Using Water Wisely for California Dairies

Waterside Economizer at The Energy–Water Nexus

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Waterside economizers have gained prominence in recent years because of greater focus on reducing utility costs and increasing efficiency. While data centers are taking most of the limelight in waterside economizer applications due to their ever-increasing loads and new ASHRAE thermal guidelines,[1] the application of these systems in other industries is also showing promise. This article discusses the applicability of waterside economizers at dairies, offers guidance on various design and control considerations for optimal performance, and provides field data from one such installation.

The Dairy Industry

California's Central Valley produces approximately 41 billion pounds (18.6 billion kg) of milk annually, accounting for approximately 21%[2] of the total milk produced in the United States. For this milk to be considered Grade A, it needs to be be cooled to 50°F (10°F) or less within four hours or less, and to 45°F (7.2°C) or less within two hours after the completion of milking.[3] However, most dairies cool the milk to about 38°F (3.3°C) to account for heat gain while in storage and during transportation.

This cooling load is roughly constant throughout the year, and using an approximate industry standard flow rate of 8 gallons (30.3 L) of milk/cow/day, this load equals about 20,000 tons (70,320 kW) of refrigeration load each day of the year!

To meet this load, a good number of medium and large dairies,* which account for approximately 58% of all dairies in California,[4] employ a two-stage milk cooling process whereby a plate-and-frame heat exchanger is used to first precool milk using groundwater before being cooled by a chilled glycol loop.[5] While the groundwater precooling loop, often referred to as free cooling,

* From this data, all dairies with average number of cows per dairy greater than 1,500 are assumed to fall under medium/large category.

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is designed to cool milk and reduce the load on the mechanical refrigeration system, it achieves moderate heat extraction from the milk, usually ranging from 5°F (2.8°C) to 15°F (8.3°C). Many times the heat transfer is on the low end of this spectrum because of the higher groundwater temperatures, which are increasingly found in the region. Therefore, the second stage, i.e., the mechanical refrigeration system, must handle the majority of the cooling load.

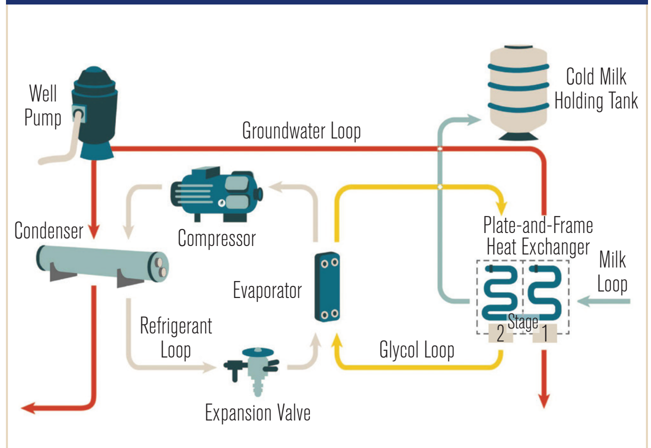
Refrigeration systems in dairies are typically built-up units with semi-hermetic compressors that operate based on load. Condensers on the refrigeration systems are also commonly cooled by groundwater. These condensers, which dictate the efficiency of the system by controlling the head pressure or condensing temperature, typically operate at fixed condensing temperatures ranging between 100°F (37.8°C) to 120°F (48.9°C) using direct acting pressure regulators, which throttle the water flow to maintain a fixed head pressure.

These high condensing temperatures result in inefficient operation of the refrigeration system, but are inevitable since improving this efficiency would require either increasing the flow rate of water through the condensers, which comes at the expense of greater water use and corresponding pumping energy, or reducing the temperature of the water flowing through the condensers, which is not achievable since groundwater is roughly at constant temperature year-round. These seemingly high condensing temperatures are not due to commissioning or maintenance issues, but are a norm in the industry due to various issues described in this article. *Figure 1* provides the typical setup of the system described above.

