Evaporative Condenser Lab and Field Test Results

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ABSTRACT

The use of evaporative processes to improve vapor compression system cooling efficiency is an important vehicle for reducing energy use and peak demand in hot-dry climates. Evaporative condensers demonstrate efficiency advantages by reducing the temperature of the condensing environment from the outdoor dry bulb temperature to close to the outdoor wet bulb temperature. Their efficiency is essentially unaffected by high ambient temperatures in dry climates and indoor comfort is not compromised in humid conditions in contrast to evaporative coolers. The impact is most significant during utility peak periods when the difference between dry and wet bulb temperatures is often greatest.

This paper presents findings from two distinct studies on the AquaChill evaporative condenser introduced to the market in 2010. A laboratory study was conducted at the Western Cooling Efficiency Center (WCEC) at UC Davis to study evaporative condenser longevity with and without the implementation of various water management strategies. Concurrently, a study investigated field performance of another AquaChill unit, installed in an existing home in Davis, CA and monitored for the entire 2011 cooling season. The major findings of this research include:

- Longevity tests showed a 24% decline in efficiency after 2,000 hours of run time (equivalent to 5 years of operation in Davis, CA) with no water management strategy.
- Small-scale water management strategy tests suggest that a bleed strategy that uses significantly less water than manufacturer's recommendations may be sufficient to prevent coil scaling.
- The field installed unit performed at a seasonal full load condenser efficiency of 16.9 EER and an average field-measured rate of 1.8 gal/hr per ton during full load operation.

Background

Residential air conditioning has become increasingly common throughout the United States over the past 30 years as comfort demands have increased and market demands have pushed compressor based cooling into climates not previously seen. Increasingly, air conditioners are being installed in milder, transitional climates to compensate for these increased comfort demands, as well as increased building loads seen from the trend towards larger homes and greater window areas. The 2009 Residential Energy Consumption Survey (RECS) shows that 61% of residential homes have central air conditioning.

Evaporative cooling has been used successfully throughout history to provide cooling and is especially effective in hot-dry climates. The use of evaporative processes to improve cooling efficiency is an important vehicle for reducing energy use and peak demand in hot-dry climates.

Direct space cooling through evaporative cooling does not provide the same quality of comfort as compressor based processes in that for most evaporative technologies, moisture is added rather than removed from the air. While this may be acceptable in dry climates it is not in humid climates where air conditioning is relied upon not only for sensible cooling but for dehumidification. Evaporative condensers utilize the efficiency of evaporative cooling to cool air entering the condensing unit, while also providing dehumidification identical to a conventional air conditioning system. Evaporative condensers may play a key role in reducing cooling energy use in new homes, and also in cost effectively improving existing homes that have high loads due to sub-standard wall insulation and windows, which may be more costly to upgrade.

Previous Research

Previous research has demonstrated the efficiency benefits of evaporative condensers. Davis Energy Group (DEG) has completed simulations, laboratory and field testing of a variety of evaporative condensers. With Building America support, a Freus unit was field tested in the Southern California desert town of Borrego Springs in 2006 and 2007 (Springer et al, 2008). Performance results showed significant energy savings over standard air-cooled condensing equipment. In the summer of 2007, Davis Energy Group evaluated two residential Freus installations for a Pacific Gas & Electric (PG&E) technology evaluation report (DEG, 2008). Monitoring data from the sites were used to develop a performance algorithm using MicroPas hourly loads. Simulation projections suggest 21-33% annual cooling energy savings and 22-35% coincident peak cooling demand savings in typical Central Valley California applications.

During 2009, DEG worked with Beutler Corporation (manufacturer of the AquaChill evaporative condenser) to assess AquaChill design and performance, and identify potential enhancements in the AquaChill design. Condenser coil and other design improvements were incorporated into the "second generation" system and lab testing of this design showed improved performance over the previous version, with a 15 EER rating at AHRI conditions (75°F outdoor wet bulb temperature). Lab testing of a production AquaChill unit was also completed by Southern California Edison (SCE, 2009) and reported an EER of 13.5 at AHRI conditions with actual fan energy use applied instead of the standard AHRI default value of 365 Watts/1000 cfm. Performance degradation at higher outdoor temperatures was found to be much less than conventional air-cooled equipment. Operational EERs, which include indoor fan energy use, ranged between 14.2 in mild conditions down to 13 in hot-dry conditions (115°F outdoor dry bulb, 74°F wet bulb).

