and industrial facilities are cooled using vapor compression cycles (VCC). The performance of such systems degrades with high outdoor temperatures causing high peak electric demand increase, reduced efficiency and lower cooling capacity. An Integrated Thermal Energy Storage System (ITESS) utilizing chilled water provides additional subcooling for a VCC condenser, thereby increasing the capacity of the entire system and providing significant reductions in electric demand and consumption. The ITESS uses a dedicated chiller to cool a thermal storage tank, typically at night when electricity demand and rates may be lower. This thermal reservoir is used during the following day to sub-cool refrigerant leaving the condenser. This additional cooling increases the overall cooling capacity of the chiller without increasing the electrical demand.

The following paper outlines the results of a demonstration of the ITESS at an industrial facility in Syracuse, NY. The existing 176-ton (615-kW) chiller, which provides cooling for air conditioning a laboratory space and chilled water for compressor testing, was retrofitted with a 33-ton (116-kW) supplemental chiller, 10,000-gallon (37,854-liter) water tank, four sub-coolers, and two sub-cooler pumps. The ITESS was instrumented with a number of sensors to measure critical parameters to assess its performance. The test results showed that the cooling capacity of the existing chiller increased by 2.2% - 34.2%, depending on operating conditions, with the addition of subcooling. The ITESS increased existing chiller efficiency between 0.6% - 28.5% and has the potential to reduce power demand by 0.7%-34.3%. Total energy consumption for the system was essentially unchanged, increasing on average by approximately 0.05%, well within the margin of error.

1. INTRODUCTION

Many commercial and industrial facilities are cooled using VCCs. The performance of such systems degrades with high outdoor temperatures causing high peak electric demand increase, reduced efficiency and lower cooling capacity. As the number of installed systems increases and the average summer outdoor temperatures rise, electricity consumption and peak demand requirements will become even greater challenges for the utility grid.

An ITESS utilizing chilled water could provide additional subcooling for a VCC condenser, thereby increasing the capacity of the entire system and providing significant reductions in electric demand and consumption. The ITESS uses a dedicated chiller to cool a thermal storage tank, typically at night when electricity demand and rates are lower. This thermal reservoir is used during the following day to sub-cool refrigerant leaving the condenser. This additional cooling increases the cooling capacity without increasing electrical demand with the greatest effectiveness on hot days. Unlike water storage systems where chilled water is used directly for air conditioning, the ITESS does not require as large a storage capacity. In contrast to ice storage systems, the chiller's evaporating temperature is higher, which improves performance when actively chilling the water. Furthermore, ITESS uses water instead of glycol, further reducing the system performance penalty and operational costs.

The following paper outlines the results of a demonstration of the ITESS, developed by Johnson Controls, Inc. (JCI), at the Bitzer plant in Syracuse, NY.

2. INTEGRATED THERMAL ENERGY STORAGE SYSTEM (ITESS)

Integrated Thermal Energy Storage (ITES) is a novel concept in improving cooling performance of air conditioning systems at peak-load conditions. Compared to other chilled-water thermal storage systems, ITES has a much larger available water temperature difference because the warm water returns to the tank at a temperature close to the refrigerant liquid temperature leaving the condenser. Furthermore, a high tank temperature reduces the amount of energy needed for tank cooling and improves system performance at high ambient temperatures. (Kopko et. al, 2014, Kopko, 2016). An existing chiller system used for demonstration purposes with the ITESS is illustrated in Figure 1. The existing chiller system at the Bitzer plant includes a 175-ton (615-kW) chiller, a 35% by volume Propylene-Glycol/Water (PGW) storage tank, and a constant speed circulation pump. The chiller includes two refrigerant circuits, one with two compressors and one with three compressors, to enable maximum flexibility through variable, part-load operation. The chiller is run, as needed, to maintain a desired set point temperature in the PGW tank. PGW solution from the tank is then circulated throughout the building to provide both space conditioning and meet cooling demands from the compressor test facility. Some long-term compressor tests are run 24 hours per day, 7 days per week. Thus, the chiller is continuously in operation to meet the cooling demand.