The secondary use/need of the once-through water used in the milk cooling process (both precooling and condensation), is known to vary widely with some dairies, wasting the majority of this water, while others use this water for other requirements. As a general rule, the once-through water from condensers and precooler is collected in open tanks and used for flushing manure from the freestalls and milk barns.

While most dairies filter out the manure from this flushed water, some sites allow the filtered water to either evaporate by holding the water in ponds or run the water into neighboring fields. Other dairies use this filtered water to farm neighboring fields. When the water is not used for farming, the majority of the water and corresponding energy used can be saved if a suitable solution is developed to move the cooling process away from the existing groundwater-based system.

FIGURE 1 Traditional milk cooling system.



When the water is used for irrigating crops, the amount of water and associated energy savings from moving to other types of cooling processes is comparatively less and also seasonal, since farming typically does not happen year-round. Ultimately, the amount of water needed is site-dependent. However, the overreliance of the industry on groundwater, with the prevailing drought conditions in the region, poses a serious reliability risk to the industry.

While the inefficiencies in these cooling systems and overreliance on groundwater provide ample, cost-effective opportunities to make a positive environmental impact, significant challenges also need to be overcome.

First, the refrigeration vendor/contractor industry serving dairies in California is small, local, and comparable to a cottage industry. Approximately 20 to 25 vendors control 95% of the market. This trusted network presents higher barriers to entry for not only new players, but also to new technologies. The desire to adopt efficient technologies and the knowledge base required for their correct implementation is usually lacking. Therefore, any solution proposed needs to be acceptable to the vendors from a technical, implementation, and maintenance point of view.

Second, the industry's lack of appetite for investment in efficiency must be overcome. Utility costs account for less than 10% of operating costs and only 2%[6] of total costs for a typical dairy. Energy and cost savings do not always provide enough motivation to move the market toward the adoption of efficient technologies. Hence, in addition to efficiency and cost savings, any solution that is proposed needs to show direct positive impact on the core business of milk extraction and cooling.

The major issues that appeal to typical dairy owners include increased reliability of the cooling system, decreased reliance on groundwater, reduced maintenance costs, and a solution that will address the complete refrigeration system rather than take a piecemeal approach.

Some solutions addressing these issues that have gained partial acceptance over the years include upgrading to air-cooled condensers and installing closed-loop fluid coolers for milk precooling. While air-cooled condensers help reduce reliance on groundwater, they fall short from an efficiency standpoint due to improper and inefficient head pressure control. This is particularly the case due to the closed nature of the industry, which has shown tremendous resistance to the adoption of newer technologies such as microchannel condensers, floating head pressure controls, etc. Additionally, the copper tubing in air-cooled condensers has been known to crack and leak refrigerant due to their continuous exposure to the methane/ammonia-rich dairy environment.

Similarly, while replacing groundwater precooling with a closed-loop fluid cooler has also had some success, it fails to address the inefficiencies associated with the mechanical refrigeration system described above. Therefore, while both of these solutions partially address some of the key issues, they fall short of providing the complete solution.

Waterside Economizer

The application of waterside economizers to dairies addresses all the above-described issues while substantially reducing the use of water in the cooling process and improving the overall system efficiency. While a majority of components and design criteria needed for the adoption of waterside economizers for dairy application are similar to data centers, a few key differences exist.

First, a closed-loop fluid cooler needs to be considered instead of open cooling tower. With a closed-loop fluid cooler (referred to as "tower" from here on), two completely isolated loops of water coexist. The first loop is the process fluid needing to be cooled, which is isolated from exposure to ambient air/atmosphere by being circulated through closed coils inside the tower.

The second loop is the open loop of water or sump water that is sprayed on the coils for the evaporative cooling process to take place. By separating these two streams of water, the quality of the process fluid is maintained, which eventually helps maintain the performance of the condenser and plate-and-frame heat exchanger. From a performance standpoint, one obvious disadvantage is the extra approach temperature that is added to the overall tower performance. However, this is unavoidable to ensure the integrity of the process fluid and to reduce the maintenance cost of the overall system.

