Low Charge Ammonia Packaged Refrigeration Systems: Achieving Ultra-Reliable Operation

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Introduction

The refrigeration industry has been migrating to natural refrigerants at an accelerated pace due to the fast approaching deadlines set by the Montreal Protocol and subsequent Kigali agreement. Ammonia, one such natural refrigerant, has been widely used for decades but is also being burdened with increased regulation since traditional refrigeration systems utilizing central machine rooms require such large ammonia quantities. However, the benefits of ammonia cannot be dismissed. Within the last five years, a stronger focus has been on the development of industrial low charge ammonia packaged refrigeration systems for industrial refrigeration similar to how halocarbon based packaged refrigeration systems have evolved in the commercial industry. What has been critically dismissed in pursuing systems with 'ultra-low charge', in some cases, is reliability and efficiency. Achieving ultra-reliable, efficient operation with low ammonia charge is the key to success for low charge ammonia packaged refrigeration systems.

Executive Summary

In the United Sates, increasing regulations directed towards owners of large ammonia systems has resulted in higher operating cost and increased liability. In response, many owners, particularly in the cold storage market segment are demanding low charge systems. Low charge ammonia caught the attention of equipment manufacturers and engineers in the industrial refrigeration industry. The phrase "low charge" is immediately interpreted to mean "as efficient as" and "safer than" a traditional central machine room system. However, two other aspects that are just as, or more, critical are the ultra-reliable operation and meeting the stated refrigeration capability. Ultra-reliable operation, as established by Evapco for packaged low charge ammonia refrigeration systems, is the safe, consistent and stable startup, operation and shutdown at all load and ambient conditions.

During the early development, Evapco approached low charge ammonia packaged system design too aggressively trying to apply innovative new concepts to the system design and controls to meet the 'ultra-low charge' claims of some other manufacturers. The 'ultra-low charge' numbers promoted were less than one pound of ammonia per ton of refrigeration for direct air-cooling penthouse systems and ounces of ammonia per ton of refrigeration for chillers, or secondary non-volatile fluid refrigeration systems.

As is customary in developing any product, Evapco performs extensive testing on full scale products. This testing provides valuable information into how low charge ammonia systems operate differently than a traditional system. These packages are new systems that behave differently due to the dynamic operation created by close coupled components. The odds of successfully producing a packaged low charge ammonia refrigeration system simply by assembling smaller sized components used in a traditional system design is highly improbable. Thorough testing of these systems through a wide range of operating conditions proved numerous factors will affect a packaged refrigeration system thermal capability, amount of charge required, efficiency and reliability. These factors include the close-coupled package arrangement, system feed type, condensing method, ambient temperatures, room application temperature, component commercialization, load variations, oil management and even designing to comply with building codes.

Testing confirmed the amount of refrigerant charge needed to operate at a full load and design temperatures is different than the charge required to operate at part load and/or low ambient temperatures. Based on Evapco's extensive research and testing, it seems some manufacturers claimed charge required for and thermal capacity of their packaged ammonia refrigeration systems don't take into account the wide range of conditions the package will be subjected to during actual operation.

Only after reliable operation is established can meaningful values for the actual thermal capability, efficiency, CoP and ammonia charge be determined. The purpose of this paper is to present some findings during design and testing that led to the development of fully rated packaged low charge ammonia refrigeration systems.

Design Considerations

The close-coupled, compact nature of a packaged system is a primary driving factor in reducing overall refrigerated facility ammonia charge compared to a conventional central machine room design that uses long pipe runs to transfer ammonia through the closed system. This benefit of reduced ammonia charge for packaged systems does not come without its challenges. Low charge system operation is much more dynamic and requires control systems which are more responsive as these systems do not have the ballast of large ammonia charges and long pipe runs to 'dampen' upset conditions. It became clear that applying a conventional refrigeration system design and standard control logic is not a 'copy-paste' undertaking for low charge packaged refrigeration systems.

System Type, Condensing Method, and other Components

The primary influence which impacts total ammonia charge is the type of system. Aside from systems using a non-volatile secondary circuit, direct expansion (DX) systems are widely thought to be the only means of achieving low charge. Compared to traditional recirculated liquid systems that operated at up to 4:1 recirculation rates, that perception would be true. However, tube and fin evaporator coil technology has improved where optimum thermal capability occurs at recirculation rates of 1.1:1 or 1.2:1. As a result, the ammonia charge per ton of refrigeration of a recirculated liquid coil operating at 1.2:1 can be equal to or better than that of a DX coil. This technology improvement provides opportunity for significant charge reduction in the evaporator and through reduced piping and component size of pumped liquid systems.

Another factor influencing the charge required packaged refrigeration system charge is the type of condenser used; air-cooled or water-cooled. Water-cooled condensing systems will generally require less charge than air-cooled condensing systems due to their higher heat transfer coefficients and lower volume. In addition, oil temperature control, compressor differential pressure control and freezing effects need to be considered for proper operation at off-design low ambient temperature conditions.

However, each of these issues can be managed with proper control of the water supply temperature and flow rate to maintain minimum condensing temperatures.