During the summer of 2009, the Sacramento Municipal Utility District (SMUD) worked with ADM Associates to complete monitoring and field evaluation of 26 AquaChill units (Keesee et al, 2010). The data was analyzed and compared to usage data for typical residential homes in SMUD territory. Findings from the study include that air conditioning energy use can be reduced by 29% for a typical single family home in SMUD territory and peak power can be potentially reduced 23% compared to a typical single family 4-ton unit.

In 2010, DEG conducted a study for PG&E to evaluate evaporatively-cooled condensers as a potential component of a Zero Net Energy (ZNE) strategy for new and existing homes (DEG, 2010). The results of the study showed that evaporative condensers have substantial benefits and can be cost effective in hot-dry climates where cooling energy use is significant.

Laboratory Testing

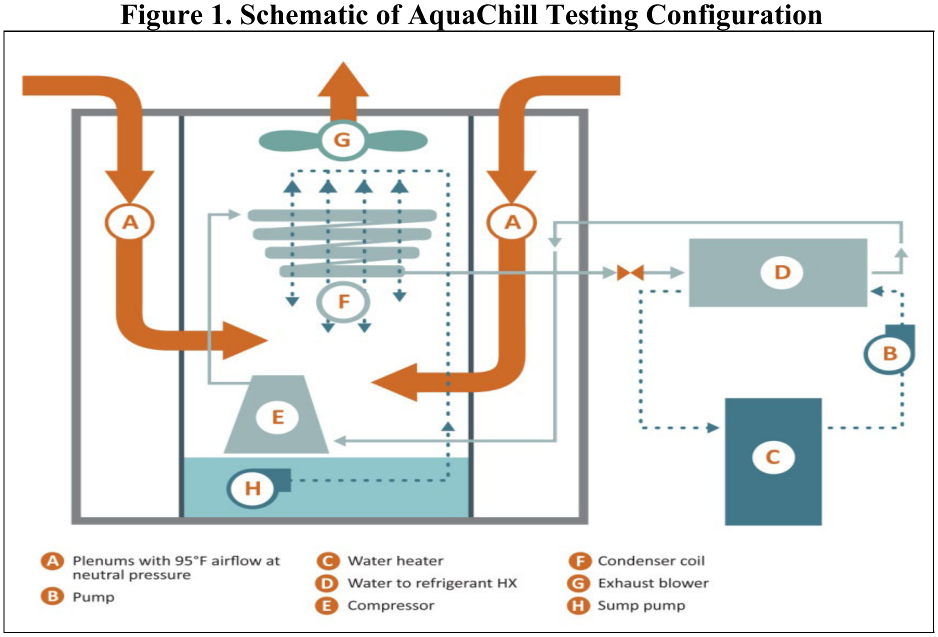
The Western Cooling Efficiency Center completed a longevity test on a 3-ton AquaChill unit and designed a small scale test setup to evaluate water management strategies in four parallel tests.

AquaChill Longevity Test Design

WCEC installed the AquaChill condensing unit in the laboratory in March 2011 and a test setup was configured to facilitate continuous longevity testing (Figure 1). A plenum was constructed around the air intakes on all four sides. Air was heated to 95°F and distributed to the plenum by four ducts. The wet bulb temperature of the air was monitored, but not controlled, and varied between 59°F and 73°F with an average of 66°F. Results over the 7 month test period were binned by wet bulb temperature in order to compare efficiency degradation under similar test conditions. The AquaChill was run for 1 hour, followed by ½ hour "off" to simulate cycling that would occur in actual use. During the off period, the fans supplying air to the unit were run at low speed to facilitate drying out the condenser coil.

The cooling provided by the AquaChill system was delivered to a water-to-refrigerant heat exchanger. The load was supplied by a water heater delivering 80°F water through a thermostatic mixing valve.

Figure 1. Schematic of AquaChill Testing Configuration



Instrumentation throughout the system monitored:

- Capacity of the system by measuring the differential temperature of the water across the water-to-refrigerant heat exchanger and the water flow rate,
- System energy consumption,
- Rate of cooling water evaporation (by measuring the water replacement rate through a flow meter),