The second key design difference regards the configuration of the system. In typical applications of integrated[7] waterside economizers for data centers, the return chilled water is precooled by the tower's condenser water, reducing the load on the chiller. This configuration is possible and also achievable since the design return chilled water temperature is typically around 54°F (12.2°C) and can sometimes be as high as 70°F (21.1°C). This temperature range provides ample hours of the year in most climate zones when the achievable condenser water temperature will be well below the return chilled water to perform precooling.

In the case of dairies, however, since return chilled water temperature ranges between 38°F (3.3°C) and 42°F (5.5°C), the above-described configuration is not feasible. Consequently, a similar configuration that circulates process fluid from the tower concurrently but separately to precool the milk and condense the refrigerant is considered. This configuration uses the typical preexisting plate-and-frame heat exchanger and preexisting shell-and-tube condensers found in dairies, which helps minimize the cost.

With the installation of this system at dairies, the overall cooling system efficiency is improved since the tower will be able to produce water at much lower temperatures (~57°F) [13.9°C]) than average groundwater temperature (~70°F) [21.1°C]) for the majority of the year in California's Central Valley. An illustration of this is provided in *Figure 2* where the average tower water temperature with a 3°F (1.7°C) approach to wet-bulb temperature is plotted along with the average groundwater temperature; this plot is what produces the weighted average value of 57°F (13.9°C) mentioned above. The 3°F

FIGURE 2 Wet-bulb +3°F approach versus groundwater temperature.

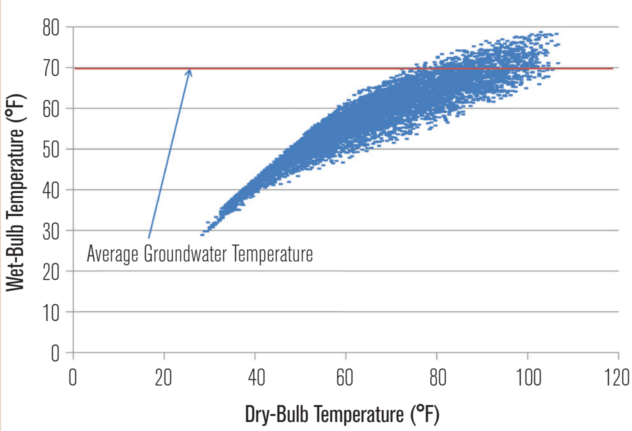
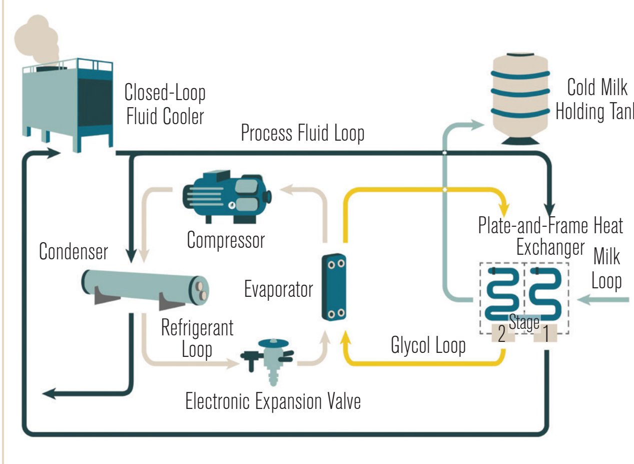


FIGURE 3 Proposed milk cooling system.



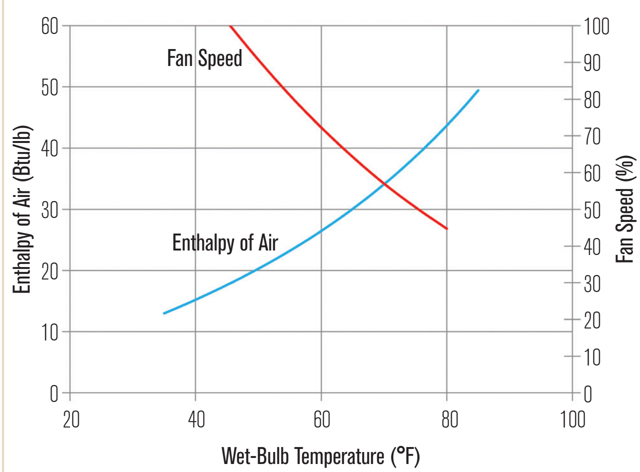
(1.7°C) approach used is based on the control strategy described in the performance data section below.

