Thermosyphon Cooler Hybrid System for Water Savings in an Energy-Efficient HPC Data Center: Modeling and Installation

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Thermosyphon Cooler Hybrid System for Water Savings in an Energy-Efficient HPC Data Center: Modeling and Installation

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ABSTRACT

The Thermosyphon Cooler Hybrid System (TCHS) integrates the control of a dry heat rejection device, the thermosyphon cooler (TSC), with an open cooling tower. A combination of equipment and controls, this new heat rejection system embraces the "smart use of water," using evaporative cooling when it is most advantageous and then saving water and modulating toward increased dry sensible cooling as system operations and ambient weather conditions permit. Innovative fan control strategies ensure the most economical balance between water savings and parasitic fan energy. The unique low-pressure-drop design of the TSC allows water to be cooled directly by the TSC evaporator without risk of bursting tubes in subfreezing ambient conditions.

Johnson Controls partnered with two national laboratories—the National Renewable Energy Laboratory (NREL) in Golden, Colorado, and Sandia National Laboratories in Albuquerque, New Mexico—to deploy the TSC as a test bed at NREL's high-performance computing (HPC) data center in the first half of 2016. Located in the Energy Systems Integration Facility (ESIF), this HPC data center has achieved an annualized average power usage effectiveness rating of 1.06 or better since 2012. Warm-water liquid cooling is used to capture heat generated by computer systems direct to water; that waste heat is either reused as the primary heat source in the ESIF building or rejected using evaporative cooling. This data center is the single largest source of water and power demand on the campus, using about 7,600 m^3 (2.0 million gal) of water during the past year with an hourly average Internet technology load of nearly 1 MW (3.4 million Btu/h)—so dramatically reducing water use while continuing efficient data center operations is of significant interest. This new heat rejection system being deployed at the ESIF has gained interest because the climate at the laboratory in New Mexico is similar to that of the laboratory in Colorado, and the laboratory data centers in New Mexico utilize an hourly average of 8.5 MW (29 million Btu/h) and are also one of the largest consumers of water on-site.

In addition to describing the installation of the TSC and its integration into the ESIF, this paper focuses on the full heat rejection system simulation program used for hourly analysis of the energy and water consumption of the complete system under varying operating scenarios. A follow-up paper will detail the test results. The evaluation of the TSC's performance at the laboratory in Colorado will also determine a path forward at the laboratory in New Mexico for possible deployment in a large-scale system not only for data center use but also possibly site wide.

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INTRODUCTION

Large computer data centers generate significant amounts of waste heat that must be removed from the servers. Ideally, this low-grade heat can be used for other purposes—one useful possibility is for building heating. But if there is not a use for all the waste heat, the remaining heat must be rejected, typically to the atmosphere. Traditionally, system designers have had two basic choices for rejecting waste heat to the atmosphere: via sensible cooling, such as an air-cooled heat exchanger; or via evaporative cooling, such as a cooling tower. There are also many hybrid heat rejection systems. Some currently commercially available systems include all-in-one products that combine some functions of both evaporative and sensible cooling into a single product, parallel combinations of separate wet and dry cooling devices, and series combinations of dry and wet cooling devices. The thermosyphon cooler (TSC) hybrid system, developed by Johnson Controls, is an example of the latter. This system, a combination of equipment and controls, places a dry cooling device, a TSC, upstream and in series with a wet cooling tower. Johnson Controls partnered with two national laboraties—the National Renewable Energy Laboratory (NREL) in Golden, Colorado, and Sandia National Laboratories in Albuquerque, New Mexico—to deploy the TSC in Colorado as a test bed at the laboratory's high-performance computing (HPC) data center in the first half of 2016.

Traditional Choices for Rejecting Waste Heat to Atmosphere

Air-cooled heat exchangers use the ambient air dry bulb (DB) temperature as the heat sink, meaning that the process fluid being cooled must be at a higher temperature than the ambient DB temperature. Air by itself is a relatively poor conveyor of heat. An amount of air of 28.3 L (1.0 ft^3) increasing 5.6°C (10°F) in temperature is capable of removing only approximately 180 J (0.17 Btu) of heat; consequently, it takes a large volume of air movement to reject a given amount of heat to the atmosphere. Additionally, because the economical coil face velocity is limited to approximately 3 m/s (600 ft/min), air-cooled heat exchangers usually are quite large in plan area. The good news, though, is that they require no water.