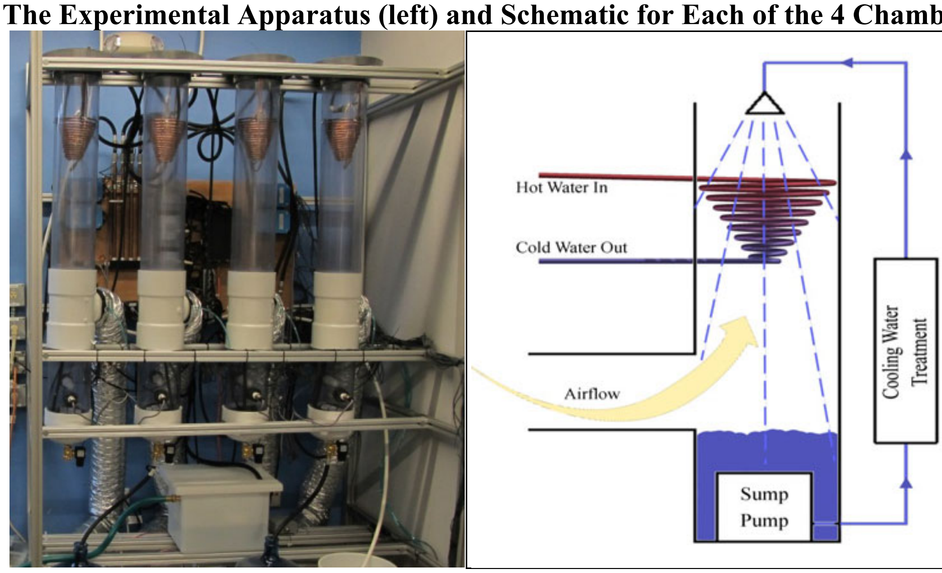
- Differential air pressure between the plenum and the exhaust and the differential air pressure across the inlet of the AquaChill, and
- Temperature and humidity of the intake and exhaust air.

Data acquisition equipment interfaced with LabVIEW 2010 software, which took measurements at 1 Hz, saving the average values to a text file every 60 seconds.

Small Scale Test Design. The experimental apparatus was designed to emulate an evaporatively cooled condensing unit on approximately a 1/20 scale. Four parallel systems were constructed so that four management strategies for the cooling water were tested simultaneously (Figure 2).

Each parallel system consists of three fluid streams which converge at the coil in the heat exchange chamber. The coil simulates the condenser coil, which in this small scale test rejects the heat from hot water instead of refrigerant. This simplification reduces complexity of the experiment while still allowing for the study of scale formation on the hot copper coil. Hot water from a water heater (122°F) is supplied to the cooling coil, which is sprayed with water supplied by a pump drawing from a sump in the bottom of the chamber. Evaporated water is replaced by a peristaltic metering pump controlled by a float switch. The air flow at 95°F, which is supplied by a fan and metered to 50cfm by a constant air flow damper, carries heat and evaporated water away from the cooling coil. Similar to the AquaChill test, the wet bulb temperature of the incoming air was monitored but not controlled, but in this case the systems were compared directly under identical conditions to account for changes in humidity. Finally, a peristaltic pump was used to bleed sump water at a specified rate.

Figure 2. The Experimental Apparatus (left) and Schematic for Each of the 4 Chambers (right)



Instrumentation throughout the system measures:

- capacity of the cooling coils by measuring the hot water flow rate in each coil and the temperatures at the inlets and outlets of each coil,
- rate of the bleed water removal and makeup water replenishment in each chamber by measurement of the calibrated peristaltic pump run-time,
- the air pressure differential across each cooling coil and the temperature and relative humidity of the incoming airflow, and

- cooling water conductivity in each sump.

Data acquisition equipment interfaced with LabVIEW 2010 software, which took measurements at 1 Hz, saving the average values to a text file every 60 seconds. Water sump samples were manually collected weekly to assess sump water quality parameters including pH, hardness, suspended solids, and elemental concentrations.

Cooling water management strategies varied between chambers. One strategy studied includes a sump bleed which offers potential benefits of salt removal and reduced scale by draining some of the sump water during operation; however this strategy uses additional water. To test the implications of bleed rate on performance, a no bleed (control), a low bleed rate (+8% increase in water use), and a high bleed rate (+40% increase in water use) were tested. The fourth test chamber was equipped with a physical water treatment approach (static magnetics) with no bleed. Three GMX-400 static magnets (0.4 Tesla each) were installed on the rubber hose between the sump pump and the nozzles. Magnetic water treatment has been demonstrated to alter the mineral scale crystalline phase resulting in more aragonite (orthorhombic $CaCO_3$) and less calcite (rhombohedral $CaCO_3$; Coey and Cass, 2000). In previous research, the WCEC had observed the magnets to improve the performance (28%) of evaporatively cooled heat exchangers compared to no treatment (Pistochini et al., 2010).