By circulating this lower-temperature water through the precooling stage, a significant amount of cooling load is now shifted from the mechanical refrigeration side to the precooling side that results in energy savings from reduced use of the refrigeration system. Furthermore, by circulating this lower-temperature water through the condensers, the condensing temperatures are brought down substantively, gaining efficiency on the refrigeration side. In fact, other opportunities to further improve the system efficiency on the refrigeration side are also possible and discussed below. *Figure 3* shows the proposed cooling system with a waterside economizer.

Since the cooling load at a dairy is fairly constant year-round, system level savings can be maximized if the tower can produce the coldest possible water at all times, which will ensure that the maximum possible cooling is handled in the precooling stage. In doing this, however, a few design factors need to be considered: a) the sizing of the tower, b) the impact of circulating very cold water (~35°F [1.7°C] to 55°F [12.8°C]) through the condensers, and c) the part-load efficiency of the mechanical cooling system.

First, in selecting and sizing a tower, three parameters are usually considered: (1) the design load (i.e., condenser water range and flow rate), (2) the desired approach temperature (condenser water supply temperature less wet-bulb temperature), and (3) the highest anticipated wet-bulb temperature of the location. When

FIGURE 4 Maintaining a constant approach temperature.



the performance of the tower is based on these three selection criteria, it can be observed that the approach temperature increases from the design value as the wet-bulb temperature drops. This behavior is due to the decrease in latent heat capacity and enthalpy of air at low wet-bulb temperatures. In other words, air has a lesser ability to give off heat for the evaporative cooling process at low wet-bulb temperatures.

For typical commercial building applications, this elevated approach temperature at low wet-bulb temperatures is not an issue since cooling load varies proportionally with outside air conditions. However, when considering a waterside economizer for constant-load applications, this design parameter becomes important. An illustration of this relationship can be seen in *Figure 4* in which the enthalpy of air and the fan speed of a tower are plotted with respect to wet-bulb temperature.

Using a manufacturer's product selection software, a constant cooling load of 60 tons (211 kW) (144 gpm [9.1 L/s], 10°F [5.6°C] range), and a fixed 5°F (2.8°C) wet-bulb approach is used across different wet-bulb temperatures to solve for fan speed. As the wet-bulb temperature lowers, enthalpy of air also drops, leading to an increase in fan speed to maintain the desired approach.

At 45.5°F (7.5°C) wet-bulb temperature, the fan operates at 100% speed to maintain the desired approach temperature. Below this wet-bulb temperature, the selected tower can no longer maintain the desired wet-bulb approach for the load. This result means that in sizing towers for economization in constant-load applications, consideration should be given to whether or not the tower can maintain the desired approach at the lower end of the wet-bulb range.

The 5°F (2.8°C) approach temperature used in this example is for illustration purposes only, and no standards apply for the dairy application. Since no code or standard requirements apply, one popular selection/sizing methodology is the "Jan. 1 and July 1" performance evaluation. In this selection method, the approach temperatures for the given load are evaluated at Jan. 1 conditions (winter wet-bulb conditions) and July 1 conditions (summer wet-bulb conditions) to determine whether the desired approach values are being met. The typical target approach temperature ranges between 5°F (2.8°C) to 8°F (4.4°C). However, if the approach temperatures during these two conditions are found to be beyond this desired range, the tower is upsized or reselected.

A cost benefit analysis of different selections with corresponding approach temperatures can be performed to determine the optimal selection for a given application since low approach towers can significantly increase cost and footprint.