The existing configuration was retrofitted with a 33-ton (116-kW) supplemental chiller, 10,000-US gallon (37,854-liter) supplemental water tank, a total of four sub-coolers (plate heat exchangers), and two sub-cooler pumps for each of the existing chiller's refrigerant circuits. (Each refrigerant circuit has two sub-coolers connected in series.) The supplemental chiller operates during off-peak hours to chill water, which is stored in the supplemental water tank. During on-peak hours, chilled water from the tank is circulated through the added plate heat exchangers to sub-cool the refrigerant, providing a potential capacity and efficiency gain for the main chiller.

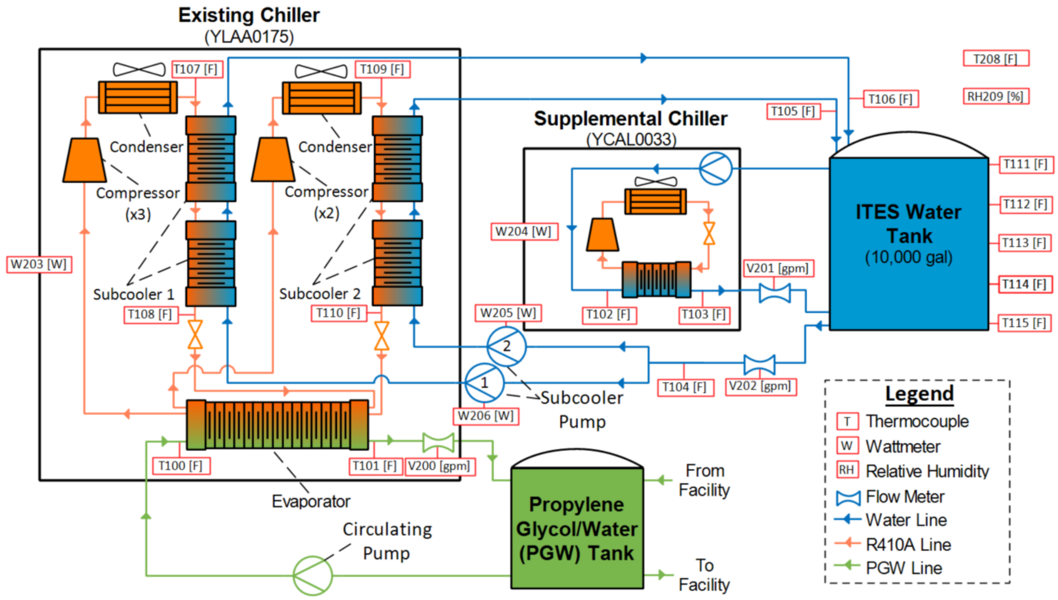

Figure 1: Schematic of Existing Chiller System with ITESS

3. SYSTEM INSTALLATION

3.1 ITESS Installation

The supplemental chiller and water storage tank, shown in Figure 2a, were installed on steel and wooden pads, respectively. The sub-cooler pumps were installed in a waterproof box to protect the pumps and the electronics from rain and direct sun light. Temperature sensors were inserted into the sub-cooler pipes to measure the water supply and return temperature. The sub-cooler pumps maintained a set differential temperature between two sensors, which allowed the system to maximize the cooling capacity of the water storage tank. The sub-cooler heat exchangers were attached to steel fixtures, as shown in Figure 2b and plumbed to the refrigeration lines of the existing chiller. CPVC pipes were installed to transfer cooling water between the storage tank the supplemental chiller and the storage tank and the sub-coolers. These pipes were left uninsulated, which ultimately resulted in losses in the system.

3.2 DAQ Installation

The measurement equipment depicted in Figure 1 was installed to collect data for the evaluation of the ITESS. Five thermocouple wires were attached to a CPVC pipe at equal distances, which was lowered into the water storage tank. To measure the water and PGW temperatures, seven thermocouple probes were inserted into pipes through drilled holes and sealed using compression fittings. A dual sensor attached to a support rail was used to measure the relative humidity and temperature of the ambient air. To measure the refrigerant inlet and outlet temperature at the sub-coolers, four thermocouple wires were directly attached to copper tubes using cable ties. These connections were also insulated. Three magnetic flow meters were inserted into the water and PGW pipes through pipe fittings (iron strap-on saddles) and mounted to them. Four watt-meters were installed to measure the power consumption of the existing chiller, supplemental chiller, and the sub-cooler pumps. The DAQ system, which consists of the DAQ chassis and modules, was installed in an electric enclosure as shown. The measurement devices were connected to the input modules. The output modules were connected to the chiller and sub-cooler pump contactors to turn them on and off. While the supplemental chiller was turned off automatically when the set temperature was reached, the chiller and sub-cooler pumps were turned off by using the contactors at a set time. The supplemental chiller pump, however, was not controlled using the same settings as the supplemental chiller itself. As such, the supplemental chiller pump often ran during times when it was not needed. This control deficiency led to unnecessary energy consumption and is an item to be noted for future improvement, as are the uninsulated pipes transferring cold water between the storage tank and sub-coolers.