AquaChill Longevity Test Results. The AquaChill was run for 2,074 hours over a period of seven months. During the test 11,059 gallons were evaporated and no water was bled from the system. Assuming an average run time of 400 hours per year, this is approximately 5 years of service in Davis, California. The average water hardness as $CaCO_3$ over the course of the experiment was 362 mg/L, resulting in an estimated 33 lbs (15kg) of potential scale forming constituents added to the system over the course of the experiment. The result was a 9% decrease in capacity, a 19% increase in power, and a 25% decrease in the efficiency of the system (Table 1). The measurement of EER includes all power for the condensing unit but does not include the power for an evaporator fan.

Table 1. AquaChill Performance When New and After 2,074 Hours of Run Time at Conditions 95±1°F DB and 64±2°F WB. *Power and EER Do Not Include Power for an Evaporator Fan

	Capacity (kbtu/hr)	Power* (kW)	EER* (kbtu/hr/kW)
Test Start	34.9	1.80	19.4
Test End (% Change from Start)	31.8 (-9%)	2.15 (+19%)	14.8 (-24%)
Test End + Cleaning (% Change from Start)	31.7 (-9%)	2.07 (+15%)	15.3 (-19%)

Inspection of the system showed large amounts of scale on the condenser coil and a large number of clogged nozzles, resulting in a 30% reduction in total water flow (from 8.2gpm to 5.8gpm). Eight of the twenty nozzles were 100% clogged and five of these were located in the corner farthest away from the pump, preventing an entire section of the coil from being wetted. However, cleaning the nozzles and restoring water flow to the coil did not yield much of an improvement, increasing the EER slightly to 15.3. The large amount of scale on the coil resulted in thermal resistance to coil heat transfer as well as a reduction in condenser airflow. At the end of the experiment, an averaging pitot tube at the exit of the exhaust estimated a 30% reduction in airflow.

Figure 3. AquaChill Coil at End of Test

In addition to the long term degradation of the nozzles and coil heat transfer, the AquaChill had two sump pump failures and the basket surrounding the pump needed to be cleaned once.

Aqueous chemistry principals (Snoeyink and Jenkins; 1980) were applied to improve understanding of scale formation in the evaporative cooling unit. The following discussion includes the highlights; however a comprehensive discussion is beyond the scope of this article. Scale formation in evaporative coolers is increased due to elevated temperatures at the coil and elevated pH values due to evaporation (pH>9 were observed compared with typical influent tap water at pH 8.2). In contrast, only elevated temperatures are a factor in water heaters. Scale and water samples were collected from various locations within the evaporative cooling unit, and elemental distributions were highly dependent on sampling location. The sump water contained very high concentrations of salts, such as sodium (Na) and chlorine (Cl), which is expected due to their high solubility. Magnesium (Mg) and calcium (Ca), hardness constituents, were present in low concentrations in the sump water. By contrast, Mg and Ca were both found in the solid precipitates, though their precipitate elemental composition varied with sampling location. Future research will include evaluating other water treatment and management approaches and working to better understand the mechanisms controlling scale formation.

Small Scale Test Results. The small scale test system evaluated three water management strategies simultaneously against a baseline "no-bleed/no-treatment" system. The test was run for 450 hours of operation over a two month period, evaporating approximately 150 gallons of water in each chamber. The estimated average hardness of the inlet tap water over the course of the experiment was 285mg/L as $CaCO_3$.

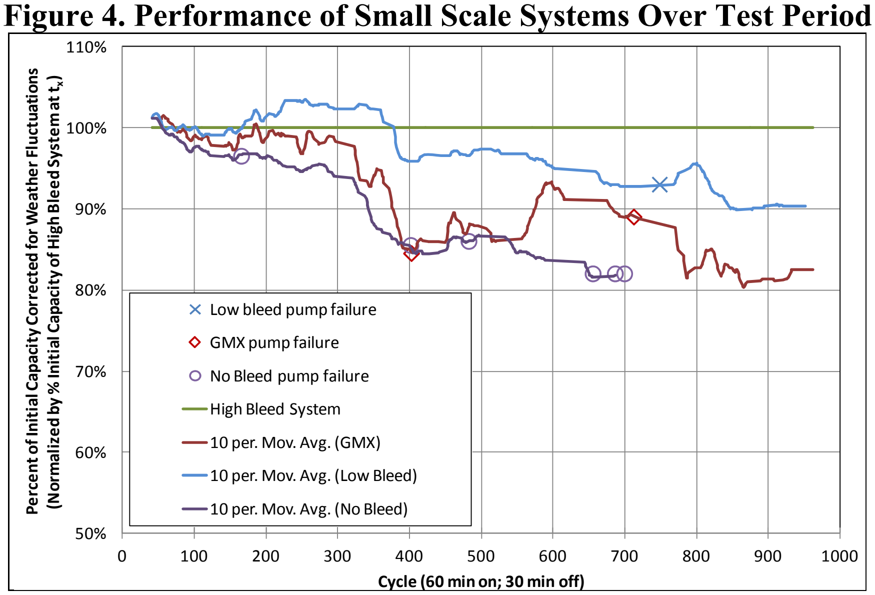
The sump water in all chambers reached an equilibrium concentration of hardness minerals approximately five days after beginning the experiment. In the "no treatment" and magnetic treatment chambers, this equilibrium concentration was 1500 mg/L as $CaCO_3$. The sump water for the low bleed chamber reached an equilibrium concentration of approximately

