Ultra-low charge ammonia chillers for energy efficiency in industrial applications

Ammi Amarnath
Electric Power Research Institute
EPRI 3420 Hillview Ave
Palo Alto, CA, 94043
USA
aamarnath@epri.com

Sara Beaini, Ph.D.
Electric Power Research Institute
EPRI 3420 Hillview Ave
Palo Alto, CA, 94043
USA
sbeaini@epri.com

Chris Holmes
Electric Power Research Institute
EPRI 3420 Hillview Ave
Palo Alto, CA, 94043
USA
cholmes@epri.com

Mukesh Khattar, Ph.D.†
Electric Power Research Institute
EPRI 3420 Hillview Ave
Palo Alto, CA, 94043
USA

Aaron Tam
Electric Power Research Institute
EPRI 3420 Hillview Ave
Palo Alto, CA, 94043
USA
atam@epri.com

Colin Lee
Electric Power Research Institute
EPRI 3420 Hillview Ave
Palo Alto, CA, 94043
USA
colee@epri.com

Keywords
domestic energy efficiency, demand response, industrial energy saving

Abstract
Ultra-low charge air-cooled ammonia (R-717) chillers offer versatility for industrial applications with both energy efficiency and water saving capabilities. Field evaluation of this new innovative product demonstrated its energy and water saving potential with the safe usage of zero GWP natural refrigerant based, air-cooled packaged chiller at a food processing industrial host site in the USA. Two key energy efficiency advances of the technology enable the significant reduction of ammonia refrigerant charge by an order of magnitude, specifically by a factor of 20 compared to conventional ammonia-based chillers. The two innovations are: (a) Advanced microchannel heat exchangers, which have improved heat transfer effectiveness due to the increased surface area; and (b) A new, pre commercial, semi hermetic compressor with no mechanical seal between the compressor and the compressor motor. The advanced microchannel heat exchanger has integrally brazed airside fins, which gives higher heat transfer effectiveness. The heat exchanger is all aluminium; efficiency in heat transfer allows for the same capacity to be delivered with much lower refrigerant charge. A mechanical seal is one of the most vulnerable point of refrigerant leak in a refrigeration system, and this is the first type of compressor compatible for ammonia refrigerant that is available globally. The new semi-hermetic compressor has aluminium windings since typically the motor windings are made of copper, which are incompatible with ammonia. Accordingly, the combination of these two innovations enabled the development of a packaged, air-cooled, ultra-low charge ammonia-based chiller, which eliminates and reduces the many burdensome regulations that otherwise govern the use of ammonia in industrial plants. The evaluated chiller uses less than 1.5 pounds (0.68 kg) of ammonia refrigerant per ton refrigeration (TR) capacity of the chiller, which corresponds to less than 75 pounds (35 kg) for the 50 TR chiller at the field demonstration site. While the field evaluation project is on-going, the air-cooled ammonia (R-717) system has been evaluated against an existing conventional water-cooled chiller with R-507A as a baseline at the food processing site. Field performance results show up to 40 % improvement in energy efficiency and water savings of 2.35 gallons of water per kWh of electricity used by the air-cooled ammonia chiller.

Introduction
Industrial food processing is a key part of the energy-intensive manufacturing group of the industrial sector's energy consumption. The industrial sector itself accounts for up to 25 % of total electricity consumption in the United States[1]. This presents an avenue for introducing versatile energy efficiency technologies in the effort to reach energy goals, as well as a potential area for decarbonization through electrification. Furthermore, industrial food processes frequently employ chillers with high global warming potential refrigerants such as synthetic hy-

† Deceased Feb 13, 2020

1. U.S. Energy Information Administration, https://www.eia.gov/energyexplained/use-of-energy/industry.php.

drofluorocarbon (HFC). HFC refrigerants can be expensive to manufacture and have significant negative environmental impact. This paper presents the results of a field demonstration of an ammonia-based process cooling system in a food processing industrial application. The ammonia system is over 20 % more efficient than comparable HFC based process cooling systems. The field demonstration results advance technological and scientific knowledge by demonstrating that an ultra-low charge, and practically leak-free, ammonia refrigerant system can meet safety requirements with limited regulatory burden, while demonstrating energy efficiency. The regulatory burden for traditional, higher-charge, ammonia systems is a significant barrier that has prevented broader use of this natural refrigerant for a more efficient vapor compression cycle. Additionally, this system demonstrated the effectiveness of a refrigerant charge reducing and water-saving innovation using a microchannel, air-cooled condenser. This eliminates the need for water for cooling, which can be a limited and precious resource in drought-prone regions such as California. The exclusion of water usage also means there is no need for chemical usage to treat cooling tower water. The entire system can be pre-packaged, factory charged, and brought to a site as an integrated package that simplifies field installation and makes it cost effective with a smaller footprint than a comparable water-cooled chiller system.