On the other hand, as the air is passed through a cooling tower, moisture is added to the airstream in an evaporative cooling process, as shown in Figure 1(a). This same 28.3 L (1.0 ft^3) of air passing through a cooling tower and going through a 5.6°C (10°F) change in wet bulb (WB) temperature is now capable of removing approximately 865 J (0.82 Btu) of heat. This represents approximately 380% more heat removed for every 28.3 L (1.0 ft^3) of air moved through the cooling tower. This reduces not only the required fan energy but also the cooling tower's plan area relative to the air-cooled heat exchanger. Additionally, the cooling tower heat transfer process is bounded by the lower ambient WB temperature instead of the higher ambient DB temperature. On hot summer days, the coincident WB temperature can be 11.1°C–22.2°C (20°F–40°F) lower than the DB temperature. This allows for significantly lower maximum process temperatures to be maintained. However, evaporatively cooled systems, such as those employing cooling towers, depend on a continuous source of low-cost water to reliably and economically address the cooling requirements.

Water and wastewater costs have risen and are projected to continue to rise much faster than most other utility commodities. Increasing population, rising standards of living, and aging infrastructure along with changing weather patterns are increasing competition for and reducing the assured reliability of a continuous water supply.

Although evaporative cooling systems have many performance advantages during peak summer conditions, these advantages diminish with cooler ambient temperatures and lower loads. Additionally, operational cost differences between evaporatively cooled and sensibly cooled systems are strongly influenced by the cost of energy, which can change significantly between peak and off-peak hours, and the cost of water. When looking at the range of ambient temperatures, heat rejection loads, and energy prices experienced during a year, it's clear that the best option may be neither an evaporatively cooled system nor a sensibly cooled system but a hybrid combination of both.

Thermosyphon Cooler

When conditions are favorable, the TSC, shown in Figure 1(b), precools the heated water in the main cooling loop before any remaining heat is removed across the plate frame heat exchanger connected to the cooling towers. At any given set of conditions, the water evaporated by the cooling tower is directly proportional to the thermal load applied to it. Cooling tower water usage is reduced because any thermal load removed sensibly to the atmosphere by the TSC is thermal load that no longer needs to be rejected by the cooling tower. The addition of the TSC upstream of the cooling tower allows the system to run "wet when it's hot and dry when it's not."

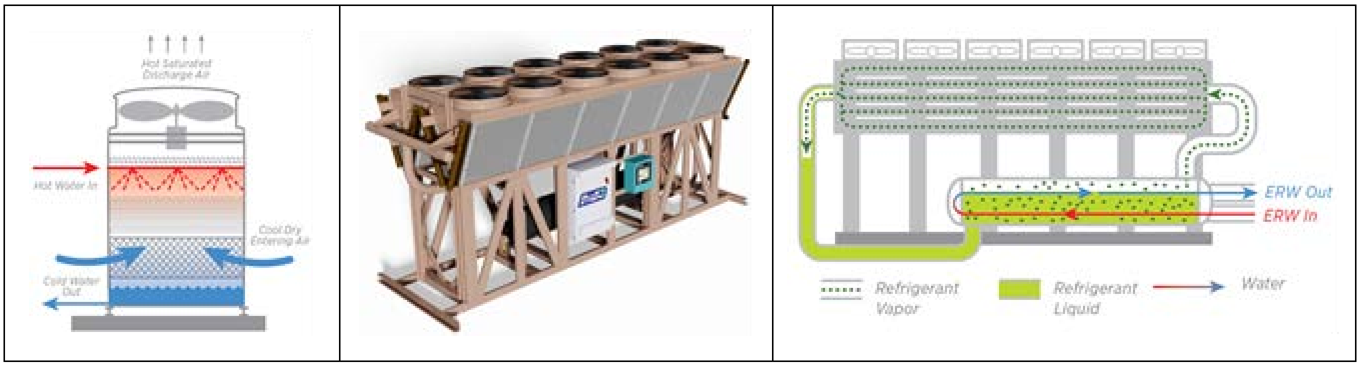

Figure 1 (a) Counterflow cooling tower diagram, (b) TSC, and (c) conceptual design of the TSC.