Figure 2: ITESS: a) supplemental chiller and water storage tank; b) sub-cooler plate heat exchangers

4. DATA ANALYSIS

A detailed evaluation of the ITESS was conducted, including a comparison between the operational data collected for the proposed technology and the established baseline. The goal of the analysis was to compare the following parameters important to the overall performance of the cooling system: cooling capacity, peak power demand, existing chiller efficiency, and energy consumption. Data was collected every 30 seconds and averaged over a 24-hour period from 9 am to 9 am. This period, illustrated in Figure 3, included two baseline test periods (9 am to noon and 6 pm to 9 am), the subcooling period (noon to 6 pm), and the tank cooling period (9 pm to 3 am). In the baseline mode, the existing chiller operated without any additional subcooling. In the subcooling mode, the sub-cooler pump(s) moved chilled water from the tank through the sub-coolers. In the tank cooling mode, the supplemental chiller cooled down water in the tank and the existing chiller operated normally. On certain days, the subcooling period was extended beyond 6 pm to maximize utilization of the ITESS. The tank cooling period ended when the water inlet temperature to the supplemental chiller reached 44°F (6.7°C), which was often before 3 am. An example of daily data collected showing the change in cooling capacity due to the subcooling benefit is illustrated in Figure 4.

A pure baseline test period with only the existing chiller running was not established due to technical difficulties with the existing chiller at the beginning of the demonstration project. Alternately, baseline performance is dependent on both measured data for the baseline periods and calculated performance during the subcooling periods. Baseline performance during the subcooling periods is calculated using an efficiency curve dependent on the ambient temperature. This curve was derived using measured data of the existing chiller and applied to estimate existing chiller power consumption without additional subcooling.