Air-cooled condensing systems require additional considerations to properly manage liquid ammonia in the system during periods of shutdown. Similar to a water-cooled condenser, oil temperature control and compressor differential pressure control are major issues associated with startup of an air-cooled condensing system driven by the over-performance of the air-cooled condenser resulting from high temperature differentials between minimum condensing temperature and very low-ambient conditions.

The emphasis on designing ultra-low charge packaged systems by reducing the size of key system components can inadvertently complicate and limit system operation. For example, vessels are traditionally larger volume for conventional central machine room systems that utilize long pipe runs to store the ammonia charge surges. In a close-coupled package system with short pipe runs, the surge volume and vessel size can be significantly reduced.

Efficiency

System designers and purchases should not evaluate low charge packaged systems on refrigerant charge only. The packaged system efficiency and coefficient of performance (CoP) are equally important. The design of the low charge system, recirculated liquid versus DX, and type of condenser used result in a wide range of charge values and installed power for a specified heat rejection capability The efficiency and CoP of the packaged system must be taken into account during the design phase with primary consideration directed toward the efficiency of key components – compressor and motor, pump (if recirculated liquid), evaporator fans, condenser fan or fluid cooler or cooling tower. The system's control logic also impacts overall system efficiency. The use of variable frequency drives (VFD), slide valve control and economized system design will positively influence the efficiency of the system, if properly applied. As an example, applying speed control to evaporator fans can increase the CoP at part load operation but may not provide adequate airflow to a particular room.

Another important consideration is the total efficiency of the refrigerated facility. The use of multiple packaged systems on a refrigerated facility, referred to as distributed refrigeration, is often more efficient than a central machine room system when taking into account the reduced pressure drop (elimination of long pipe runs), system suction temperatures matched to each room's application temperature, and more prevalent use of VFD's.

Installation

Consideration must also be extended to the installation requirements of each system. Air-cooled condensing systems requiring only electrical utilities offer simpler installations in exchange for increased charge and energy consumption. Water-cooled condensing systems reduce charge and energy consumption for the same refrigeration capability but also require water, water treatment and additional maintenance attributed to evaporative cooled products.

Codes

As previously mentioned, codes and regulations applicable to ammonia systems have changed considerably over the last five years. Complying with these codes and regulations can influence system design and complicate system operation. However, applying factory assembled low charge package systems designed and built to be in accordance with established codes and standards can reduce the impact of regulations due to the low ammonia charge associated with each isolated system.

The Metrics

When developing a low charge ammonia packaged refrigeration system, attention is directed toward limiting the total charge quantity per system (i.e., 500 lbs satisfying IIAR's new Low Charge Ammonia Response Management guidelines) or charge per ton, CoP, and the installed cost of the unit. However, these metrics get influenced by the unique operational challenges associated with achieving ultra-reliable operation for each system feed, condensing method and room application temperature.

Evapco's test results have proven that operating packaged systems at ultra-low refrigerant charge is possible, but only for a limited range of operating conditions. Some of these ultra-low charge systems do not provide the refrigeration capacity and/or system efficiencies when operating outside a limited range of conditions. This issue can lead some to conclude low charge systems are not a viable solution for refrigerated facilities. Ultra-reliable, safe and efficient operation of a packaged low charge ammonia system can be achieved through thorough testing at a wide range of conditions.

Testing Facilities

Testing is a fundamental requirement to researching and developing fully rated packaged low charge ammonia refrigeration systems that are ultra-reliable and efficient. During the last five years, Evapco has performed numerous laboratory tests on multiple full-scale systems at its Research Center in Taneytown, MD (USA). The facilities at Evapco's disposal have been instrumental in gathering technical data related to system operation and the development of system controls to effectively manage the ammonia at conditions enveloping a wide range of load and ambient conditions. These facilities are described below to support the discoveries and data presented later in the paper.

Low Temperature Environmental Chamber

The first packaged low charge ammonia refrigeration system prototyped by Evapco was a recirculated liquid system utilizing air-cooled condensing. This unit was tested in Evapco's Low Temperature Environmental Chamber [Fig. 1] to research how the system would be affected while operating in climates with extremely low ambient temperatures. The test chamber is designed similar to a refrigerated warehouse with a fully functioning ammonia refrigeration system, insulated walls and ceiling, and underfloor heating. This test chamber is normally used for testing Evapco's forced air fin and tube evaporators and is capable of producing room temperatures as low as -40 °C [-40 °F]. In this case, the chamber created the ambient conditions for testing the packaged low charge ammonia refrigeration system prototype. The first prototype unit was tested at ambient dry bulb temperatures ranging from -23 °C to 38 °F [-9 °F to 100 °F] measuring thermal capability and observing system operation. Testing packaged systems in this chamber was limited in both size and time available. Evapco decided to design and install a test stand dedicated to testing packaged low charge ammonia refrigeration system.