The dry sensible TSC comprises a lower, easily cleanable flooded shell and tube evaporator and an overhead air-cooled condenser. The onboard controller automatically and continuously adjusts the speed of the condenser fans based on ambient conditions, loads, and utility costs to achieve the most operationally cost-efficient way to reduce the overall system water usage.

A diagram of the operation of the components is shown in Figure 1(c). Warm process water enters the tubes of the lower flooded shell and tube evaporator. As the water is cooled, refrigerant surrounding the high-efficiency, enhanced tubes absorbs the heat and begins to boil. This refrigerant vapor is then drawn to the colder surfaces of the overhead air-cooled condenser. Sensing the current ambient and process temperatures and knowing the current energy and water costs, the controller determines the optimum speed to run the condenser fans. As the heat is removed from the refrigerant vapor to the moving airstream, the vapor condenses back into liquid, where it collects in the vertical liquid header pipe connecting the outlet of the condenser to the inlet of the evaporator. The difference in liquid height between liquid in the vertical liquid riser and the level of the liquid refrigerant in the evaporator provides the gravity-driving force to circulate the refrigerant in the system. Refrigerant flows in a naturally recirculating and self-regulating manner from the evaporator to the condenser without the need for any pumps or compressors.

Care must be taken when circulating water through any dry sensible cooling device that may be subjected to subfreezing ambient air conditions. In the TSC, if thermal load is lost during low ambient temperature conditions, a combination of sensors, valves, and controls automatically limits heat loss by stopping the refrigerant flow between the evaporator and condenser sections and energizing evaporator heaters as necessary to keep the water from freezing.

INSTALLATION

These two U.S. Department of Energy national laboratories have partnered on recent projects deploying HPC liquid-cooled systems and working through energy-efficient data center designs because the locations have similar climate conditions that provide many great opportunities for air- or water-side economization. Both have been learning from one another as they work toward having the ultimate energy-efficient data center with the least environmental impact. The combined data centers at the laboratory in New Mexico utilize an hourly average of 8.5

MW (29 million Btu/h) and are one of the largest consumers of water on site. This is one of the many reasons that the two national laboratories have partnered on this project, and the collaboration will assist in determining the operational value of the TSC.

HPC Data Center

Located in the Energy Systems Integration Facility (ESIF), this HPC data center has achieved an annualized average power usage effectiveness (PUE) rating of 1.06 or better since 2012 (PUE equals total data center power divided by Internet technology [IT] equipment power). Warm-water liquid cooling is used to capture heat generated by computer systems direct to water; that waste heat is either reused as the primary heat source in the ESIF building or currently rejected using evaporative cooling. This data center is the single largest source of water and power demand on campus, using approximately 7,600 m^3 (2.0 million gal) of water during the past year with an hourly average IT load of nearly 1 MW (3.4 million Btu/h)—so dramatically reducing water use while continuing efficient data center operations is of significant interest.

An energy-performance-based design-build process was used to construct the ESIF that took a holistic approach to energy efficiency to ensure a symbiotic relationship among the data center and the facility's offices and laboratories. The request for proposal (RFP) prioritized key performance parameters as "Mission Critical," "Highly Desirable," and "If Possible" with energy criteria throughout. The RFP required the HPC data center to achieve an annualized PUE of 1.06 or lower and an energy reuse effectiveness (ERE) of 0.9 or lower by reusing waste heat from the data center to provide heat to other parts of the building. This led to the following design strategies:

- Water-side free cooling, cooling tower plant
- Low-approach cooling towers and heat exchanger
- Low-pressure-drop air delivery system
- Low-pressure-drop piping design
- All fans and pumps utilizing variable-frequency drives.

The data center was designed to support power and cooling infrastructure up to a maximum of 10 MW (34 million Btu/h). It is currently equipped (generators, power distribution panels, cooling towers, fan walls, etc.) to power and cool up to 2.5 MW (8.5 million Btu/h) of electrical load from HPC equipment. Ample space is allotted for additional infrastructure that can be expanded in 2.5-MW modular increments. The cooling supply and return pipes are sized for the full 10-MW capacity. The data center floor provides approximately 930 m^2 (10,000 ft^2) of uninterrupted, usable machine room space, and it is designed to primarily house the liquid-cooled HPC and related systems. The facility does not utilize traditional computer room air handling units. Instead, for any heat load not dissipated to liquid, the facility utilizes a full hot-aisle containment strategy to eliminate mixing hot exhaust air with the cool supply air.