There are worldwide initiatives that aim to achieve carbon emission reductions globally to combat climate change. Many countries have goals to reduce their emission levels significantly in the coming decades, as well as investments in clean energy, energy efficiency and energy resilience. In Europe, the European Union (EU) has ratified the Paris Agreement to reduce emissions by at least 40 % below 1990 levels by 2030[2]. In the United States, while the federal administration has formally notified their withdraw from the Paris Agreement, 25 states joined the United States Climate Alliance to commit to the goal of 26 %–28 % below 2005 levels by 2025. In particular, California has established its climate leadership within the United States with a target of 40 % below 1990 levels by 2030 and to reach carbon neutrality by 2045[3].

REFRIGERANT REGULATIONS

Hydrofluorocarbon (HFC) refrigerants are predominantly used in process cooling applications due to several reasons: they are non-toxic, non-flammable and have low ozone depletion potential. They are also compatible with copper used in hermetic or semi hermetic compressor motors. However, these synthetic HFC refrigerants tend to have very high global warming potential (GWP), which has prompted many regulations in recent years to limit and phase down their usage. The Kigali amendment to the Montreal Protocol went into effect in 2019 and was ratified by over 20 counties, which includes the phase down of 85 % of HFC refrigerants by the 2040s. In the EU, centralized refrigeration systems for commercial use with capacity over 40 kW will be banned from using refrigerants with GWP above 150 starting 2022, and stationary refrigeration and air-conditioning equipment will be banned from using refrigerant with GWP above 2,500 starting 2020[4]. Even though the Kigali amendment has yet to be ratified in the U.S. and the Environmental Protection Agency's (EPA) Significant New Alternatives Policy (SNAP) 20 rule was vacated in court, states like California have taken the lead in introducing regulations similar to the Paris Agreement. The California Air Resource Board (CARB) has proposed the most stringent regulations within the U.S., by banning the sale or installation of new systems with refrigerants with GWP greater than 150 starting in 2022[5]. Nationwide regulation will depend heavily on the success of California and other states such as New York and Massachusetts, which also have legislation in place to start phasing out high GWP refrigerants.

AMMONIA REFRIGERANT

Ammonia (R-717) is one of the oldest known natural refrigerants and offers three distinct advantages over industrial HFC refrigerants. First, R-717 is a naturally occurring substance that is environmentally friendly and does not deplete the ozone layer or contribute to global warming. Second, R-717 has superior thermodynamic qualities – it requires a sixth of the refrigerant flow as compared to R-404A, and therefore requires a sixth in size for a compressor. It is also inherently more energy efficient on a thermodynamic cycle, with 9–17 % improvement. Overall energy efficiency of the system can exceed 20 %–25 % once features such as premium motor, electronic expansion valve, and variable capacity compressor are included. Third, though R-717 is a hazardous substance, its recognizable odour is its greatest safety asset. Unlike most other industrial refrigerants that have no odour, ammonia refrigeration has a proven safety record because leaks are not likely to escape detection. However, use of R-717 in process cooling is hampered by many limitations such as potential leaks and special handling due to its B2L refrigerant classification. ASHRAE standard 34 classifies class B2L as refrigerants with higher toxicity and lower flammability[6]. Most traditional ammonia-based cooling systems used also require large amounts of ammonia, typically requiring 20 lbs–30 lbs[7] (9 kg–13.6 kg) per ton (3.51 kW) of capacity. This results in special handling and management plans, severely limiting the application of the technology. While advancements in the industry has seen the introduction of low charge ammonia chillers, which reduces the amount of ammonia needed to 5 lbs–10 lbs (2.3 kg–4.5 kg) per ton of capacity, these amounts are still subject to rigorous regulations. Additionally, they are either water cooled or evaporative cooled, both of which are consumers of water, which can be a limited resource in drought regions such as California.

R-717 is subject to restrictions on the federal, state and local levels. In particular, the U.S. EPA has different regulations applying for site inventory thresholds of 500 lbs and 10,000 lbs (230 kg and 4,500 kg) and requires emergency release notification in the event of leaks exceeding 100 lbs (45 kg) in a 24-hour

2. European Environment Agency, https://www.eea.europa.eu/.

3. United States Climate Alliance, http://www.usclimatealliance.org/.

4. Refrigerant Scenario – Rules and Regulations, CAREL, https://natref.carel.com/refrigerant-scenario-rules-and-regulations.

5. California Air Resources Board, https://ww2.arb.ca.gov/homepage.

6. Safety Standard for Refrigeration Systems and Designation and Safety Classification of Refrigerants, ASHRAE Standard 15 and 34, https://www.ashrae.org/technical-resources/bookstore/standards-15-34.

7. Shecco, World Guide to Low Charge Ammonia, http://publication.shecco.com/publications/view/world-guide-to-low-charge-ammonia----complete-report.

Figure 1. AURA Ultra-Low Charge Ammonia Air-Cooled Chiller by Mayekawa.