1165 mg/L of $CaCO_3$ and the sump water for the high bleed chamber reached an equilibrium concentration of approximately 640 mg/L of $CaCO_3$. The residence time for dissolved constituents is 34 hours in the low bleed system and 7 hours in the high bleed system; in the no treatment and magnets, the salt residence time is the duration of the experiment. The observed plateau in the hardness concentrations indicates that each of the systems reached steady state between hardness sources (added tap water) and sinks (mineral scale precipitation and bleed water where applicable). In the high bleed system, there is less time for the precipitation reactions to occur, so the system is likely farther from an equilibrium status.

Over the course of the experiment (700 cycles for the no treatment, 950 cycles for others) the high bleed system did not decline in capacity. However, fluctuations in capacity were observed due to wet bulb temperature fluctuation. Therefore, the remaining three data sets were normalized by the high bleed data set to correct for the wet bulb temperature fluctuation. The data is presented as the percent of the initial capacity of the system under test divided by the percent initial capacity of the high bleed system at time t_x (Figure 4). Capacity of the no bleed system declined to 82% of initial capacity relative to the high bleed after 700 hours of operation. The magnetic treatment declined to 82% of initial capacity relative to the high bleed after 800 hours of operation. The low bleed system declined to 90% of initial capacity relative to the high bleed after 950 hours.

Failure of the sump pumps was also tracked and is a useful measure of performance. The high bleed system had no failures, the low bleed system had one failure (749 hours), the magnetic system had two pump failures (403 and 713 hours), and the no bleed system had six pump failures (166, 402, 483, 656, 687, and 700 hours). It is notable the magnetic system appeared to reduce pump failures even though the improvement in heat transfer of the coil was minimal. It should also be noted that biological growth in the water occurred approximately halfway through the experiment in the no treatment chamber and approximately three quarters of the way through the experiment in the low bleed chamber. It did not significantly affect the water properties and is not expected to impact pump performance; however future testing will prevent this growth by wrapping the clear sump in black plastic to reduce light transmission.

Figure 4. Performance of Small Scale Systems Over Test Period



Field Monitoring

Davis Energy Group conducted a field test by installing the AquaChill at an existing, occupied home in Davis, California in September, 2010. The primary objective of this study was to evaluate viability of evaporative condensers as a cost effective technology for energy use and peak demand savings in hot-dry climates in both new and existing homes. The system was monitored through September, 2011, capturing an entire cooling season. The 1967 1,230 ft^2 single story home featured these general envelope characteristics: 2x4 wood framed R-13 walls, vented attic with R-19 ceiling insulation, vinyl double pane windows, and ductwork located in the attic. A three ton AquaChill condenser was installed to replace the existing three ton condensing unit. The existing air handler and permanent split capacitor (PSC) fan motor were left in place.

Field Monitoring Methodology

The general approach was to apply detailed monitoring of indoor and outdoor conditions as well as AquaChill system performance, electrical energy and water use to evaluate seasonal performance and compare to lab test results. The site was equipped with data logging equipment capable of scanning every 15 seconds, with data summed or averaged (as appropriate) and stored every 15 minutes. Temperature and relative humidity were measured outdoors on the North side of the house in the shade and indoor near the thermostat. HVAC energy delivery was calculated using supply and return air side measurements (temperature & relative humidity), and a one-time measurement of system airflow. This was used along with power at the condensing unit and indoor fan to calculate system efficiencies. Total water consumption was recorded with a flow meter on the inlet to the sump.

The system was characterized by measuring total duct leakage (at 25 Pascals), total system airflow (with an orifice plate), and refrigerant charge verification. Results of one-time field tests include measured system airflow of 1,035 cfm (345 cfm per ton), measured fan power of 500 Watts (0.48 W/cfm), and 15% total duct leakage.