The mechanical systems serving the data center are designed around ASHRAE 0.4% conditions (with N+1 redundancy) and extreme WB conditions. Space temperatures within the data center are 25.6°C +/- 1.1°C (78°F +/- 2°F), with dew points between 5.6°C–15°C (42°F–59°F) and relative humidity not more than 60%. The data center is situated at an elevation approximately 1,770 m (5,800 ft) above mean sea level.

The energy recovery water (ERW) system provides hydronic cooling for both the HPC systems and fan wall equipment, as shown in Figure 2. The operational range of water delivered after the cooling tower heat exchanger is typically held from 18.3°C–21.1°C (65°F–70°F) so that supply air from fan walls is delivered in the range from 20.6°C–23.3°C (69°F–74°F). The ERW loop is an isolated, closed-loop system. To ensure a high quality of waste heat, HPC and related equipment are required to regulate water flow to maintain design return water temperatures of or warmer than 35°C (95°F). As of July 2016, when the TSC will be commissioned, the total IT load in operation will be approximately 0.91 MW (3.1 million Btu/h). Of this operational load, 0.76 MW (2.6 million Btu/h) is for liquid-cooled HPC systems, whereas the remaining 0.15 MW (0.5 million Btu/h) is for traditional air-cooled IT equipment.

HPC System Heat Rejection

The current flagship HPC system located in the ESIF data center is called Peregrine, and it consists of a cluster of 2,592 server nodes capable of 2.24 PetaFLOPS dedicated to performing computational work. The ERW loop supplies cooling water at up to 26.7°C (80°F) to Peregrine's 10 cooling distribution units (CDUs), which are located in separate IT racks placed between node racks on the data center floor. The CDUs act as the transfer mechanism between the warm water in the isolated server cooling loop and the ERW loop. CDUs distribute server loop water to each of Peregrine's node racks. Inside the node racks, all the heat generated by electronics is transferred to the server loop water, which then returns to the CDUs. Water is returned from Peregrine's CDUs to the ERW loop at up to 40.6°C (105°F), although 37.8°C (100°F) is more typical under current operating conditions.

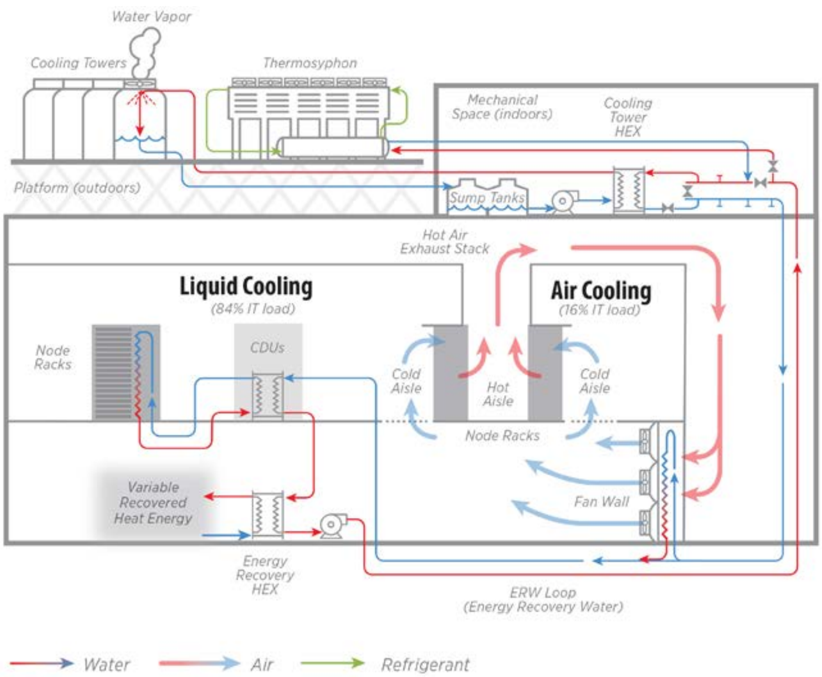

Figure 2 Cooling system schematic for the HPC data center located in the ESIF.