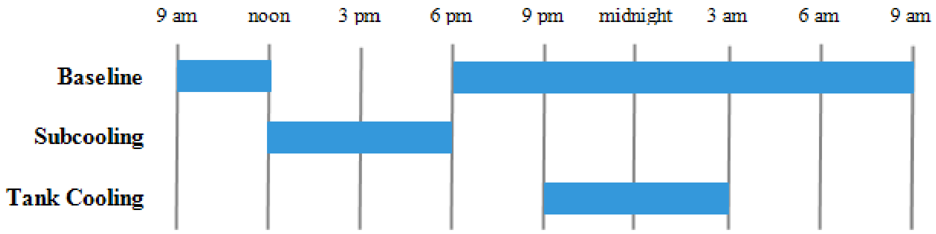

Figure 3: Testing periods

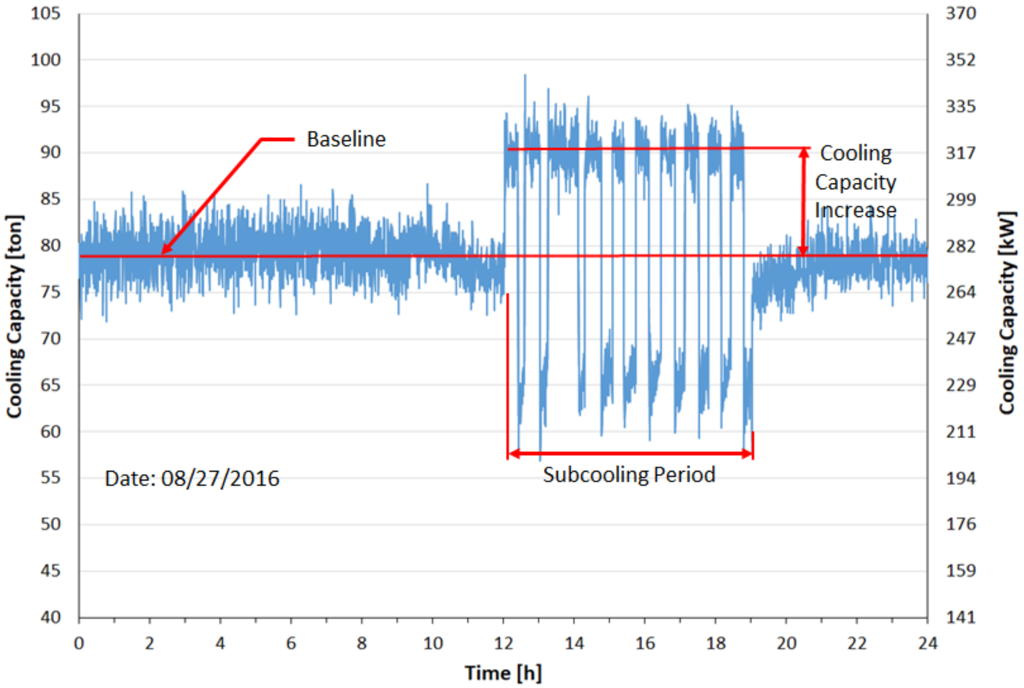

Figure 4: Measured existing chiller cooling capacity, daily test results for August 27, 2016

The net cooling capacity [Btu/h; kW_c] for the existing chiller was calculated using the PGW temperatures, PGW flow rate and PGW properties for the evaporator entering and leaving conditions, per Equation (1).

$$q_{ExCh.base} \ and \ q_{ExCh.sb} = K2 \cdot \rho \cdot V \cdot c_p \cdot (T_e - T_l) \tag{1}$$

Assuming that the additional cooling capacity [Btu/h; kW] of the existing chiller is the same as the sub-cooler capacity (the amount of heat removed from the refrigerant in the sub-coolers), the cooling capacity increase was calculated as follows:

$$q_{sb} = K2 \cdot \rho \cdot V \cdot c_p \cdot (T_e - T_l) \tag{2}$$

The efficiency [kW/ton; kW_e/kW_c] of the existing chiller was calculated using Equation 3.

$$EFF_{ExCh} = \frac{W_{ExCh,sb}}{q_{ExCh,sb}/K3} \tag{3}$$

The baseline efficiency [kW/ton; kW_e/kW_c] of the existing chiller during subcooling periods was estimated using a curve fit from the data collected during the baseline tests per Equation 3. To do this, the power demand of the existing chiller was normalized over its cooling capacity. Note that more efficient chillers have lower kW/ton (kW_e/kW_c) ratings, indicating that they use less electricity to deliver the same amount of cooling. The existing chiller efficiency was plotted versus ambient temperature. During the baseline and subcooling periods, the efficiency increases with increasing temperature due to a higher refrigerant rejection temperature.

Figure 5 shows the fitted line for the baseline chiller efficiency which was calculated by using data taken from multiple days and covers a wide range of ambient temperatures that occurred during the test period, from 37°F (2.8°C) to 94°F (34.4°C). The equation was used to estimate the normalized power demand of the existing chiller at higher ambient temperatures, which usually occurred during the subcooling period.

$$EFF_{base} = a_1 \cdot T_{amb}^2 + a_2 \cdot T_{amb} + a_3 \tag{4}$$

The additional subcooling provided by the ITESS was expected to increase chiller performance at higher ambient temperatures, which generally occurred during the on-peak hours. Furthermore, the additional subcooling was also expected to increase the chiller capacity, which would have otherwise resulted in a higher power demand if the same capacity was delivered by a larger chiller. To account for both changes, the baseline power demand of the existing chiller during the subcooling period was estimated using Equation 5. The estimated efficiency curve calculated using Figure 5 was also used to determine baseline chiller power demand during the average temperature during the subcooling period.

$$W_{ExCh,sb}^{*} = EFF_{base} \cdot K3 \cdot q_{ExCh,sb} \tag{5}$$

Equation 6 was applied to calculate the total energy consumption [kWh] of the existing chiller using measured data and the calculated performance during the subcooling period.

$$\mathrm{E_{base}} = \sum_{\mathrm{t=9am}}^{\mathrm{t=noon}} \mathrm{W_{ExCh,base} \cdot t_{ExCh,base}} + \sum_{\mathrm{t=noon}}^{\mathrm{t=6pm}} \mathrm{W_{ExCh,sb}^{*} \cdot t_{SubCool}} + \sum_{\mathrm{t=6pm}}^{\mathrm{t=9am}} \mathrm{W_{ExCh,base} \cdot t_{ExCh,base}} \tag{6}$$