For applications where standards do apply, the tower performance evaluation across the wet-bulb range is essential. As an example, California's Title 24 guidelines for data centers now require 100% economization at 35°F (1.7°C) wet-bulb temperature. If the above-selected tower and load (60 tons [211 kW]) are considered along with a 44°F (6.7°C) chilled water temperature setpoint and 4°F (2.2°C) plate-and-frame heat exchanger approach, the tower must be able to produce 40°F (4.4°C) water at 35°F (1.7°C) wet-bulb to achieve 100% economization, which the selected tower will be unable to achieve. Therefore, careful consideration to the tower performance at low wet-bulb temperatures should be given during the design stage.

The second factor to consider in an integrated economizer application is the impact of circulating low temperature water through condensers. A number of chiller manufacturers typically prescribe no less than 55°F (12.8°C) entering condenser water temperature. This is because a minimum lift is required between the high and the low side for optimal system performance. "Lift" is the difference between condensing pressure and suction pressure, and it is the amount of work that the compressor does in moving the refrigerant through the system.

While typically the lower the lift, the more efficiently the compressor operates, there are limits to how low this lift can and should be. Although manufacturers typically provide guidance based on minimum entering condenser water, the condensing pressure is, in fact, based on leaving condenser water temperature. However, since leaving condenser water temperature is dependent on dynamic variables including load, entering condenser water temperature, and flow rate, manufacturers sometimes provide guidance based on the minimum entering water temperature, which will ensure that the minimum lift is maintained at all times irrespective of other variables. This minimum lift is dependent on many factors including the oil management system, compressor type, and the type of expansion valve on the system. Expansion valves primarily perform the task of modulating the refrigerant flow to the evaporator while maintaining the desired superheat.

Thermal expansion valves (TXVs), which have traditionally been dominant in the HVAC&R industry, operate based on mechanical balance of pressures, causing them to respond slowly to changes in differential pressure. This characteristic of the TXV necessitates a minimum pressure differential across the high- and low-pressure sides of the system for them to operate as desired. If a system with TXV is allowed to operate below this design differential pressure, i.e., at lower than design condensing temperatures, the thermal expansion valve becomes undersized since it is now operating at this lower than designed pressure drop across the valve. This "starves" the expansion valve of refrigerant flow, which results in a warmer than desired evaporator and potentially unsafe superheat.

One way to overcome this limitation in the waterside economizer retrofits on built-up refrigeration systems like the ones found in dairies is to upgrade from TXV to electronic expansion valves (EEVs). While the operating principle of EEVs is the same as TXV, EEVs use electronic controls to modulate the flow of refrigerant in the system while employing stepper motors to open or close the valve port in very small increments that provides capacity modulation ranging from 10% to 100%. This control enables them to swiftly respond to changing compressor lift and provides the ability for the system to operate at lower lift. The data presented in the next section demonstrates this functionality.

The third factor to consider in an integrated waterside economizer application is the part-load efficiency of the mechanical cooling system. One of the consequences of economizer installations is the low-load conditions experienced by the mechanical cooling equipment for many months out of the year since load is shifted to the first stage. This low load is further accentuated by the lower condenser water temperatures, which increases the capacity of the cooling system. For built-up refrigeration systems with reciprocating compressors found in most dairies, it is advisable to install cylinder unloaders for proper capacity control. Unloaders provide excellent part-load efficiency while also helping maintain the required suction pressure.[8]

Performance Data

Original System

A medium-sized dairy in Winton, Calif., with a constant cooling load of approximately 42 tons (147.7 kW) used a two-stage milk cooling process depicted in *Figure 1*. During the site investigation, it was determined that approximately 20% of this cooling load was handled by groundwater precooling, while the remaining 80% was handled by the refrigeration system. The built-up refrigeration system consisted of three primary semi-hermetic reciprocating compressors (two 18 hp [13.4 kW], one 12 hp [8.9 kW]) and one backup 10 hp (7.4 kW) compressor. The three primary compressors were cooled by groundwater condensers with direct acting pressure regulators maintaining a fixed 110°F (43.3°C) condensing temperature.

