Benchmarking an Energy Evaluation Tool for Chilled Water Systems

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ABSTRACT

Following the development of an energy evaluation tool for chilled water systems there was a need to determine the accuracy. The tool quantifies the energy usage of various chilled water systems and of typical energy conservation measures that are applied to these systems. It can be used as a screening tool to identify potential areas that can be further examined, while only requiring a minimum number of inputs.

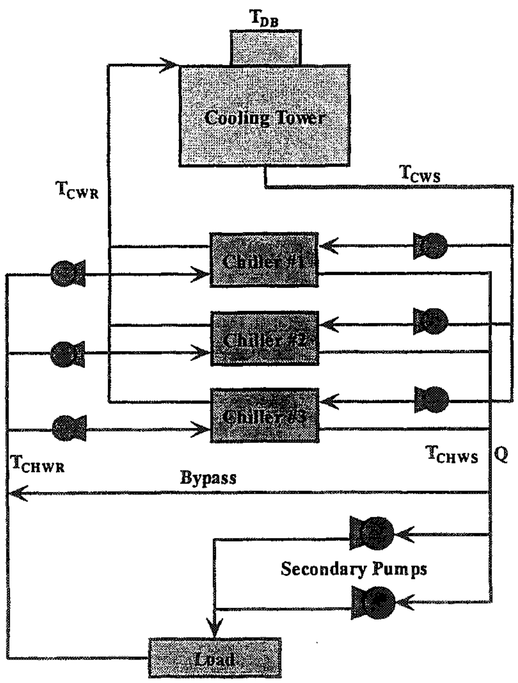
The tool is evaluated against the data obtained from an actual chilled water system consisting of three 630-ton centrifugal chillers and a three-cell cooling tower complete with two-speed fans. The collection and analysis of this data along with the problems encountered are discussed. Chiller performance curves and cooling tower power requirements are compared. Data was also obtained to investigate the effects of raising the condenser water temperature on chiller efficiency. Based on this data, a discussion of some of the tool's inaccuracies is presented. It was found that the tool closely reflected actual cooling tower performance. The prediction of chiller performance and the chiller condenser water reset relations may require further improvement.

Background

The development of the energy evaluation tool to be benchmarked in this paper is thoroughly discussed in an earlier work (Stocki, Kosanovic & Ambs 2001). To summarize, the tool allows the user to define a chilled water system consisting of up to three electric chillers, either air or water-cooled, using reciprocating, helical rotary, or centrifugal compressors. After defining the operating conditions and schedule, the annual energy requirements are calculated. Following this, a number of energy conservation measures such as chilled water reset, condenser water reset, chiller reselection, and free cooling can be evaluated. The tool calculates the energy savings and cost savings based on the cost of electricity.

The chilled water system used to benchmark the energy evaluation tool is located on the University of Massachusetts, Amherst campus. It provides chilled water for use in building air-conditioning systems in two campus buildings. The chillers operate from May until October. The chiller cooling tower satisfies the chilled water load for the remaining portion of the year.

There are three identical 630-ton centrifugal chillers using R123 refrigerant in this facility. A primary-secondary chilled water distribution system is employed. Three primary chilled water pumps maintain constant flow through each of the chiller evaporators. Two variable speed secondary pumps distribute the chilled water to the respective locations. A bypass is employed to balance the flow. The cooling tower is a three-cell tower employing two-speed fans. A schematic of this chilled water system is shown in Figure 1. The chilled water system is remotely monitored via an energy management control system. Operating conditions are available on this system and changes to the set points can be made at desktop computers.