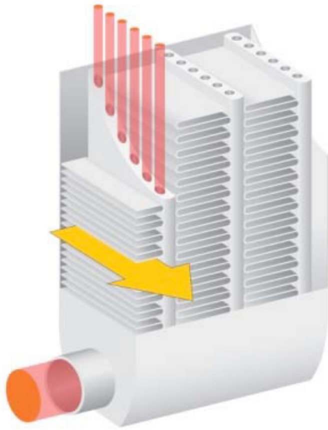

Figure 2. Advanced microchannel heat exchanger.

period. Similarly, Occupational Safety and Health Administration (OSHA) requirements apply to ammonia facilities, with additional requirements when exceeding the 10,000 lbs (4,500 kg) threshold[8]. State level programs are common too, most notably (and relevant to the field study discussed here) in California, where the quantity for increased scrutiny is 500 lbs (230 kg). Inspections and reporting are required at regular intervals, and compliance audits must also be undertaken at regular intervals[4]. Further restrictions may be applied at the local level, particularly for R-717 systems in highly populated areas. For these reasons, R-717 charge quantity reduction has becoming an increasingly hot topic in the industry since most regulations were intended to deal with large charge systems. Several efforts are currently underway to develop regulations specifically for low charge R-717 systems that can take advantage of ammonia's high efficiency while minimizing the risk of harm to due leaks.

Technology Description

This project pilot tested the AURA chiller (referred to herein as R-717 chiller) rated at 50 refrigeration ton (TR) (175 kW) and manufactured by Mayekawa shown in Figure 1. The R-717 chiller integrates several breakthrough innovations from Mayekawa detailed below that enable the development of this ultra-low charge air-cooled, packaged ammonia chiller. Two of these innovations in particular, makes the ultra-low charge air-cooled chiller practical, (a) Advanced microchannel heat exchangers; and (b) New, pre commercial, semi hermetic compressor with no mechanical seal.

The R-717 chiller uses advanced micro-channel heat exchangers as shown in Figure 2. The heat exchanger leverages high performance flat tubes with state-of-the-art airside fins, enhancing the performance on the refrigerant side and lowers airside pressure drops. Compared to conventional fin tube designs, the advanced microchannel heat exchanger has up to 40 % higher efficiency due to integrally brazed airside fins, which gives higher heat transfer effectiveness. This allows the heat exchanger to be reduced in size, which can be up to 20 % smaller with 50 % less weight. With the reduced system footprint, this minimizes structural support, installation and shipping cost. The heat exchanger is all aluminium and has a cost reduction of 5 % to 30 %. Thus, the key advantage of higher efficiency heat transfer allows for the same capacity to be delivered with just 40 %–60 % of the refrigerant. These combined benefits make an air-cooled condenser efficient and practical. Traditionally, chillers have been water-cooled or evaporatively-cooled since water is a better heat transfer medium, resulting in higher efficiency. The microchannel heat exchanger is a significant innovation since it allows the system to be air-cooled which does not require any water usage, and more importantly it operates with less refrigerant charge.

The R-717 chiller utilizes a newly developed, semi hermetic compressor with no mechanical seal between the compressor and the compressor motor. The technology has been applied in Japan but is new to the U.S. This is particularly important for a system utilizing R-717 since the mechanical seal is one of the most vulnerable point in a refrigeration system, and the seal can wear out over time and become prone to leakage. Though leakage from conventional HFC refrigerants are non-hazardous, leakage of R-717 is not tolerated due to its pungent smell and can be hazardous in large quantities. While semi hermetic and hermetic compressors for synthetic HFC refrigerants are common, no such compressor for R-717 is currently available anywhere in the world. The primary reason is that motor windings, usually made of copper, are incompatible with ammonia. This severely limits the application of R-717 due to safety concerns and systems are subject to rigorous regulations. Accordingly, the development of the semi hermetic compressor with aluminium windings for ammonia is a major breakthrough and a key component of the novel chiller package.

8. Occupational Safety and Health Administration, United States Department of Labor, https://www.osha.gov/.

The combination of the advanced microchannel heat exchangers and the semi-hermetic compressor in the demonstrated chiller technology addresses burdensome regulations that otherwise govern the use of ammonia in industrial plants, because the system is able to have ultra-low refrigerant charge and is practically leak free since there is no route for the refrigerant to escape in a semi hermetic compressor. The R-717 chiller uses less than 1.5 lbs (0.68 kg) of ammonia refrigerant per TR, which is less than 75 lbs (34 kg) for the 50 TR chiller. A refrigerant charge less than 110 lbs (50 kg) is the minimal regulatory requirement, and the ultra-low charge R-717 chiller is well under that threshold. For comparison, traditional ammonia plants use 20–30 lbs (9 kg–13.6 kg) of ammonia per TR, which is over 20 times the amount of refrigerant needed for the newly demonstrated R-717 chiller.

The newly demonstrated R-717 chiller also uses electronic expansion valves with advanced control logic. This allows the chiller to have faster response time that maintains optimal refrigerant superheat in the evaporator for more energy efficient operation as opposed to several HFC systems that still use thermostatic expansion valves.[9] Though the improvement depends on the control algorithms that dictate the chiller operation, electronic expansion valves usually perform better than thermostatic expansion, and can see efficiency gains of up to 20 %[10]. All these innovations and high efficiency features are integrated into a single packaged system for easy on-site installation. The pre-commercial chiller package is new to this industry, and there is no such packaged system using ammonia refrigerant that is presently available in the world.