Based on these operating conditions, the overall system efficiency was calculated at 1.4 kW/ton (0.40 kW/kW) and a total water use of approximately 68 million gallons/year (257 million L/year). While some of this water was used for secondary needs within the dairy, more than 50% of water was estimated to be unnecessary, but required expending additional energy to move the water to the fields.

To improve the efficiency of the overall milk cooling system, reduce the dairy's dependency on groundwater, and reduce maintenance issues associated with minerals from groundwater deteriorating the condensers and the plate-and-frame heat exchanger, the dairy decided to retrofit the system with a waterside economizer.

Installed System and Performance

As a part of the system retrofit, as depicted in *Figure 3*, the site installed a 134 nominal ton (471 kW) closed-loop fluid cooler (tower), electronic expansion valves, a new close approach plate-and-frame heat exchanger and a condenser pump that also circulated water for milk precooling. The fan on the tower was installed with a VFD to optimize the energy use. The VFD was programmed with the following control sequence:

- **High-speed mode (60 Hz, full speed):** When the approach temperature goes above 3°F (1.7°C);
- **Medium-speed mode (50 Hz):** When the approach temperature reaches 2°F (1.1°C);
- **Low-speed mode (40 Hz):** When the approach temperature reaches below 1°F (0.6°C); and
- **Shut-off mode:** When the temperature of water produced by the tower drops below 34°F (1.1°C) (to avoid freezing).

This control strategy ensures that the tower maintains a minimum approach of 3°F (1.7°C) at all times, which maximizes the economizer and precooling mode operations. Additionally, this control strategy ensures that the fan does not wastefully expend energy to gain marginal benefit. *Figures 5* and *6* provide the monitored performance data of the tower. During the monitoring period, the wet-bulb temperature ranged from 38°F (3.3°C) to 58°F (12.8°C).

In plotting *Figures 5, 6,* and *7,* approach temperature, fan power and saturated condensing temperature were averaged for each 1 degree wet-bulb temperature bin. The authors believe that with this approach, the system evaluation is easier to visualize. The fan power shown in *Figure 6* does not follow a smooth downward trend as would be expected (like in *Figure 4*). This behavior is due to two reasons: a) the installed temperature/RH sensor at the site was found to be picking up artificially high humidity from air coming from the milk parlor (which

FIGURE 5 Cooling tower approach.

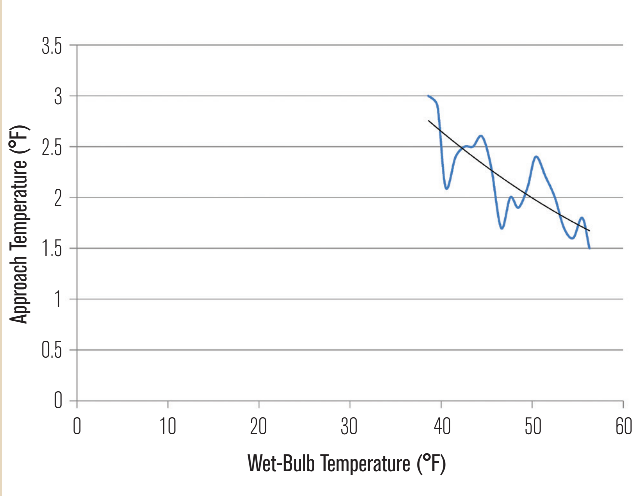
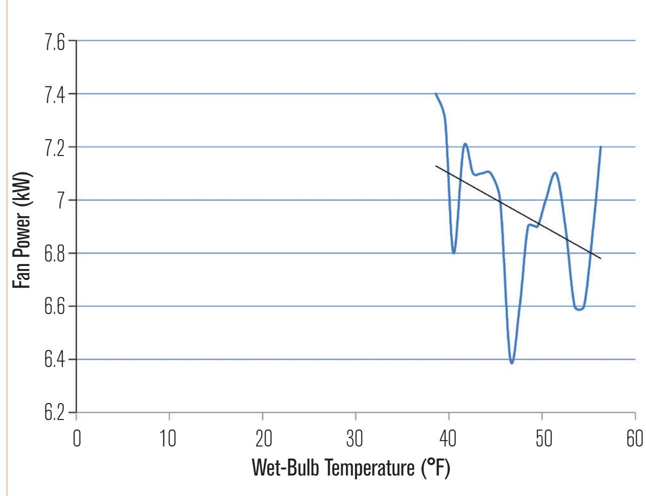


FIGURE 6 Cooling tower fan power.



was addressed later) and b) intermittent fluctuations in cooling load (which results in high return water temperature) occurs during the milking of high-yield cows.