Centrifugal Chiller Data		
Capacity, C	=	630 Tons
Full Load Power	=	465 kW
Full Load Efficiency	=	0.738 kW/ton
Supply Voltage, V	=	4,160 Volts
Full Load Current	=	67 Amps
Full Load Power Factor	=	0.963
Refrigerant	=	R123
Rated Flow Rate	=	1,300 gpm

Control System Values		
T_{DB}	=	Outdoor dry-bulb temperature, °F
Q_P	=	Primary chilled water supply flow rate, gpm
T_{CHWS}	=	Chilled water supply temperature, °F
T_{CHWR}	=	Chilled water return temperature, °F
I	=	Chiller current draw, amps
L	=	Chiller load, tons
T_{CWS}	=	Condenser water supply temperature, °F
T_{CWR}	=	Condenser water return temperature, °F

Figure 1. Chilled Water System Schematic, Chiller Data, and Control System Values

Chilled Water System – Chillers

Chiller Performance Data

Figure 1 displays the rated data for the three identical chillers in the campus chilled water facility. System data was collected from this chilled water system operating during the months of May through August of 2000. In total, 356, 480, and 332 data sets, at half hour intervals, were collected for chillers 1, 2, and 3 respectively. The control system values that were monitored for each chiller are identified in Figure 1. Since the chilled water supply and condenser water supply temperatures are system set points, these values remain nearly constant throughout the data sets. The averages of these values for each of the three chillers are shown in Table 1.

Table 1. Average Chiller Operating Conditions

CHILLER 1		CHILLER 2		CHILLER 3	
T_{CHWS}	47°F	T_{CHWS}	45°F	T_{CHWS}	47°F
T_{CWS}	84°F	T_{CWS}	84°F	T_{CWS}	84°F

Using the control system values, the following were calculated for each chiller: chiller load, L′, (tons), chiller load factor (percent of full load), LF, (%), chiller power, P, (kW), and chiller efficiency, E, (kW/ton). The chiller tonnage was calculated in order to compare the calculated value, L′, with the measured value, L. The equation used is as follows:

$$L' = \rho \times Cp \times (T_{CHWS} - T_{CHWR}) \times \frac{Q}{3} \times C1 \qquad \text{Equation (1)}$$

where,
ρ = Density of water at average of T_{CHWS} and T_{CHWR}, 62.4 lb/ft^3
Cp = Specific heat of water, 1.0 Btu/lb·°F
C1 = Conversion factor, 6.69175E-04 (tons·ft^3·min)/(Btu/hr·gal·hr)

The comparison of the measured system tonnage versus the calculated tonnage is shown in Table 2 for each chiller. The calculated tonnage values are typically between ±10% of the system values. The average difference between the two values is less than ±2% and the standard deviations are around 10% for all three chillers. Therefore, the calculation seems to verify the system readings. The system readings for the tonnage, L, are assumed to be the more accurate values and are used exclusively in further analysis.

Table 2. System Versus Calculated Chiller Tonnage

CHILLER 1		CHILLER 2		CHILLER 3	
Average Difference	1.2%	Average Difference	0.1%	Average Difference	-1.6%
Standard Deviation	8.8%	Standard Deviation	8.2%	Standard Deviation	12.3%

The chiller load factor, LF, is the ratio of the chiller tonnage, L, divided by the rated chiller capacity, C, as shown in Equation (2).

$$LF = \frac{L}{C} \times 100 \qquad \text{Equation (2)}$$

The goal was to acquire data over the full operating range, i.e. from low percent loads to full load operating conditions. Generally, this was achieved although some loading conditions occurred much more frequently than others.

The chiller power, P, was calculated using the following equation:

$$P = \frac{V \times I \times \sqrt{3} \times PF}{1{,}000} \qquad \text{Equation (3)}$$

where V is the supply voltage (4,160 volts), I is the chiller current (amps) taken from the monitoring system, and PF is the power factor. The power factor is dependent upon the chiller motor loading. The relationship of power factor to motor loading used is taken from averaged data (Avallone & Baumeister 1996) and is shown in Figure 2. This relationship was incorporated into the motor loading calculations.