After the CDUs, the ERW loop passes through a plate-and-frame heat exchanger located in a mechanical room below the data center that is centrally located between the office and laboratory space for increased heat recovery efficiency to both building spaces. Data center waste heat is used to temper the outside ventilation air for the high-bay laboratories, and it is also used in active convective heat transfer chilled beams along the office space perimeter. The waste heat that cannot be recovered makes its way through the ERW loop first to the TSC, where it is rejected sensibly to the atmosphere; and then to a plate-and-frame heat exchanger connected to the cooling tower loop, where the waste heat is rejected evaporatively to the atmosphere. The cooling tower loop currently consists of four cooling towers that turn on in stages depending on the thermal load, with typical operation utilizing two towers at one time. Water is consumed by using the open-loop tower water system through evaporation, drift, and blowdown (the process by which the tower water keeps the dissolved solids under a desired count). Chemicals are also consumed in this process (biocides, corrosion inhibitor, and bio-dispersant) to keep the water at the needed balance to avoid fouling the piping or heat exchanger. Side-stream sand filters also operate to keep the cooling tower loop clean. The four cooling towers are paired with remote indoor sump tanks to eliminate the need for basin heaters, and all outdoor pipes are sloped so that water drains back into these tanks if the tower water system serving the data center is shut down.

Integration. Only a one-day outage to the HPC data center was required to integrate the TSC into the ERW loop. This outage was needed to cut the 350-mm (14-in.) diameter ERW return pipe (prior to the cooling tower heat exchanger) to install a control valve between the existing taps intended for the 7.5-MW and 10-MW (25.6 and 34 million Btu/h, respectively) future upgrades (many years out) in order to minimize HPC production downtime. New 150-mm (6-in.) pipes were installed to these taps to act as supply and return lines to the TSC unit, along with a 150-mm (6-in.) control valve that works in conjunction with the 350-mm (14-in.) control valve, as shown in Figure 3(a). For this installation, when the TSC is running it will either reduce or remove the entire thermal load prior to the cooling tower heat exchanger interface. The other construction activities were conducted without impacting HPC operations, and they consisted of the following: a slight structural modification to the outside cooling tower platform to accommodate the TSC placement, running 150-mm (6-in.) pipes from inside the ERW tie-in points to the outside platform to connect to the TSC, electrical runs for the TSC panels and fans, lightning protection, and integrating controls with the building management system. A crane was used on two different occasions: first to lift steel pipe, followed by the steel platform material and the TSC unit itself. The TSC was placed on a platform intended for future cooling towers, as shown in Figure 3(b). Note that of the seven cooling towers shown, three are for the lab/office space (a separate, isolated system), and the other four handle the HPC data center load. Sufficient metering was also added to quantify power and water differences when the TSC is running or turned off.

Figure 3 (a) Pipe modification to the ERW loop and (b) TSC installation.

MODELING

As part of the initial evaluation of both the current and hybrid cooling systems, an hourly-based annualized system simulation model was developed to predict how the total HPC heat rejection system would perform across all 8,760 hours of a typical meteorological year. Detailed energy balances were conducted for each hour, and then the results were displayed on an interactive schematic diagram, as shown in Figure 4. Separate independent performance models were developed for the TSC, cooling tower, heat exchangers, pumps, and heating load demands. Then for the varying temperature conditions and utility costs for each hour of the year, data center loads were placed on the heat rejection system. Simulations were conducted to evaluate the impact of systems comprising different heat rejection components in operation and different control strategies. The interactive schematic allowed for real-time viewing of the hourly performance of all major system components along with calculations of key overall annual metrics. An average energy cost of \$0.07/kWh and average fully burdened water cost of \$1.61/m^3 (\$6.08/1,000 gal) were used in the modeling analysis.