With the installation of EEVs, the direct acting pressure regulators that previously throttled the water flow to maintain a fixed head pressure were removed. No floating head pressure control strategy was implemented. Instead, the head pressure was allowed to land at the achievable value based on the flow rate and temperature of the water circulated through the condensers. Based on condenser capacity and design flow rates, it was originally estimated that the lowest possible condensing temperature was between 55°F (12.8°C) and 60°F (15.5°C), which was also verified based on the monitoring data.

Figure 7 provides a snapshot of the measured saturated condensing temperature versus wet-bulb temperature. The saturated condensing temperature plotted in this figure is based on monitored discharge pressure converted to temperature equivalent. Monitoring the condensing pressure instead of condensing temperature ensures that any system subcooling does not falsely impact the analysis, and the true performance of the system is evaluated.

Based on this data, the system was found to maintain a saturated condensing temperature 15°F to 20°F (8.3°F to 11.1°F) above wet-bulb temperature down to a minimum condensing temperature of 60°F (15.6°F) at 39°F (3.9°F) wet-bulb temperature. These lower condensing temperatures represent a dramatic improvement in system efficiency in comparison to when operating at fixed 110°F (43.3°C) condensing temperature.

FIGURE 7 Saturated condensing temperature.

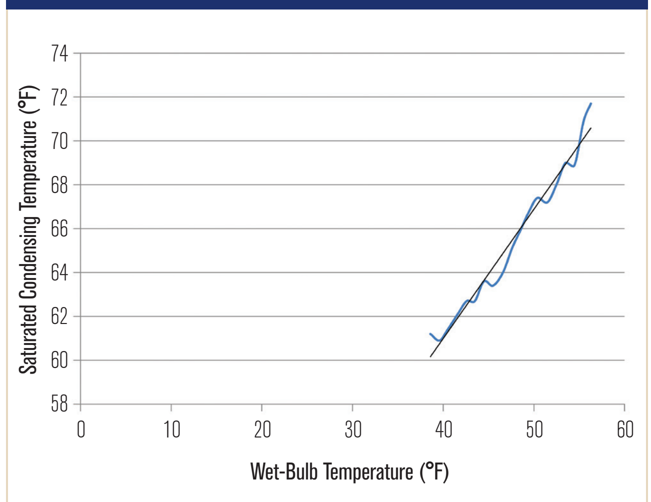


Figure 8 provides a comparison of the modeled system efficiency between the baseline and installed system. In this figure, the baseline efficiency (kW/ton [kW/kW]) includes energy use of the refrigeration compressors and the energy use of the groundwater pumping system used to circulate water for precooling and to groundwater condensers. Similarly, the overall kW/ton [kW/kW] of the installed system consists of energy use associated with the compressors, tower fan, spray pump, and the pump used for circulating process fluid to the precooler and condensers. The system is programmed to switch back to groundwater cooling any time the tower produces water at temperatures greater than 76˚F (24.4°C). Hence, at these conditions, the system is expected to operate as in baseline conditions, which can be observed

at the tail end of the installed kW/ton (kW/kW) curve in *Figure 8*.

The pump serving the precooler and condensers, which was installed as a part of this system upgrade, was equipped with a 10 hp (7.4 kW) constant speed motor. To optimize energy use on this pump, a VFD should be installed to vary the speed of the pump based on maintaining fixed pressure in the line. While this pressure setpoint is dependent on many factors, the location of the pressure transducer plays a key role in maximizing system efficiency.