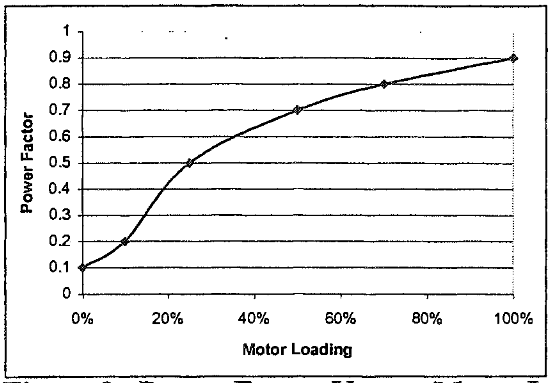


Figure 2. Power Factor Versus Motor Loading

Having calculated the power required for each data point collected, the chiller efficiency, E, is calculated as follows:

$$E = \frac{P}{L} \qquad \text{Equation (4)}$$

Having the efficiency and the percent of rated chiller capacity at every data point for each of the three chillers enables the creation of the chiller performance curves, as shown in Figure 3, for chillers 1, 2 and 3. Notice the significant difference between the curves of these identical chillers. The values for chiller 1 range between 0.25 to 0.5 kW/ton, the values for chiller 2 range from 0.43 to 0.7 kW/ton, and the values for chiller 3 range from 0.65 to 1.0 kW/ton. All performance curves indicate that the most efficient operation is between 40% to 50% load while lower load conditions can dramatically increase the kW/ton value. Also notice that for chiller 1 there is significantly less spread to the data.

Some other values worth noting from the collected data are that the maximum system capacity, 1,890 tons, was never recorded. The highest data point recorded was a total system output of 1,255 tons on a day with a dry-bulb temperature of 90°F. On the minimum side, the lowest system capacity from the data was approximately 110 tons.

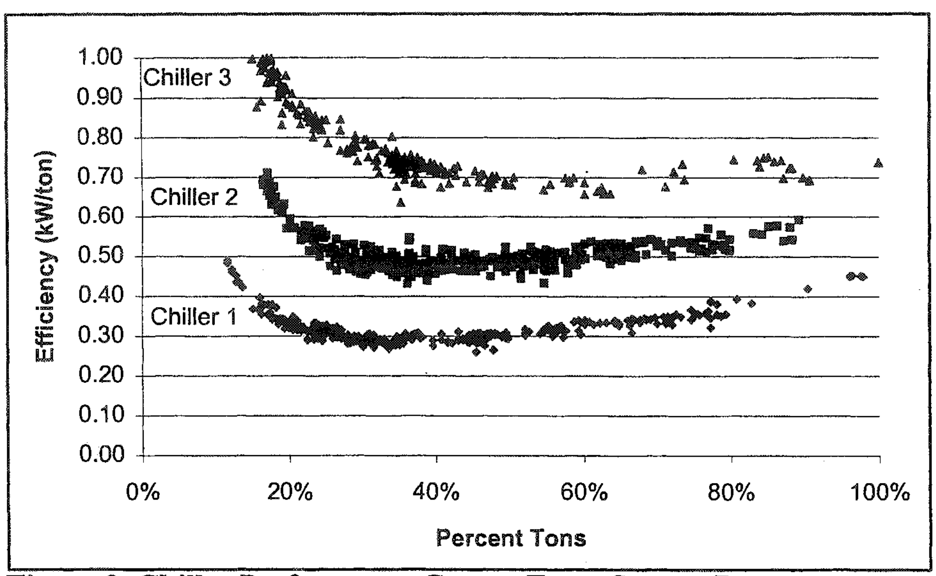


Figure 3. Chiller Performance Curves From System Data

Chiller Performance Analysis

The results shown in Figure 3 pose some problems for further analysis. It was expected that the performance curves for the three identical chillers would be similar. Given the rated efficiency of 0.738 kW/ton at full load, it would be reasonable to expect efficiencies near this rated value. However, only the values from Chiller 3 are close. Upon analyzing the data obtained from the energy management system it is suspected that the source of error lies in the values of the chiller current draw. The sources of error that are being explored by the authors include: voltage fluctuations, amperage readings being taken from a phase that is lower than the others, and improperly selected measurement coils. The authors are not aware of any performance tests that were completed when the chillers were first installed.

In the meantime, in order to evaluate the tool, only the data from chiller 3 is used. The performance curve from chiller 3 seems to be the most likely representation when both typical chiller and the full load efficiency of the chillers are considered. This is the data which will be compared with the output data available from the software tool. There are two methods that are used by the tool to obtain the generic system performance (Stocki, Kosanovic & Ambs 2001). The output provided by both methods will be evaluated here.