Some of the results from the preliminary analysis are shown in Figure 5 and Figure 6. Figure 5(a) shows the expected thermal load that will need to be rejected to the atmosphere. The initial simulations assumed a fixed total thermal load of 0.910 MW (3.1 million Btu/h). Starting at an outside DB temperature of 18.3°C (65°F), a portion of the heat created can be captured and constructively utilized by the building heating loop and thus start to reduce the heat that needs to be rejected to the atmosphere. As the outside DB continues to drop toward 8.3°C (47°F), more of the heat created can be constructively utilized for heating the building until the amount of heat captured becomes limited by the minimum return temperature of the building heating loop. At this point, the maximum heat captured for building heat is 0.434 MW (1.5 million Btu/h), yielding a remaining 0.496 MW (1.7 million Btu/h) that must still be rejected to the atmosphere.

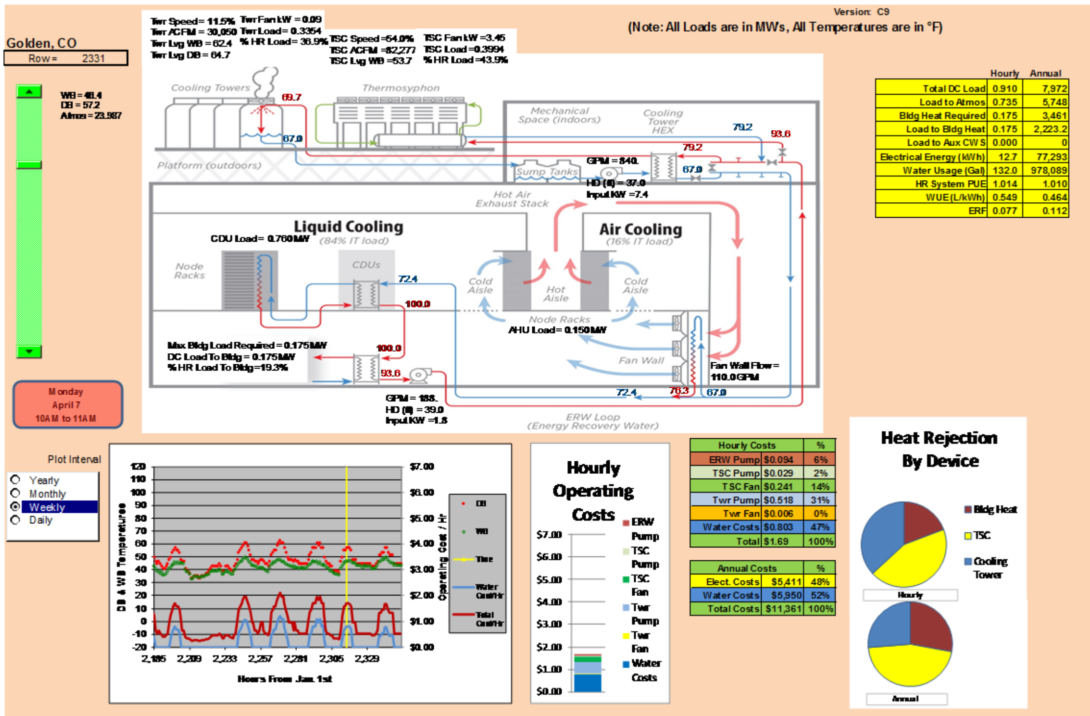

Figure 4 Typical system simulation schematic screenshot from the simulation program.

Figure 5(b) shows the projected cooling tower make-up water flow requirements with only the existing cooling tower system and with the hybrid cooling system as a function of the ambient DB temperature. With the current expected thermal loads, the TSC is able to handle the entire thermal load at DB temperatures cooler than 9.4°C (49°F), which occur approximately 50% of the year for this location.