Operating capacity and efficiency was calculated with and without measured fan energy, for both full and part load operating periods. Full load data is quantified as any 15 minute period during which the condenser is operating greater than 97% of the time and was operating greater than 90% of the time during the previous 15 minute period. This resulted in 252 data points for inclusion in this analysis. Due to the high fan watt draw of the existing fan motor, including monitored fan energy in efficiency calculations diluted calculated system efficiencies resulting in lower values than expected. For this reason, in this analysis condensing unit power only is used in the efficiency calculations for evaluation of system performance according to the following equation.

$$EER_c = \dot{Q}_{total} / ECOND$$

where:	EER_c	= condenser energy efficiency ratio (Btu/Wh)
	$\dot{\mathbf{Q}}_{total}$	= total cooling capacity of (Btu/h)
	ECOND	= condensing unit power (W)

While an uncertainty analysis was not conducted for this experiment previous work has quantified the uncertainty of EER calculations in the field using monitoring equipment with similar accuracies as those used in this study. Referring to Davis Energy Group's HVAC Energy Efficiency Maintenance Study the uncertainty for total EER calculations is ±1.69 (Hunt et al, 2010).

Field Monitoring Results

Figure 5 shows a comparison of total cooling capacity at full load operation compared to both outdoor and entering wet bulb temperatures. Capacity is presented as a nominal value relative to the rated capacity. Measured capacity never achieved the rated value of 36,000 Btu/h and averaged 84% of this or about 30,000 Btu/h, a capacity reduction of ½ ton. Cooling capacity appears to be more sensitive to conditions at the evaporator instead of at the condenser. Relative to entering wetbulb temperature, capacity increases linearly with increasing temperature, as is expected. However, the data points are much more scattered relative to outdoor wetbulb temperature and no clear trend is observed.

Note that with a PSC fan motor, it is expected that airflow and, as a result, capacity will vary over time primarily due to the condition of the air filter. However, the occupant was diligent about replacing the air filter every 3 months over the monitoring period. Since capacity was calculated with a one-time measurement of airflow, it is possible that there may be some error in the capacity measurement due to changes in airflow.

Figure 5. Full Load Nominal Total Capacity Versus Both Outdoor and Entering Wet Bulb Temperatures (WB°F)

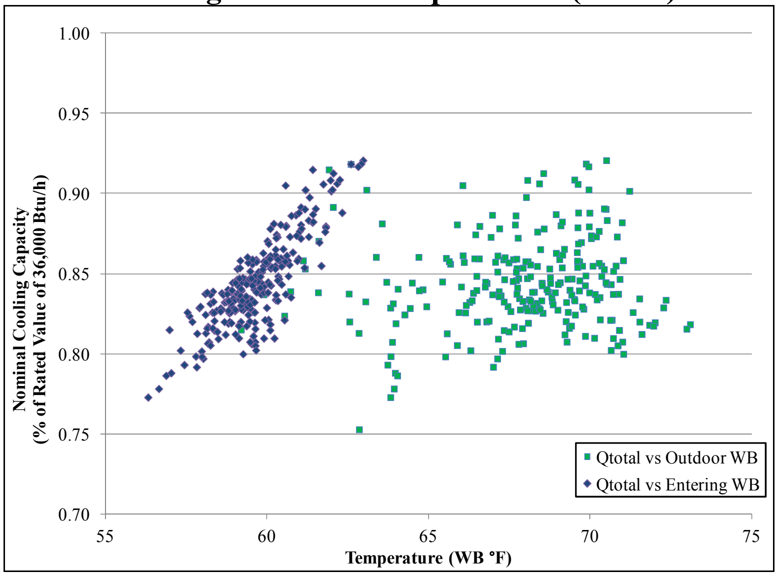
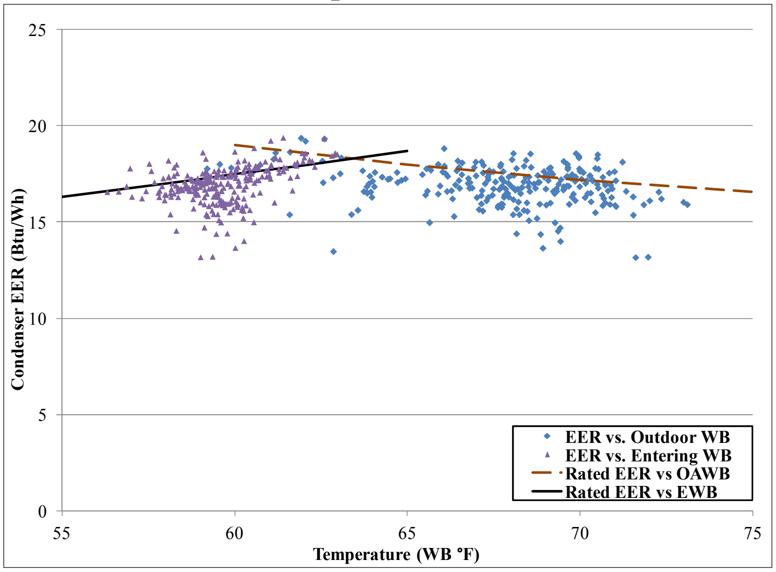