The first method relies on catalog data from chiller manufacturers. It requires knowledge of the chiller type, tonnage rating, and method of cooling. Due to its reliance on catalog data, only a limited number of sizes are available for selection. For instance, there is no 630-ton chiller in the catalog data to choose from. The generic performance curves for the 600 ton and 700 ton chillers are identical and thus, either is suitable for comparison. Figure 4 shows the actual performance curve as obtained by a curve fit through the data for chiller 3 as compared to the generic catalog performance data. Examining this figure it appears that the generic curve falls well below the data for chillers 3. The primary reason for this is that the catalog data used in the tool is very recent. Therefore, since chillers efficiencies have been continually improving, it would be expected that an older chiller would have a performance curve significantly above that of a newer one.

Recalling that the generic program data is at the ARI Standard 550/590 conditions, as shown in Table 3, the program must now use the relationships highlighted (Stocki, Kosanovic & Ambs 2001) to correct for the actual operating conditions, shown in Table 1. A comparison of the chiller data versus the corrected method 1 tool data is shown in Figure 4. There is little difference between the generic and corrected method 1 curves in Figure 4. The reason for this is a combination of two opposing relations. First, the actual desired chilled water temperature is greater than the ARI rated value, which lowers the kW/ton value. Secondly, the condenser water supply temperature is held constant while the ARI values decrease significantly at lower loading conditions. The tool relation used to account for the difference in condenser water temperature raises the kW/ton value at low part loads.

Table 3. ARI Standard 550/590 Chiller Operating Conditions (ARI 1998)

Chilled Water Temperature	44°F
Condenser (water-cooled) Entering Water Temperature	100% load - 85°F 75% load - 75°F 50% load - 65°F 25% load - 65°F 0% load - 65°F

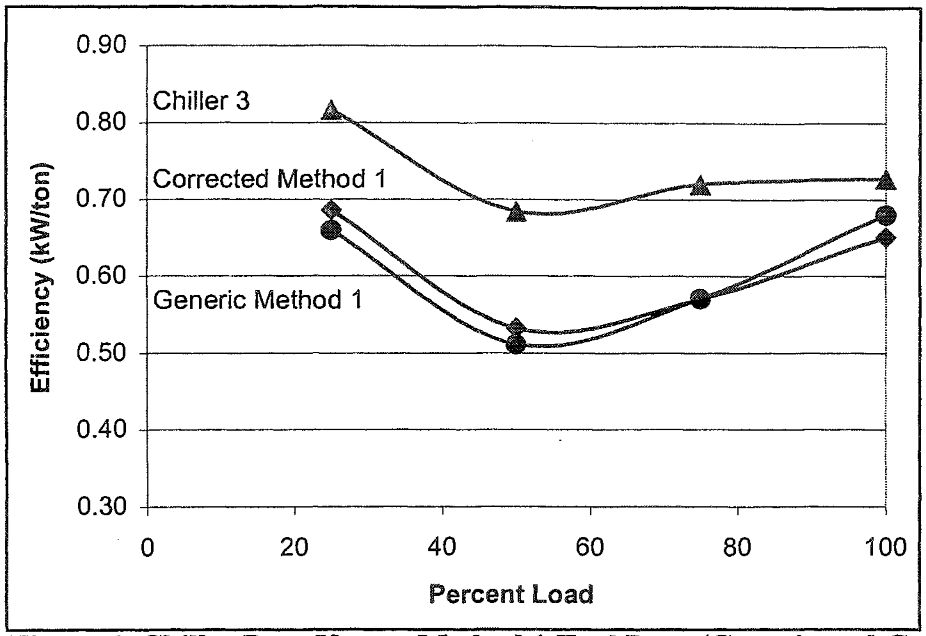


Figure 4. Chiller Data Versus Method 1 Tool Data (Generic and Corrected)

The data from the chiller 3 is now compared to the performance curves as generated by the second method (Stocki, Kosanovic & Ambs 2001). This method uses information from chiller manufacturers of how chillers, regardless of size, reduce their power requirements with the reduction in loading. This method requires knowledge of chiller type, tonnage rating, method of cooling, as well as the full load efficiency, 0.738 kW/ton in this case. The performance curves under generic and corrected conditions are compared to the actual performance curves as measured, as is shown in Figure 5.