The total ITESS power demand [kW] was calculated using Equation 7. If the supplemental chiller and the sub-cooler pumps did not operate, their power terms were zero.

$$W_{ITESS} = W_{ExCh} + W_{SubPump} + W_{SupCh} \tag{7}$$

The net ITESS energy consumption over a full 24-hour period was calculated using Equation 8. The energy consumption for the ITESS was based entirely on measured data for the power draw of each component and actual run time.

$$\begin{gathered} E_{ITESS} = \sum_{t=9am}^{t=9am} W_{ITESS} \cdot t = \sum_{t=9am}^{t=9am} W_{ExCh} \cdot t + \\ \sum_{t=SubCoolStart}^{t=SubCoolStop} W_{SupPump} \cdot t_{SubCool} + \sum_{t=SupChStart}^{t=SupChStop} W_{SupCh} \cdot t_{TankCool} \end{gathered} \tag{8}$$

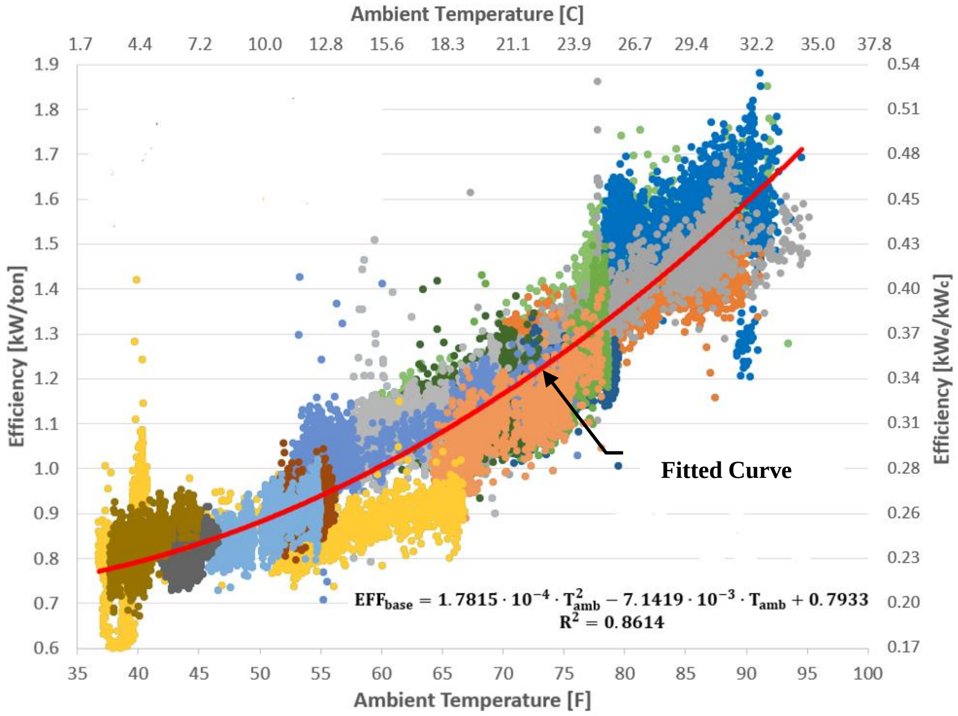

Figure 5: Baseline efficiency

6. TEST RESULTS

Daily test data were summarized and evaluated for a total of 80 days for the test period from July to October 2016. Figure 6 shows relative changes in cooling capacity, power demand, efficiency and energy usage of the existing chiller as a result of the use of additional subcooling. For the sake of completeness, all data are shown in the graph including those for the days when the existing chiller was shut down for repairs and days in late October when the additional subcooling did not result in gained capacity due to lower ambient temperatures. However, these data were excluded for the final evaluation.

Table 1 summarizes the daily average, minimum, and maximum values for cooling capacity, as well as efficiency, energy usage, and estimated power demand. The results clearly show the increase in the cooling capacity and efficiency as well as the reduction in the power demand of the existing chiller. However, the results also show a marginal increase in the average energy usage. This can be attributed to heat losses though the uninsulated sub-cooler water pipes, which account for 5% - 8% of the supplemental chiller thermal energy[1]; heat losses through the water tank; and the extended run time of the water pump for the supplemental chiller. Thus, the energy usage could be reduced by insulating water pipes, providing better insulation to the water storage tank, and integrating water pump control with the supplemental chiller control.