Technology Demonstration

DEMONSTRATION SITE

The R-717 chiller was installed and demonstrated at an industrial food processing facility. The food processing facility, Takara Sake USA Inc. was established in Berkeley, CA in 1982. Sake is an alcoholic beverage that is made by fermenting special varieties of rice; this facility is the largest sake processing plant in the Americas. Takara itself is 150 years old and was founded in Japan. The Berkeley facility has gone through two structural renovations in 1987 and 1998. It underwent a third structural renovation where it added five new 14,500 gallons (54,888 l) fermentation tanks outdoors in 2018, which are cooled with the air-cooled ammonia process chiller. Six existing 14,500 gallons (54,888 l) fermentation tanks were transitioned from being cooled by a R-22 chiller to the R-717 chiller.

The sake-making process requires mixing of rice with yeast into a broth which must be fermented for 3 weeks in fermentation tanks. Like other alcoholic beverage making processes, the fermentation process is exothermic. In order to maintain the quality of the product, heat is continually removed by a water/glycol solution, thereby maintaining constant temperature in the fermentation tanks. After fermentation, the sake is then transferred to holding tanks for 3 months for the brew to age. After aging, the fermented mixture is pressed and filtered to remove solids and sent to the bottling plant.

As Takara Sake increases its production to meet growing demand, it needed additional cooling capacity, thus they installed the more efficient ultra-low charge R-717 chiller to chill the brine and cool the fermentation tanks. The chiller cools a mixture of glycol and water to a design temperature of 35 °F (1.7 °C). Glycol is used as an antifreeze since cooling water alone to temperatures close to its freezing point of 32 °F (0 °C) runs the risk of localized freezing in the chiller.

Takara Sake has another process chiller rated at 82.5 TR (290 kW) using R-507A that is used for cooling rice/yeast mix, which is then sent to the fermentation tanks. The R-507A process chiller is a water-cooled chiller, also manufactured by Mayekawa. Takara Sake was considering the use of a similar chiller for the R-717 chiller's current application before agreeing to become the host site for the new pre-commercial chiller technology. Therefore, the existing R-507A system was also monitored to collect data on its energy and water use performance, serving as a baseline system to compare with the R-717 chiller.

The existing R-507A chiller supplies chilled water to a liquefaction tank. It produces chilled water at a design temperature of 41 °F (5 °C) and supplies it to a mixing tank which has about 1,000 gallons of storage capacity. The chilled water returns from the mixing tank at design temperature of 48 °F (8.9 °C). The actual operating temperatures vary in the field and are monitored and tracked. The chilled water from the mixing tank is supplied to the liquefaction tank jacket for cooling. The liquefaction tank is cooled from 185 °F to 59 °F (85 °C to 15 °C) over a period of about 15 hours in a batch production process. The tank jacket is initially cooled directly with the cooling tower water in the first stage of cooling, commonly referred to as "free-cooling". This is then switched to the chilled water supply from the mixing tank when cooling tower water is unable to provide additional cooling. The mixing tank stores chilled water for supply to the cooling jacket, which allows the chiller to be sized smaller than the instantaneous load on the chiller.

Takara Sake also has a R-22 water-cooled chiller that was used to serve the six fermentation tanks before the installation of the R-717 chiller. The R-22 chiller is still in service and is used to provide comfort cooling to the building. Due to the high GWP of the R-22 refrigerant, Takara Sake has since transitioned to R-453a, a widely used drop-in refrigerant for the chiller which requires no system modifications.

The cooling tower water is treated by an experienced water treatment company. The tower is serviced monthly, where the water quality is measured to determine the cycles of concentration of the cooling tower as well as the quantity of chemicals required to treat the water. Monthly reports are used to track the changes in the cooling tower's cycles of concentration to track make-up water consumption.

Instrumentations were added to both the R-717 chiller as well as the R-507A chiller to record their performance and operating conditions. The data collection began in May 2018 and is currently ongoing, the results presented in this paper includes roughly a year and a half of data collected up till December 2019. All parameters needed to evaluate the system's performance as COP or kWh/ton-hr are monitored, namely

9. Danfoss, Benefits and Advantages of Thermostatic Expansion Valves Versus Other Throttling Devices. http://files.danfoss.com/technicalinfo/dila/01/Benefits%20and%20advantages%20of%20TXVs.pdf.

10. R. Lazzarin, D. Nardotto, and M. Noro, Electronic Expansion Valves Vs. Thermal Expansion Valves, ASHRAE Journal February 2009.