The method 2 performance curves are below the actual chiller curve. The typical unloading curve used in method 2 is based on data for newer chillers and, as expected, these chillers should unload more efficiently than older ones. Examining Figure 5, there is little difference between the generic and corrected curves. As explained for the method 1 curves, the tool is using the same opposing relations to determine the corrected performance for the second method.

The second method appears to provide slightly more accurate performance profiles. The method 2 performance curves in Figure 5 are closer to the actual performance than the method 1 performance curves in Figure 4. This was expected since the input of method 2 requires the full load efficiency. A further advantage of using method 2 is the ability to enter the exact rated tonnage of the chiller. This would assist any energy analysis that could be completed using the tool. For these reasons, all further analysis in this paper use the corrected curves of method 2.

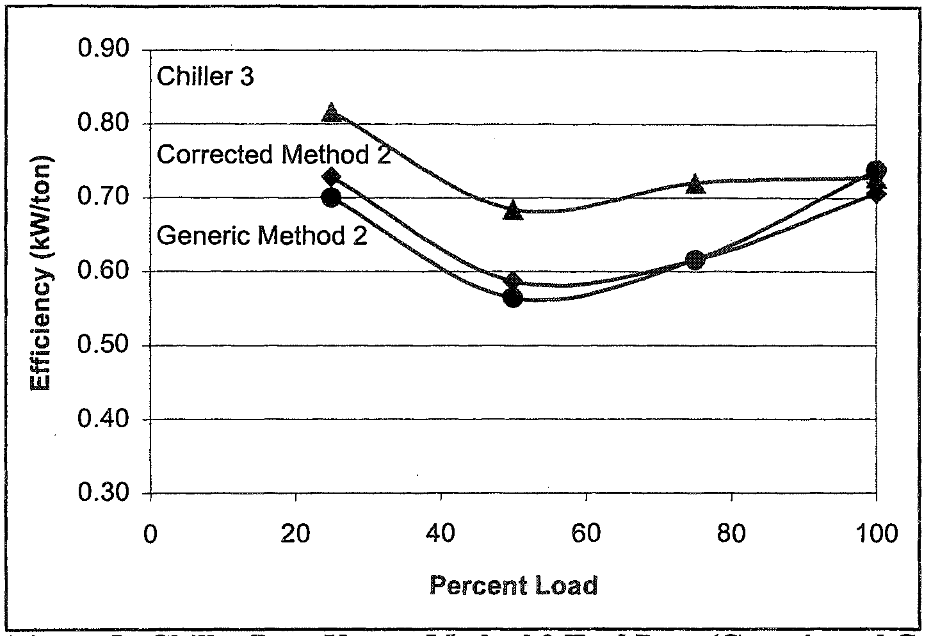


Figure 5. Chiller Data Versus Method 2 Tool Data (Generic and Corrected)

Chilled Water System - Cooling Tower

Cooling Tower Data

In order to evaluate the typical cooling tower data that was implemented into the evaluation tool (Stocki, Kosanovic & Ambs 2001), a test was performed to obtain actual cooling tower performance. On a day with an average outdoor wet-bulb temperature (T_{WB}) of approximately 60°F, the cooling tower fans were manually shut down. The condenser water temperature (T_{CWS}) was observed to drop for some time. After steady state was reached, the value of T_{CWS} was recorded. The fans were then cycled on in sequence and the resulting steady-state conditions were recorded throughout the test. A summary of the testing sequence and results are presented in Table 4.

Examining the data presented in Table 4, a common attribute of cooling towers is noticed. Cooling towers typically can achieve an approach temperature of 10°F. The approach temperature is the difference between the value of the outdoor wet-bulb temperature and the condenser water supply temperature. Notice that as the fans are cycled on, this value is approached asymptotically. In other words, increasing the fan horsepower has a decreasing effect on the value of T_{CWS} near the maximum cooling tower fan power.