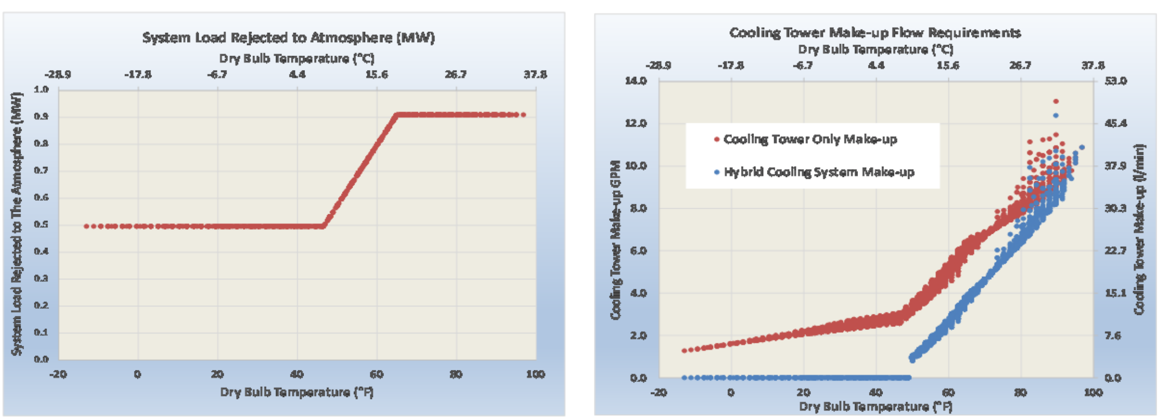

Figure 5 (a) System load rejected to the atmosphere and (b) cooling tower make-up flow rate.

As shown in Figure 6(a), on an annualized basis the system with only the cooling tower is projected to require slightly more than 8,300 m³ (2.2 million gal) of make-up water. Adding the TSC to build the hybrid cooling system reduces the annual cooling tower make-up water consumption to 3,700 m³ (0.98 million gal), a savings of 4,650 m³ (1.23 million gal)—or 56%.

Figure 6(b) shows the modeled total utility costs (energy + water) for the two heat rejection systems relative to the ambient DB temperature. On an annualized basis, the hybrid cooling system is projected to reduce the annual utility costs by 40% in addition to achieving a significant 56% annualized water savings.

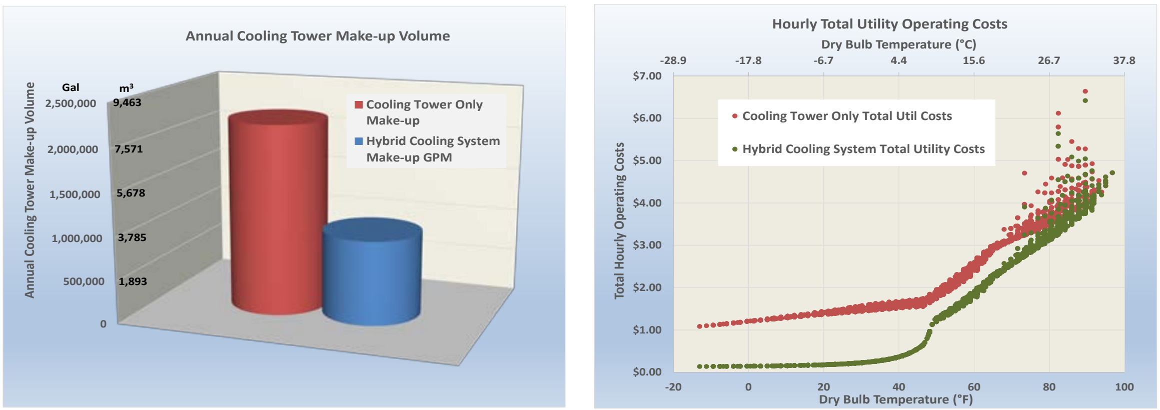

Figure 6 (a) Annual cooling tower make-up volume and (b) hourly total utility operating costs.

CONCLUSION

Improving data center operational efficiency requires focusing on both energy and water use. The warm-water liquid cooling loop employed at the ESIF's HPC data center has proven to be very energy efficient in operation, but it has a significant annual water use requirement. Initial system modeling results indicate that the use of a hybrid heat rejection system comprising a sensible heat rejection device located upstream and in series with an open cooling tower can significantly reduce both the annual water consumption and operational cost relative to the existing traditional cooling tower system. A follow-up paper will detail the test scenario conditions and provide the test results. These tests will also be used to validate the system simulation model and make any refinements as needed. The evaluation of the TSC's performance at the data center in Colorado will also determine a path forward at the laboratory in New Mexico for possible deployment in a large-scale system—not only for data center use but also possibly site wide.

ACKNOWLEDGMENTS

Thomas Carter and Zan Liu are employed by Johnson Controls. Johnson Controls developed and manufactures the TSC that is used as the dry heat rejection device in the hybrid cooling system described in this paper. They also developed the full heat rejection system simulation program.

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