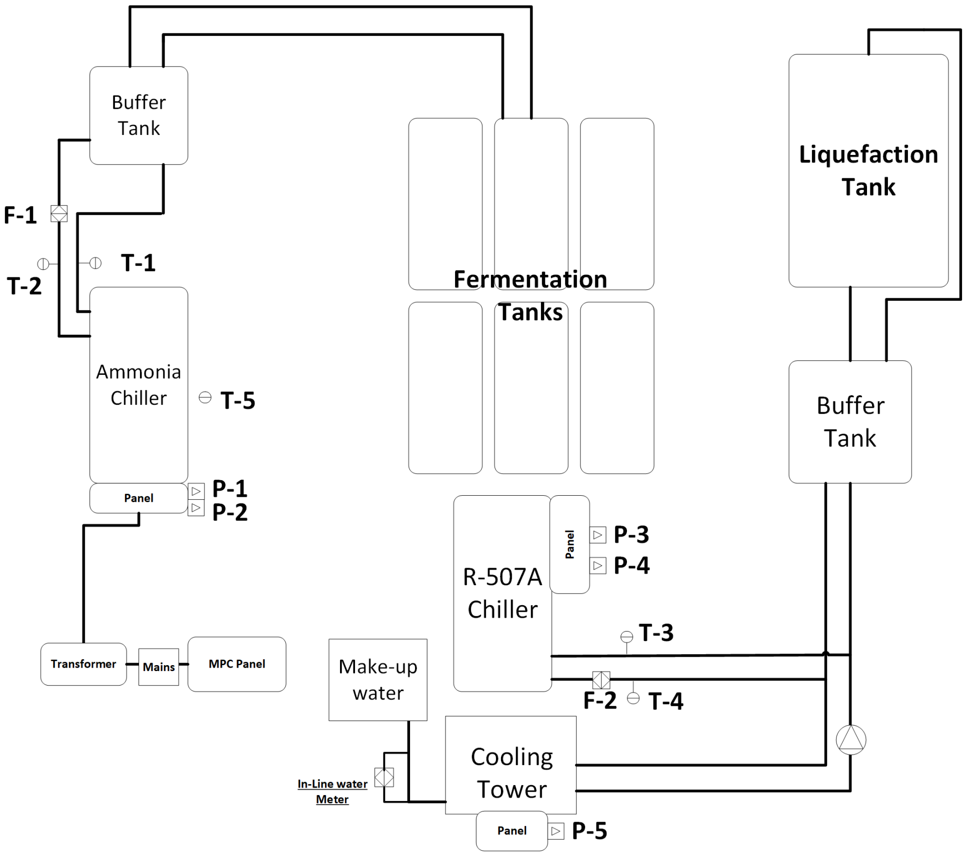

Figure 3. Simplified Chiller System Schematic at Takara Sake.

Table 1. Data Acquisition Measurement and Instrumentation List.

	Measurement	Instrumentation
T-1	Chilled water supply temperature – R-717 chiller	Thermocouple
T-2	Chilled water return temperature – R-717 chiller	Thermocouple
T-3	Chilled water supply temperature – R-507A chiller	Thermistor
T-4	Chilled water supply temperature – R-507A chiller	Thermistor
T-5	Ambient dry bulb temperature	Outdoor air temperature sensor
F-1	Chilled water flow rate – R-717 chiller	UltraSonic flow meter
F-2	Chilled water flow rate – R-507A chiller	UltraSonic flow meter
P-1	Compressor power – R-717 chiller	Precision energy meter
P-2	Condenser fan – R-717 chiller	Precision energy meter
P-3	Compressor power – R-507A chiller	Power meter
P-4	Condenser water pump – R-507A chiller	Power meter
P-5	Cooling tower fan power – R-507A chiller	Power meter

power, temperature, and flow rates measurements. A simplified system schematic of the ammonia and R-507A chillers is shown in Figure 3 and the corresponding instrumentation list is provided in Table 1.

EVALUATION METHODOLOGY

The R-717 chiller is evaluated against the R-507A chiller baseline for both energy and water consumption per unit of delivered cooling. The primary approach for energy savings is to evaluate the coefficient of performance (COP) of the systems, which is a common dimensionless metric of evaluating vapor compression technologies. The COP is the ratio of the rate of cooling to the power consumption, a COP of 2 means the system provides 2 units of thermal cooling capacity per unit of input electric power.

A chiller's performance depends on three major parameters: evaporating and condensing temperature as well as percent capacity. The operating temperatures determine the lift and work done by the compressor, which is the most significant component in the system's overall power consumption. Percent capacity is also an important parameter that impacts system efficiency since a chiller's heat exchanger becomes "oversized" when operating at lower capacities. While the ammonia is air-cooled instead of water-cooled, specific operating conditions are selected for a fair comparison. The data is filtered for the same chilled water supply temperature (from chiller to load), percent capacity, as well as ambient dry bulb temperature. Chilled water supply temperature is used as a proxy for the evaporating temperature, and ambient dry bulb temperature is used a proxy for the condensing temperature. Ambient temperature was selected as a parameter for both chillers because it allows for the most direct comparison between the chillers even though the R-507A chiller is water-cooled and is affected by the relative humidity of the ambient conditions. Since the R-717 chiller is serving the fermentation tanks and the R-507A chiller is serving the liquefaction tank, the chilled water supply temperature as well as chiller loading can be significantly different. Moreover, the liquefaction tank can be cooled with just the cooling tower water without operating the chiller, so it is important to evaluate these two systems at the same conditions for a fair comparison.