Figure 6 shows measured full load condenser EER, EER_c, (not including indoor fan energy) as a function of both outdoor air wet bulb temperature and evaporator entering wet bulb temperature. Performance data for the AquaChill is only published at AHRI conditions; therefore, in order to compare monitored performance to rated conditions, performance curves were developed using the rated EER of the AquaChill at AHRI conditions[1] and the eQUEST default curve for evaporatively cooled condensers (EvapCond-EIR-fEWB&OWB) to predict operating efficiencies at various conditions. In the rated EER versus EWB curve, an average outdoor wetbulb temperature from monitoring data of 68°F was used to fix this variable. An average entering wetbulb temperature from monitoring data of 60°F was used to fix this variable in the rated EER versus OAWB curve.

It can be seen that there is generally good alignment between monitored and rated data. While this eQUEST curve is a helpful point of comparison, to the authors' knowledge validation of the eQUEST curve with field or lab data has been limited. Average seasonal full load condenser efficiency over the 2011 cooling season was calculated at 16.9 EER.

[1] The rated AquaChill EER of 14.7 was converted to condenser EER by removing the AHRI assumption for fan energy of 0.365 W/cfm and 400 cfm/ton. This results in an EER_c of 17.9.

Figure 6. Full Load Condenser EER (Btu/Wh) Versus Both Outdoor and Entering Wet Bulb Temperatures (WB°F)



A multiple linear regression analysis was conducted to develop a predictive relationship between condenser EER and both outdoor air and entering air wet bulb temperatures. The DOE2 simulation approach was used which assumes a bi-quadratic relationship of the following form:

$$EER_c = c_1+c_2*OAWB+c_3*OAWB^2+c_4*EWB+c_5*EWB^2+c_6*OAWB*EWB$$

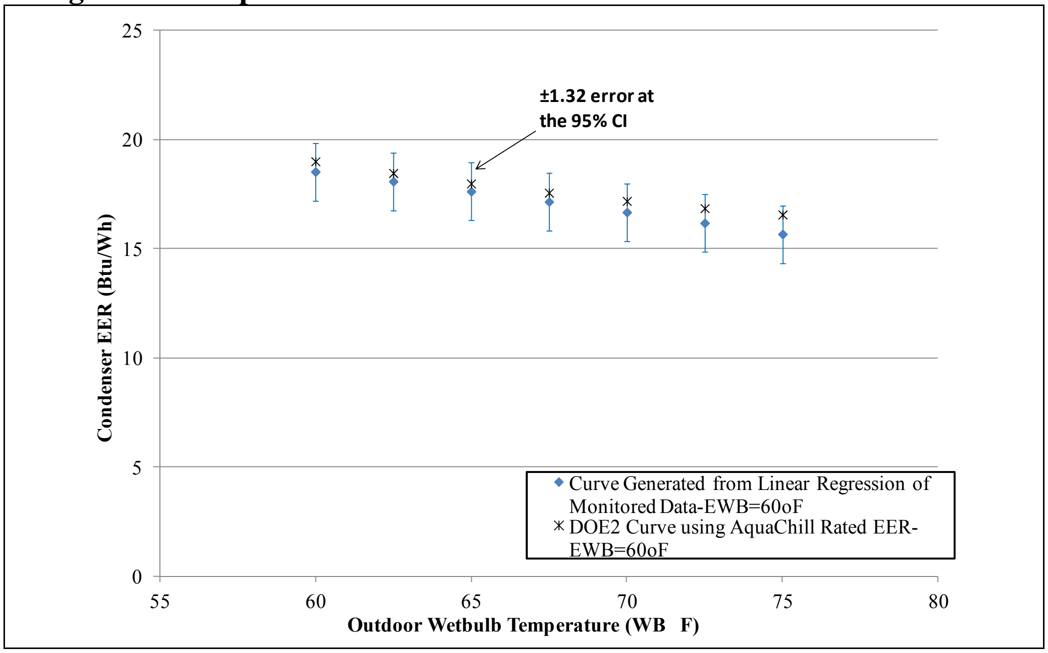
where: c_n = constants determined through the regression,
OAWB = outdoor wet bulb air temperature, °F,
EWB = evaporator entering wet bulb temperature, °F

The *linest* function in Excel was used to estimate the coefficients of the curve based on full load monitoring dataset of 252 data points. This exercise resulted in good alignment between the monitored data and the predicted relationship with a 95% confidence interval of (-1.32, 1.32)[2]. The F probability distribution was evaluated to test the hypothesis that the observed relationship between the dependent and independent variables occurred by chance and resulted in a 0% chance.