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[1] NAIMA 3E software was used to estimate pipe heat losses.

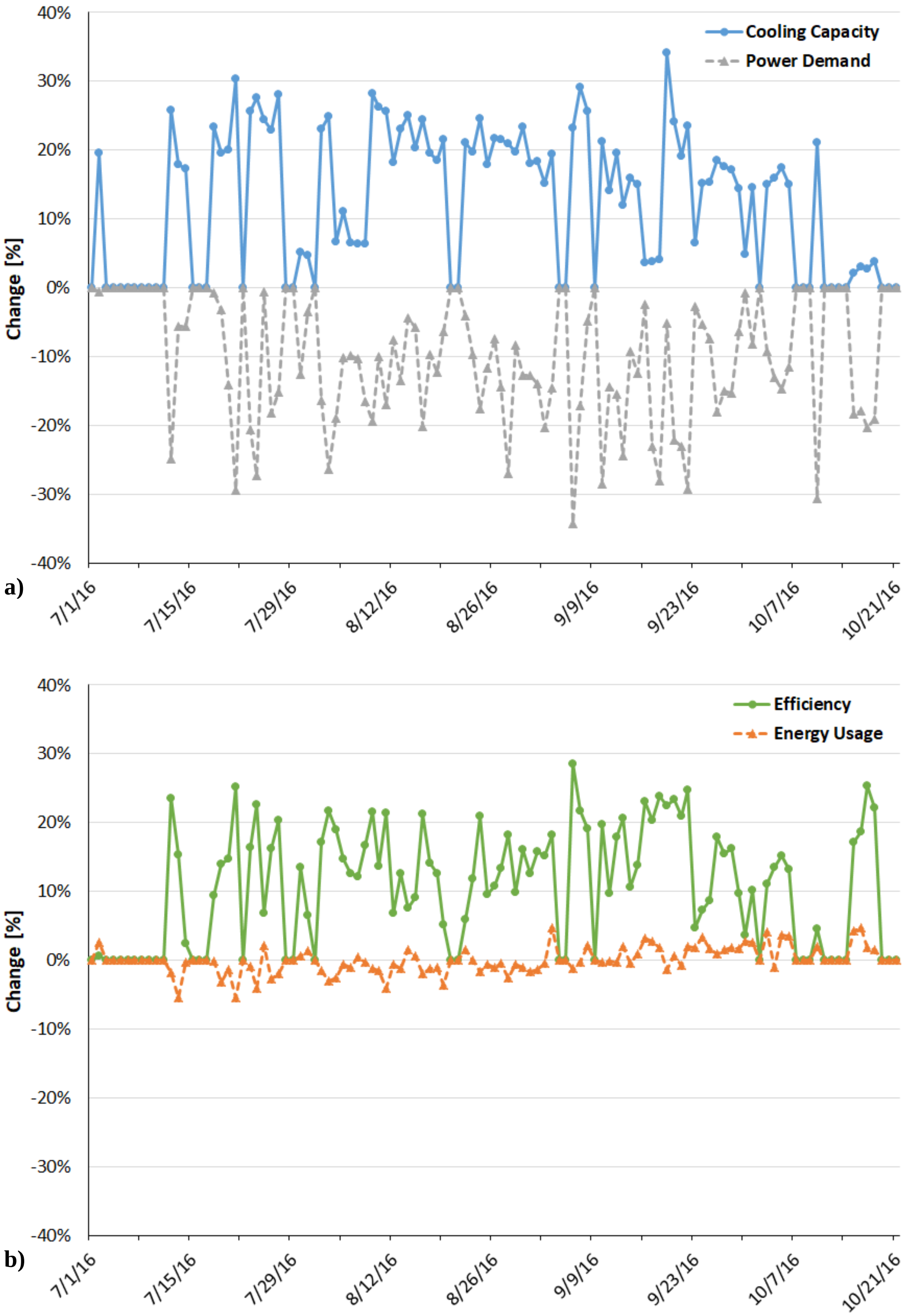

Figure 6: Differences Between Baseline and ITESS Performance: a) cooling capacity and power demand; b) efficiency and energy usage