The capacity of both chillers is calculated using the following equation.

$$\dot{Q} = \dot{m} * c_p * dT \tag{1}$$

Where $\dot{Q}$ is the rate of cooling delivered (kW), $\dot{m}$ is the mass flow rate of the chilled water delivery loop (kg/s), c_p is the heat transfer coefficient of the chilled water (kJ/kg-K), and dT is difference between the supply and return water temperature (K). While $\dot{m}$ and dT are measured directly in the field, c_p is based on the properties of the secondary fluid, which in this case is water and its properties are well understood.

For power consumption, the calculation for the chillers are different due to the cooling tower loop in the R-507A chiller. The pump power for delivery chilled water to the loop is not considered.

$$\dot{P}_{717} = \dot{P}_{comp} + \dot{P}_{cond,fan} \tag{2}$$

$$\dot{P}_{507A} = \dot{P}_{comp} + \dot{P}_{cond,pump} + \dot{P}_{CT,fan} \tag{3}$$

Where $\dot{P}$ is the power consumption (kW), subscript 717 represents the ammonia (R-717) chiller, 507A represents the R-507A chiller, *comp* is the compressor, *cond,fan* is the condenser fan of the air-cooled chiller, *cond,pump* is the pump for delivery water to the condenser of the water-cooled chiller, and *CT,fan* is the cooling tower fan.

The efficiency of the chillers is calculated using the capacity and power consumption data with the following equation.

$$COP = \frac{\dot{Q}}{\dot{P}} \tag{4}$$

Water savings of the R-717 chiller is calculated based on the cycles of concentration (COC) of the R-507A system, which is obtained from the water treatment company monthly reports. Essentially, COC refers to the mineral concentration of the condenser water in relation to the makeup water (water that is added to compensate for evaporation losses, drift and blowdown). A higher COC means less blow down as well as less make up water. Depending on water conditions and ongoing monitoring, significant added benefit can be achieved by increasing COC. However, at higher cycles, managing corrosion rates, suspended solids, and microbial growth become more challenging, unless there is quality monitoring procedure in place and the supply water can be maintained at a good quality. The COC of the system can be calculated as shown in the equations below.

$$MU = E + BD + D \tag{5}$$

$$COC = \frac{MU}{BD} \tag{6}$$

Where *MU* refers to the fresh makeup water added, *E* refers to the amount of water evaporated during the heat rejection process, *BD* refers to blown down, the water being drained from the system intentionally to limit scaling from the water, and *D* refers to any water that is removed from the system due to drift. *E* can be calculated using the heat of vaporization of water per ton of cooling, and it is possible to estimate the total amount of water used by chiller energy consumption if drift is assumed to be negligible.

To solve for the total Makeup water needed to reject the heat due to the ammonia system if it were water-cooled, both the average monthly COC from the R-507A system cooling tower was used as well as the COP of the ammonia system compressor, resulting in in total water gallons per cooling capacity delivered. This value is in turn converted to gallons of water saved per kWh of electric power used based on the COP of the ammonia system (includes compressor, fan and pump power).

Other non-energy and operational benefits and impacts of the system would be assessed from facility operational data such as reduction in cooling tower chemical usage and through operator interviews such as economic benefits, productivity, environmental and chemical impacts, and safety measures.

Statistical Analysis

To compare the two chiller's performance at comparable operating conditions, statistical analysis method was used to determine the statistical significance of the field data results. The ammonia and R-507A chillers are assumed to be independent samples with unequal variances. The following equation for the difference in means of the two chiller's COP was used according to Wonnacott (1972)[11] and detailed in Eq. (7)–(8).

$$\bar{X} - \bar{Y} \pm t_{v,\alpha/2}\sqrt{\frac{s_X{}^2}{n_X} + \frac{s_Y{}^2}{n_Y}} \tag{7}$$

The value of $t_{v,\alpha/2}$, calculated confidence interval, depends on the degrees of freedom and the desired confidence interval and can be tabulated based on these parameters. The number of degrees of freedom v is given by

$$v = \frac{\left(\frac{s_X{}^2}{n_X} + \frac{s_Y{}^2}{n_Y}\right)^2}{\frac{\left(\frac{s_X{}^2}{n_X}\right)^2}{n_X - 1} + \frac{\left(\frac{s_Y{}^2}{n_Y}\right)^2}{n_Y - 1}} \tag{8}$$

If the magnitude of the confidence interval is smaller than the difference in means, then it can be concluded that the difference in COP between the R-717 chiller and the R-507A

11. Wonnacott, Thomas H. and Ronald J. Wonnacott. Introductory Statistics for Business and Economics. John Wiley & Sons, Inc., 1972.

chiller is statistically significant. A confidence interval of the difference in means was calculated for each operating condition, based on capacity, chilled water supply temperature, and condenser water temperature. The difference in means and associated confidence interval are then aggregated based on the capacity range. This is done using a weighted average method, where the number of data points in each condition is compared to the total number of data points within that capacity range.