Also measured during the test, were the amperage readings from the fans. Calculating the power in a similar manner as for the chillers, it was found that the fans consume 5.4 kW at low speed and 26.4 kW at high speed. The maximum fan power of the entire tower is thus 79.2 kW.

Cooling Tower Analysis

It is now useful to compare the test data with the cooling tower data that is used in the tool. Table 4 shows the condenser water supply temperature determined by the tool and as measured. The data used in the tool are based on default performance curves given in Marley 1985. Since this generic performance assumes an entering cooling tower water temperature, the tool adjusts this performance data based on actual entering conditions observed during the test. Examining this table, the tool data closely follows the trend observed during the cooling tower test. The difference between the condenser water supply temperatures is typically less than 2°F. This would therefore suggest that the tool should be able to closely predict the fan operating condition required to produce any given condenser water supply temperature at a given outdoor wet-bulb temperature.

Table 4. Cooling Tower Performance Measured Data and Tool Data

Fan 1	Fan 2	Fan 3	Measured Data			Tool Data		Difference
Status	Status	Status	T_{WB} (°F)	T_{CWS} (°F)	Approach (°F)	T_{WB} (°F)	T_{CWS} (°F)	In T_{CWS} (°F)
Off	Off	Off	62.8	96.0	33.2	60	98	2.0
Low	Off	Off	62.7	90.8	28.1	60	89	-1.8
Low	Low	Off	58.9	80.4	21.5	60	82	1.6
Low	Low	Low	59.1	74.5	15.4	60	77	2.5
High	Low	Low	58.6	71.7	13.1	60	72	0.3
High	High	Low	58.2	69.8	11.6	60	69	-0.8
High	High	High	58.7	68.9	10.2	60	67	-1.9

Also used in the tool is the fan percentage power at each operating condition. The values used in the tool are based on data from Marley 1985 and are compared to the measured values in Table 5 at each loading condition. Overall, there is close agreement between the tool data and the measured values.

Table 5. Cooling Tower and Chiller Power Analysis

T_{CWS}	Fan 1	Fan 2	Fan 3	Percent Fan Power		Demand (kW)		
(°F)	Status	Status	Status	(Marley 1985)	(Measured)	Tower	Chiller	Total
96.0	Off	Off	Off	0%	0%	0	378	378
90.8	Low	Off	Off	5%	7%	5	388	394
80.4	Low	Low	Off	10%	14%	11	300	311
74.5	Low	Low	Low	15%	20%	16	260	276
71.7	High	Low	Low	43%	47%	37	243	280
69.8	High	High	Low	72%	73%	58	245	303
68.9	High	High	High	100%	100%	79	245	329

Chilled Water System – Chiller and Cooling Tower

Condenser Water Reset Analysis

One of the energy conservation measures considered in the tool is the lowering of condenser water temperature to obtain higher chiller efficiencies, lower kW/ton, and thus lower chiller energy requirements. During the cooling tower test, outlined in Table 4, only chiller 3 was satisfying the chilled water demand. Data was recorded from this chiller and the required power and efficiency were calculated using Equations (2) and (4). On average, the chiller was running at approximately 440 tons or 70% load during the entire test. Table 6 summarizes the chiller efficiency at each of the condenser water temperatures obtained during the test as shown in Table 4.

From the measured performance curve for chiller 3, as shown in Figure 3, the efficiency of this chiller is approximately 0.7 kW/ton at 70% load under the operating conditions shown in Table 1. The variation in Table 6 demonstrates the general trend expected; as the condenser water supply temperature drops, the chiller efficiency improves.