Table 1: Daily average, minimum, and maximum values for ITESS performance gains

	Average	Minimum	Maximum
Cooling Capacity [ton; kW]	11.0; 38.7 (17.7%)	0.75; 2.64 (2.20%)	19.3; (67.9) (34.2%)
Efficiency [kW/ton; kW_e/kW_c]	0.195; 0.055 (15.0%)	-0.353; -0.100 (0.60%)	0.390; (1.111) (28.5%)
Estimated Power Demand [kW]	-10.0 (-14.0%)	-0.50 (-0.65%)	-25.8 (-34.3%)
Energy Usage [kWh]	-71.6 (-0.05%)	-276 (-5.5%)	419 (4.8%)

The changes in cooling capacity and power demand of the existing chiller are depicted in Figure 7. For reference, curves are included that show the theoretical benefit from cooling refrigerant liquid temperature leaving the condenser at 5°F (-15°C) above the ambient temperature to 48°F (8.9°C). The theoretical benefit from sub-cooler operation should result in an increase of about 25% in both capacity and efficiency at 90°F (32.2°C), which is the summer design condition for Syracuse, NY. It is obvious that the cooling capacity gains primarily occurred at higher ambient temperatures because of the cooling load of the building and the higher refrigerant heat rejection temperatures. The small cooling capacity changes (up to 10%) at high ambient temperatures could be attributed to compressor cycling.

In general, the measured data agree with the theoretical benefit within the uncertainty of the data (Figure 7). Power demand decreased with the increasing ambient temperatures. The energy usage decreased with the increasing ambient temperature.

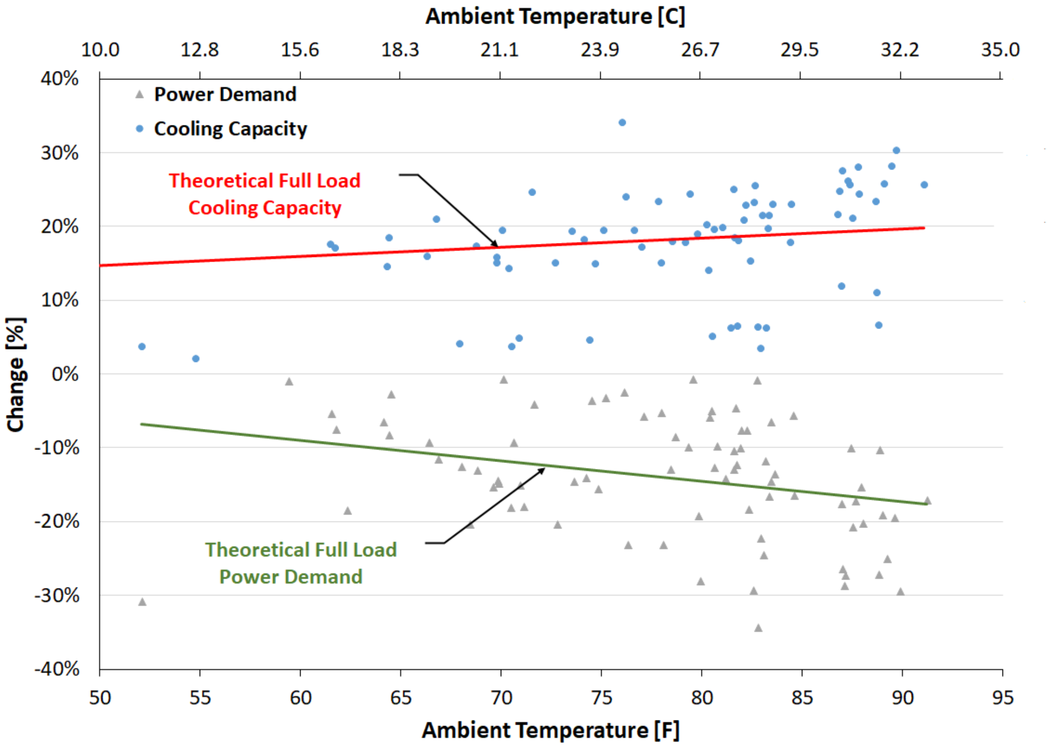

Figure 7: Cooling capacity and power change vs. ambient temperature

6. CONCLUSIONS

An Integrated Thermal Energy Thermal Storage System (ITESS) which provides additional subcooling for a condenser by utilizing chilled water was installed at the Bitzer Compressor Plant in Syracuse, NY in April 2016 and monitored between July and October 2016. The collected data were analyzed. The application of the additional subcooling showed the following advantages and disadvantages:

- The cooling capacity of the existing chiller increased between 2.2% - 34.2% depending on the cooling load and ambient temperatures. The cooling capacity increases primarily occurred at higher ambient temperatures and are consistent with the theoretical 25% increase at 90°F (32.2°C) ambient conditions.
- The efficiency of the existing chiller increased between 0.6% - 28.5% due to the increased cooling capacity.
- The power demand of the existing chiller has the theoretical potential to decrease between 0.7% - 34.3% as compared to a chiller system with comparable increased capacity. Actual power demand increased with the demonstration ITESS due to use of a supplemental chiller and poor control of supplemental equipment.
- The energy usage fluctuated between a 4.7% increase and 5.5% decrease with an average increase of 0.05%. The fluctuation in energy usage is attributed to heat gains though the sub-cooler pipes and water storage tank as well as longer-than-necessary operating time of the supplemental chiller water pump. This increased energy consumption occurred during the supplemental chiller operation during off-peak hours (8pm to 9am). In addition, the low energy consumption changes are within the margin of error of the watt-meters.
- In general, the advantages of the additional subcooling were higher at higher ambient temperatures due to higher refrigerant heat rejection temperature in the condenser.

NOMENCLATURE

a	coefficient from curve fit			
cp	specific heat	(Btu/lbm-°F; kJ/kg-K)		
CPVC	Chlorinated Polyvinyl Chloride			
DAQ	data acquisition system			
E	energy	(kWh)		
EFF	efficiency	(kW/ton; kW_e/kW_c)		
ITES	Integrated Thermal Energy Storage			
ITESS	Integrated Thermal Energy Storage System			
K2 (EN)	8.0209	(ft^3/h-gpm)		
K2 (SI)	0.001	(m^3/L)K3 (EN)	12,000	(Btu/ton-h)
K3 (SI)	1	(-)		
kWh	kilowatt hours			
M	flow meter			
PGW	propylene glycol/water			
q	capacity	(ton; kW_c)		
RH	relative humidity	(%)		
T	temperature	(°F; °C)		
t	time	(hr)		
V	volumetric flow rate	(gpm; L/s)		
VCC	Vapor Compression Cycle			
W	watts or wattmeter	(W)		
ρ	Density	(lbm/ft^3; kg/m^3)		

Subscripts

1, 2, 3	numbers
amb	ambient
base	baseline (existing) chiller parameters without subcooling
e	entering (inlet)
ExCh	existing chiller
l	leaving (outlet)
sb	sub cooling period, sub-cooler
Sub-cool	subcooling period
SubPump	sub-cooler pump
SupCh	supplemental chiller
TankCool	tank cooling period
TESS	Integrated Thermal Energy Storage System

REFERENCES

ANSI/AHRI Standard 550/590 (I-P) (2013), *Performance rating of water-chilling and heat pump water-heating packages using the vapor compression cycle.*

ANSI/AHRI Standard 551/591 (SI) (2015), *Performance rating of water-chilling and heat pump water-heating packages using the vapor compression cycle.*

ASHRAE (2013), *ASHRAE Handbook: Fundamentals*, Atlanta, GA, USA.

ASHRAE (2012), *ASHRAE Handbook: HVAC Systems and Equipment*, Atlanta, GA, USA.

BSR/ASHRAE Standard 184P (2014), *Method of test for field performance of liquid-chilling systems*.

Kopko, W.L., Welch, A.M., Kulankara S. (2014). *Subcooling system with thermal storage*, US patent application, US 20140260376 A1.

Kopko, W.L., (2016), *Integrated thermal energy storage*, 16th International Refrigeration and Air Conditioning Conference at Purdue, July 11-14, West Lafayette, IN, USA.

Martin, C., Kalinowski, P., (2017), *Integrated thermal energy storage for cooling applications*, NYSERDA Report 17-17, https://www.nyserda.ny.gov/About/Publications/EA-Reports-and-Studies/Other-Technical-Reports.

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