Results

The performance of the chillers is evaluated at the same operating conditions (chilled water supply temperature, ambient dry bulb temperature, and chiller loading) to allow a fair comparison. While the chilled water supply flow rate is monitored for both chillers using ultra-sonic flow meters, the flow meters are subject to a high degree of uncertainty. A detailed review of the collected data shows wide fluctuations in the data which are outside the operating ranges of the system. These fluctuations can be caused by vibrations or water damage in the case of the R-507A flow meter. Therefore, instead of relying on the flow meter readings, it is assumed that the chilled water supply flow rate for both systems is constant at 232 gallons per minute (GPM). This assumption was made after consulting the plant operators, since the chilled water pumps are designed to provide a constant flow of chilled water to the buffer tanks.

SYSTEM SAVINGS

As mentioned above, the two chiller systems have different designed operating conditions. Furthermore, due to the intrinsic uncertainties in a field demonstration study, it is challenging to find comparable operating conditions. The results presented here represent a summary of the ongoing analysis at a set of operating conditions. Figure 4 shows the COP of both chillers at 70 %–80 % of their rated capacity and at ambient dry bulb temperatures between 65 °F (18 °C) and 70 °F (21 °C) for a range of chilled water supply temperatures. The results represent the average performance of both chillers for over 3 hours of operation at these conditions throughout the monitoring period. There is a clear improvement in the system COP for the R-717 chiller compared to the R-507A chiller, ranging from 38 % to 43 %. According to the manufacturer's data, the R-717 was predicted to have efficiency improvement of ~20 % over the R-507A chiller. Field performance comparisons vary from the rated model data due to the additional variables that are not controlled in a real-world environment. One example is the operating schedule of the sake plant, which impacts the number of operational hours at different system capacities and corresponding efficiencies. Furthermore, the operating conditions for the manufacturer's rated model may differ from that of the field demonstration site. Berkeley has a relatively mild climate with an average relative humidity close to 80 %, so the wet-bulb temperature will be close to the dry-bulb temperature, meaning the condenser water supply temperature would be higher than that of dryer climates. It is expected as the evaluation of the system continues, more data would be available for additional comparisons.

Following the analysis aforementioned for the water savings, the average monthly gallons of water saved with the air-cooled R-717 chiller are 2.35 gallons/kWh electricity used or a total of 805,360 gallons per month, based on an average monthly COC of 2.85. With the elimination of a cooling tower for heat rejection, the plant saves significantly on chemical usage and water treatment and maintenance costs.

DISCUSSION

The field demonstration of the ammonia shows promising energy savings results for ultra-low-charge ammonia air-cooled chiller systems. It served to show that air-cooled systems can have efficiency on par or even above that of water-cooled systems if advanced heat exchangers are used and will help reduce energy consumption and environmental impact with more market penetration. This study shows the viability for semi-hermetic compressors for ammonia, which significantly reduc-

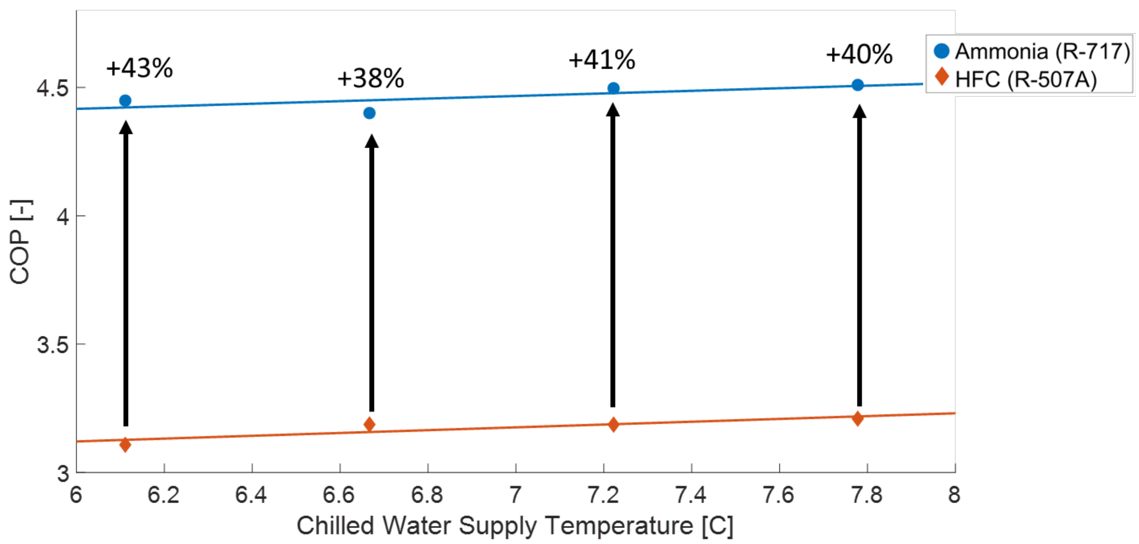

Figure 4. Chiller COP comparison at 70 %–80 % rated capacity and 65 °F–70 °F (18 °C–21 °C) ambient dry bulb temperature.