It is useful to compare this measured change in efficiency with the relationship used in the tool as obtained from Monger 1999. Recalling that the relation used considers the percent decrease in chiller efficiency with decrease in condenser water temperature (Stocki, Kosanovic & Ambs 2001), the measured data must be converted to this format. Doing this enables the measured and program curves to be simultaneously graphed as shown in Figure 6. There is a significant discrepancy between these two curves. The measured data indicates that chiller efficiency savings upwards of 30% are possible. It appears that the curve implemented into the program is quite conservative. This could lead to some pleasant surprises upon implementation. Some further investigation is needed to determine why the measured values predict such a dramatic efficiency improvement before the relation used by the tool is adjusted.

Table 6. Measured Chiller Efficiency at 70% Load with Various Condenser Water Temperatures

Condenser Water Supply Temperature, T_{CWS} (°F)	Chiller Efficiency, E (kW/ton)
96.0	0.89
90.8	0.83
80.4	0.67
74.5	0.60
71.7	0.58
69.8	0.57
68.9	0.57

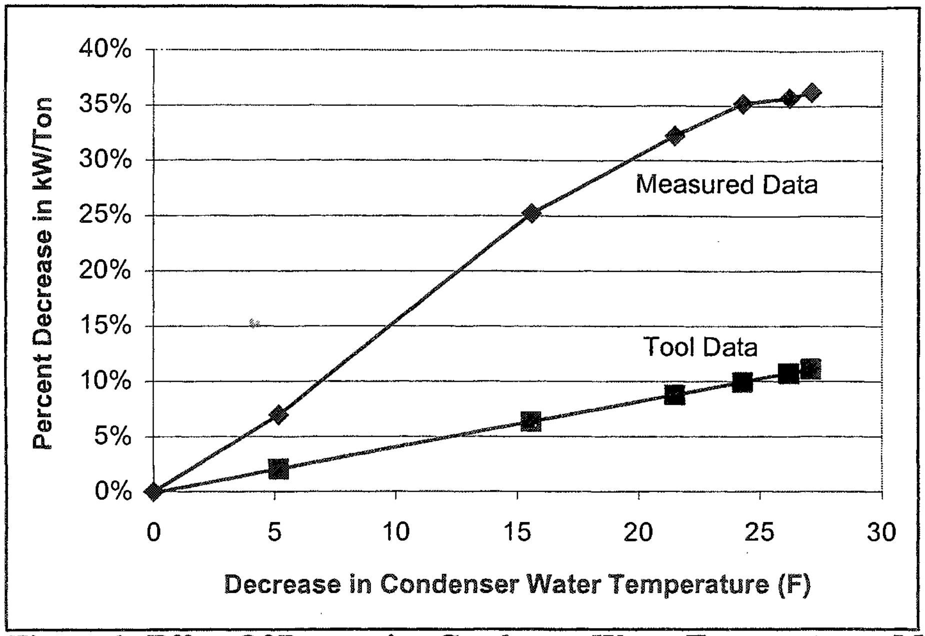


Figure 6. Effect Of Decreasing Condenser Water Temperature: Measured Versus Tool Data (Monger 1999)

Net Chilled Water System Demand Analysis

Assuming that all of the pumping electric demand required during the cooling tower test remained constant, the electric demand of the cooling tower and the chiller 3 can be examined together. Table 5 shows the average fan and chiller demand required during the test. The total of these two values as well as the tower fan operating schedule are also displayed. Recall that the chiller was operating at an average of approximately 70% load for the entire test.

The most important characteristic to notice of this data is that the tower demand becomes much more significant as the tower fans are switched to high speed operation. This test has revealed the ability of cooling tower fan demand to negate chiller savings that occur from reducing the condenser water supply temperature. It appears that the optimum setting during the testing conditions occurred when the total demand was lowest, 276 kW, with all fans on low speed, at a T_{CWS} value of 74.5°F.

Table 7 shows the tool data for the chiller and tower fan power at the tested conditions. Corrected method 2 performance data, as shown in Figure 5, was used to obtain the initial chiller data. Examining the chiller demand column, the power values start off significantly different than the measured values, and then converge at the 74.5°F value of the condenser water supply. Following this, the values from the tool remain slightly higher. There are two opposing factors, which cause this crossover. Figure 5 shows the difference in the efficiency at 70% load. Chiller 3 has a higher kW/ton value than predicted by the tool, which causes the higher initial power requirements. The effect of the condenser water temperature, as shown in Figure 6, is significantly different for the measured and tool data. This reduces the difference between the efficiency values.