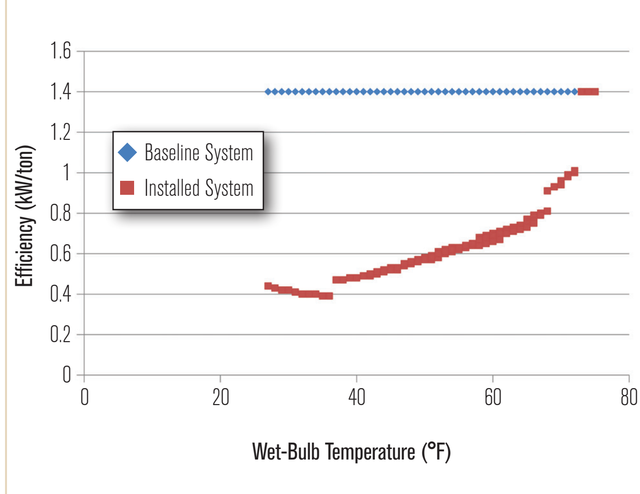
This transducer should be located close to the plate-and-frame heat exchanger since this will ensure that a constant flow rate is circulated through the precooling stage at all times, which will maximize the amount of milk cooling in the precooling stage and subsequently reduce the load on the refrigeration system. This location also ensures that the pump sees the changing load in the system (i.e., compressors turning ON/OFF) and responds accordingly by changing the flow and head, which maximizes savings on the pump.

With this project, the overall water use at the dairy decreased by 60% to approximately 27 million gallons/year (102 million L/year). This project resulted in approximately 40% reduction in system energy use.

Conclusion

The application of integrated waterside economizer continues to gain increasing acceptance across industries. Within the dairy industry, waterside economizer retrofits substantially improve the overall system efficiency as demonstrated through this article. In addition to energy benefits, when retrofitted to existing groundwater based systems, waterside economizers deliver substantial water savings while also prolonging the life of equipment. While other technologies such as air-cooled condensers with advanced controls can potentially result in substantial energy and water savings, the industry at this time has yet to embrace such alternatives and continues to look at waterside economizers to deliver on much needed savings. Furthermore, while the economic value of water saved at this time through these retrofits is only limited to the embedded pumping energy, the industry values the resource highly due to prolonged drought in the region that has put the long-term viability/sustainability of the industry at risk.

FIGURE 8 Baseline and installed system efficiency.



To maximize the savings potential from the implementation of the waterside economizer in dairies, some of the factors described in this article need to be considered. Critical aspects including equipment type, selection/sizing, and control strategies require careful evaluation to ensure the right balance between cost and energy savings. Applying this technology to the existing groundwater-based cooling systems in the California dairy market could result in significant energy and groundwater savings. These techniques should be considered for future markets to continue leveraging the benefits of waterside economizers.

References

1. ASHRAE. 2015. *Thermal Guidelines for Data Processing Environments, Fourth Edition.* Atlanta: ASHRAE.
2. USDA. 2015. "California Agricultural Statistics 2013 Crop Year." U.S. Department of Agriculture, National Agriculture Statistics Service. https://www.nass.usda.gov/Statistics_by_State/California/Publications/California_Ag_Statistics/Reports/2013cas-all.pdf.
3. USDHHS. 2015. "Grade 'A' Pasteurized Milk Ordinance." U.S. Department of Health and Human Services and Food and Drug Administration.
4. CDFA. 2015. "California Dairy Statistics Annual: 2015 Annual Data." California Department of Food and Agriculture and the United States Department of Agriculture.
5. Ludington, D., et al. 2004. "Dairy Farm Energy Management Guide California." Southern California Edison.
6. Ellerby, J. 2010. "Challenges and Opportunities for California's Dairy Economy." California Center for Cooperative Development.
7. Taylor, S. 2014. "How to design and control waterside economizers." *ASHRAE Journal* 56(6).
8. Reindl, D. 2013. "Sequencing and control of compressors: Industrial refrigeration." *ASHRAE Journal* 55(11). ■

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