es the potential for refrigerant leakage from the system. This addresses one of the biggest challenges for ammonia systems, since ammonia itself has toxicity and flammability issues. By reducing both the refrigerant charge and the leakage, the R-717 chiller is a much more practical solution than conventional ammonia systems with large amounts of refrigerant charge and are subject to many regulations. Another important note is that freshwater is a valuable resource, particularly in places prone to droughts like California, and cooling tower water requires the use of many chemicals to control lime scale build up and disinfect the water to prevent microbiological growth. The newly demonstrated air-cooled R-717 chiller is a water saving technology that eliminates the need for chemical treatment procedures, while mitigating global warming potential concerns with refrigerants. Furthermore, traditional air-cooled systems require a large condenser for heat exchange surface area and can even have a larger footprint than water-cooled systems with their associated cooling towers. The reduced footprint from the microchannel heat exchangers makes this system much more practical when space constraints are present.

The adoption of the R-717 chiller technology can have significant impact on the industrial refrigeration. The following market analysis considers the adoption of the R-717 chiller in California as an example market size to replace current industrial chillers, since this on-going study and evaluation has been funded by the California Energy Commission. Whether the R-717 chiller can be used to replace all industrial chillers current deployed in the field will depend on parameters such as chilled water supply temperature and the required lift. But it is possible that this technology can be a suitability replacement for most applications currently employing HFC refrigerant with further innovations, especially in light of more aggressive GWP regulations in recent years. In California alone, the industrial sector consumes over 36,400 GWh of electricity annually, and an estimated 3,326 GWh is contributed to refrigeration electricity use, mostly for food and beverage. The field demonstration of the technology showed a noteworthy 40 % improvement over conventional chillers, which is determined for a specific set of operating conditions. The seasonal performance improvement is assumed to be lower at a more conservative 20 % over conventional equipment, using the manufacturer model as a reference. This gives a total potential energy savings of 665 GWh per year in just California. Many industrial chillers are also water-cooled and require cooling towers, and there can be significant water savings from switching over to air-cooled systems. Assuming 34 % of industrial chillers are water-cooled, a conservative estimate, converting these to air-cooled chillers can provide 3.4 billion gallons of water savings annually. Most importantly, the R-717 chiller offers a zero GWP solution to industrial refrigeration. This is contrasted by the high GWP refrigerants, primarily R-410A and R-134A, currently used in industrial chillers. Assuming most chillers leak 3 % of their refrigerant charge per year, the R-717 chiller can reduce GHG emissions by 8,654 metric tons of CO_2. Additionally, the reduction in electricity use can reduce emissions by 303,274 metric tons of CO_2. This savings may be less if the R-717 chiller is deployed in a region where the electricity generation is cleaner. While this market projection is performed with respect to the state of California, the potential impact of the system is applicable globally, where market adoption can be accelerated by legislation for achieving local and regional emission goals and energy savings.

Conclusion

This paper presents the results of a field demonstrated ultra-low charge air-cooled R-717 chiller for industrial applications with both energy efficiency and water saving capabilities. This new innovative technology demonstrated the viability of a new, pre-commercial, semi hermetic compressor for ammonia using aluminium windings, as well as advanced microchannel heat exchangers that significantly reduces the amount of refrigerant charge by a factor of 20. The combination of these two major breakthroughs make the ultra-low charge air-cooled packaged chiller much more practical by drastically reducing the amount of refrigerant charge required and eliminating a main source of refrigerant leakage, while operating a more efficient industrial chiller. This eliminates and reduces the many burdensome regulations that otherwise govern the use of ammonia in industrial plants. The demonstration of the R-717 chiller showed efficiency improvement over a conventional HFC refrigerant chiller by up to 40 %, while giving 2.35 gallons of water saved per kWh of electricity used and associated chemical savings. In summary, the demonstrated ultra-low charge R-717 chiller is a more energy efficient and environmentally friendly technology compared to current higher GWP refrigerant-based chillers.

Acknowledgements

The authors would like to acknowledge the California Energy Commission for its support and funding of this study under award number CEC EPC-16-048. The team would like to acknowledge the guidance provided by the CEC Contract Agreement Manager, Mr. Rajesh Kapoor. Also, the team would like to acknowledge Mayekawa who supplied the AURA chiller system and Mr. Troy Davis for providing research guidance, as well as Takara Sake, who provided the demonstration site for this work. The co-authors would like to finally acknowledge their colleague and dear friend, Dr. Mukesh Khattar, Principal Investigator of the project, who guided the project team with technical rigor. Dr. Khattar passed away unexpectedly in February 2020. We dedicate this project and many other projects in his memory and career legacy that included innovative work providing environmental and societal benefits through energy, water and operational efficiencies.