Table 7. Chiller and Tower Demand from the Tool at Tested Conditions

T_{CWS} (°F)	Chiller Demand (kW)	Tower Demand (kW)	Total Demand (kW)
96.0	286	1	287
90.8	277	3	280
80.4	268	9	277
74.5	260	23	283
71.7	260	39	299
69.8	255	52	307
68.9	255	57	312

Comparing the tower demand columns from the Tables 5 and 7, highlights the differences in cooling tower performance. The tool demand follows the general trend as measured. One value to note is that the tool predicts that the condenser water temperature of 68.9°F can be obtained without using the maximum tower demand of 79 kW. This is consistent with Table 4, which indicates that two fans on high speed and one on low can achieve this temperature.

The combined effects of the chiller and tower fan are shown in the total demand column of Tables 5 and 7. Although the tested results indicate that the optimal condition would be a condenser water supply temperature of 74.5°F, the tool results indicate that 80.4°F gives the lowest total demand requirements.

Results

This investigation has provided many interesting insights into the problems that can be encountered when analyzing energy management system values and the accuracy of the energy evaluation tool developed for chilled water systems. Examining data from the campus chiller plant yielded three very different performance curves for the three identical chillers. Only the values for chiller 3 were utilized as they corresponded most closely to the rated efficiency values. Further research is needed to explain the very low kW/ton values obtained for chillers 1 and 2. Benchmarking the chiller performance indicated that the energy evaluation tool developed can generally follow the trends, however, due to the reliance of the tool on very recent catalog data, the kW/ton values predicted are lower at all loadings. Cooling tower performance was found to have a slight variation from that used in the program. As expected, testing and tool data confirmed the importance of lowering the condenser water temperature on chiller efficiency. The tool, however, appears very conservative in this calculation. Finally, the combination of cooling tower fan power and chiller power when lowering the condenser water temperature gives slightly different pictures when test data is compared to tool output. The differences in chiller power were found to be primarily at fault in this case.

This benchmarking procedure has indicated some of the limitations of the tool and pointed to specific areas that could use future improvements depending on the accuracy of the output required. Examples of changes include modifying chiller performance based on the age of the chillers in use, adjusting the effect of condenser water temperature on centrifugal chiller performance and further modifying tower performance based on actual cooling tower water temperatures.

Conclusions

This paper has focused on the benchmarking of an energy evaluation tool. The tool is used to estimate the energy usage of chilled water systems and evaluate the savings of implementing various energy conservation measures to the system.

Chiller data was taken during the summer of 2000 from a chilled water facility located on the University of Massachusetts, Amherst campus. There are three 630-ton centrifugal water-cooled chillers in this facility. Condenser water is supplied via a three-cell cooling tower complete with two-speed fans. Data from the three chillers was used to create performance curves. Analyzing the data identified problems in the monitoring system values. Due to these problems, only the data taken for chiller 3 was compared directly with data generated by the tool. Cooling tower data was obtained and compared to the relations used in the tool. Cooling tower performance, both achievable temperatures and power required at various fan stages correlated well. The benefits of lowering the condenser water temperature were measured and found to be even greater than predicted by the tool.

Overall, chiller performance was adequately correlated for the purposes of the tool. The efficiency values provided are consistently higher than those measured because of the reliance by the tool on very recent chiller performance information. Some modifications may be incorporated into the tool at a future date to account for the age of the chiller. The chiller relations used for condenser water temperature reset may also require adjustment due to the large difference between measured data and the relations used by the tool. However, the discrepancy may also suggest that the measured values are at fault. Therefore, further investigation is needed to fully understand why the measured efficiency improvements are so much greater than that predicted by the tool.

Due to the large number of tool capabilities that were not covered in this paper, it is recommended that further study be completed to evaluate the accuracy of all the relations used within the energy evaluation tool. Finally, the authors wish to thank Jason Burbank at the University of Massachusetts, Amherst, for his cooperation and assistance.

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