Figure 7 compares the condenser EER curve generated from the linear regression relative to outdoor wet bulb temperature to the eQUEST default curve. Entering wetbulb temperature was fixed in both curves to the average value from monitoring data (60°F). The predicted values from the linear regression and those from the eQUEST curve are within 5% of one other. After compensation for error at the 95% confidence interval the values are still within 13%. When this is compounded by the instrumentation uncertainty the values are within 24%.

[2] This confidence interval doesn't include instrument uncertainty.

Figure 7: Comparison of Curve Fit with Monitored Data & DOE2 Curve



The linear regression model was also used to estimate the condenser EER at AHRI rating conditions of 75°F outdoor wet bulb and 67°F entering wet bulb, resulted in an estimated EER of 20.2. However, the AHRI operating conditions are outside of the range of the monitored data and require extrapolation of the regression curve. The wet bulb conditions that the system experienced were fairly narrow given the hot-dry climate of the California central valley. Further field studies are necessary to better quantify this value and the performance curve over a wider range of conditions.

Water Consumption. The average water usage of the unit was observed to be 5.4 gal/hr during full load operation and 5.1 gal/hr seasonally based on total water consumption and total run time. For the 3 ton system this equates to an average of 1.8 and 1.7 gal/hr per ton of air conditioning capacity respectively. The bleed rate for the system was set at the minimum setting and field measurements estimate the rate to be on average 0.6 gal/hr, resulting in an average seasonal evaporation rate of 4.5 gal/hr. This bleed rate yields 13% excess water on average over the season. The monitored average water consumption rate is lower than rates observed in previous studies for this climate zone: approximately 5.7 gal/hr evaporation and 2.1 gal/hr purge (SCE, 2009). The monitored purge rate is also less than the manufacturers recommended bleed rate of 2.0 gal/hr, based on the supply water $CaCO_3$ hardness of 362 mg/L. However, it is greater than the low-bleed rate case (8% excess water) seen in the WCEC small scale testing which yielded 90% of initial capacity after 950 hours of run time.

Once the scale was dried, the sump was cleaned by removing the majority of scale with a vacuum and the remaining by flushing the system with a calcium-removing cleaning agent. None of the nozzles appeared to be clogged. It was noted that there was a substantial accumulation of scale and debris (i.e. leaves and dirt) around the sump pump basket (Figure 8). The basket was thoroughly cleaned per manufactures recommendations for seasonal start-up and shut-down, which cleared the obstructions. Based on the level of buildup this step is essential to prevent the sump pump from being starved of water and to reduce the risk of pump failure as seen in the longevity test.

Figure 8: Condenser Coil (Left) and Water Reservoir (Right) at the End of the Cooling

Conclusion

The lab and field tests demonstrate the benefits of evaporative condenser technology in regards to energy efficiency and longevity. Field testing showed condenser efficiencies close to those established in lab testing and minimal degradation at higher outdoor temperatures. In the WCEC lab testing after 2000 hours of runtime with no water management strategy the system remained operational with a condenser EER of 14.8.

The small scale laboratory experiment is still ongoing. However, the results to date suggest that the bleed rates recommended for AquaChill users maybe be higher than necessary. For hard water areas, the manufacturer of AquaChill recommends a high bleed rate (40% increase in water consumption). The small scale experiments suggest that using just a fraction of that water may be adequate. This is further supported by evidence that running the full scale AquaChill system for 2,000 hours with no bleed yielded only a 24% decline in condensing unit efficiency over an equivalent five year run time. The efficiency of the unit was seen to maintain a higher efficiency by implementing a water quality management strategy of 8% excess water bleed rate and even more with 40% excess water. Further analysis is being conducted by the WCEC to determine optimal bleed rates.

The field tested unit performed within the range of the manufactures provided specifications. The overall seasonal full load condenser efficiency was 16.9 EER. Over the cooling season the unit did accumulate some scale and debris build up at the low bleed rate setting (0.6 gal/hr, 13% excess) but was able to be cleaned during recommended seasonal maintenance.

Further research on installed units in other regions is required to help predict how evaporative condensers will perform in other climates and under other water quality scenarios.

Acknowledgements

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