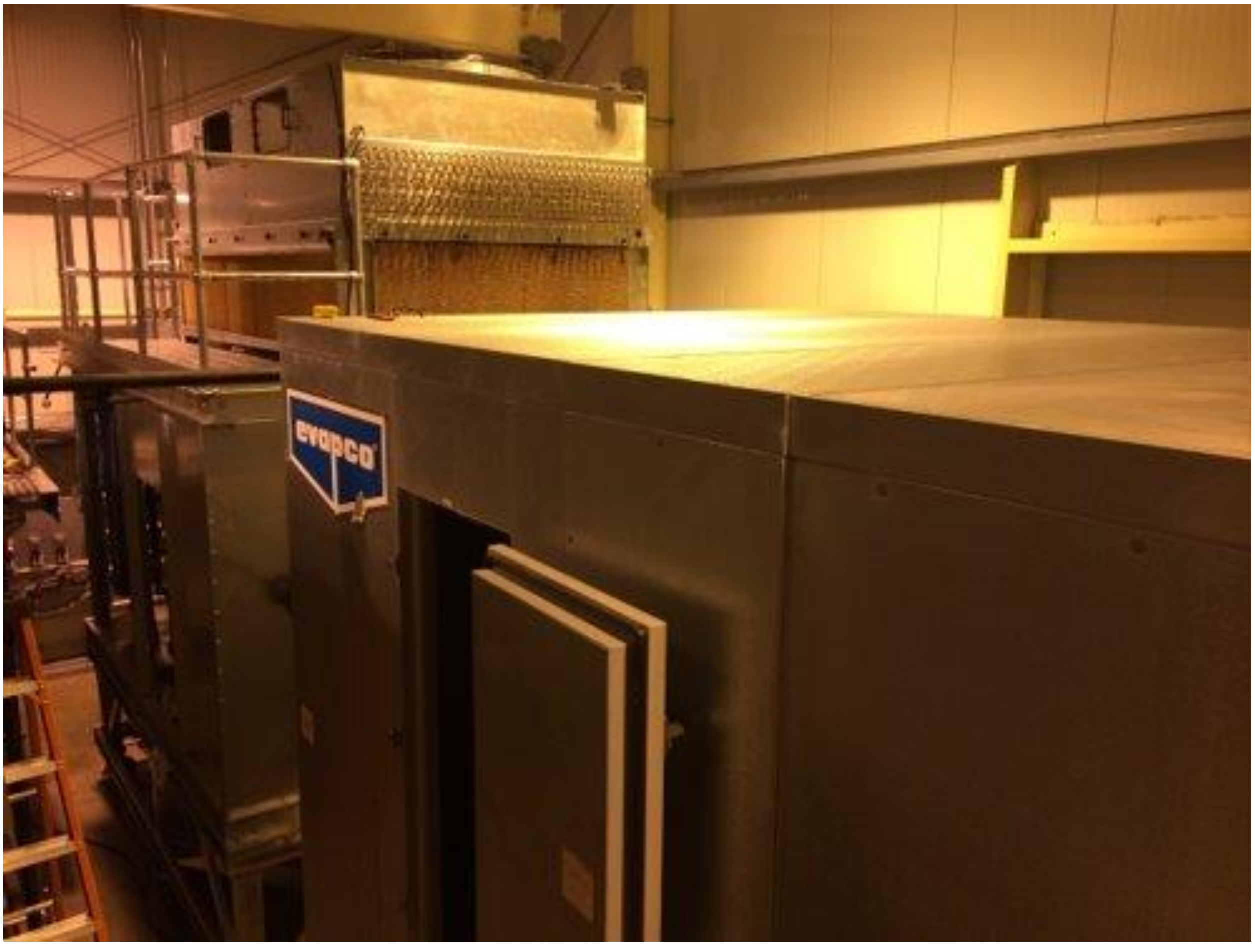

Figure 1: Prototype in Low Temperature Environmental Chamber

Test Stand

In 2015, Evapco designed and installed a dedicated test stand suitable for testing a multitude of packaged low charge ammonia refrigeration designs. The principle of operation is illustrated in Figure 2. The tested unit sits over a Test Plenum Heat Coil section (C). The fans in the penthouse section (B) recirculate air through the evaporator coils in the penthouse section where heat is rejected and the Test Plenum Heat Coil section where heat is introduced to simulate the system load. When testing water-cooled condensing systems, the heat load provided to the Test Plenum Heat Coils comes from the water absorbing the heat from the water-cooled condenser. An alternate boiler loop (D) is the heat source of the test plenum heat coil section for testing systems utilizing air-cooled condensing. This test stand allows Evapco to run various packaged low charge ammonia systems at various operating conditions.

The system's refrigeration thermal capability is measured with abundant instrumentation. Temperature, pressure, flow rate, liquid level and power of the unit, components and the test plenum section are continuously recorded using RTD's, pressure and liquid level transmitters and power meters to quantify system performance and evaluate system operation. The accuracy of the instrumentation used results in capacity tolerance less than 2 kilowatts [0.5 refrigeration tons] with a tolerance on system power of ±1%. Measurements and calculations of the air, refrigerant, and heat load are used for heat balance to ensure accuracy of the test. The response of the control system and liquid management during part load operation is evaluated by adjusting the amount of heat transferred to the Test Plenum Heat Coils.

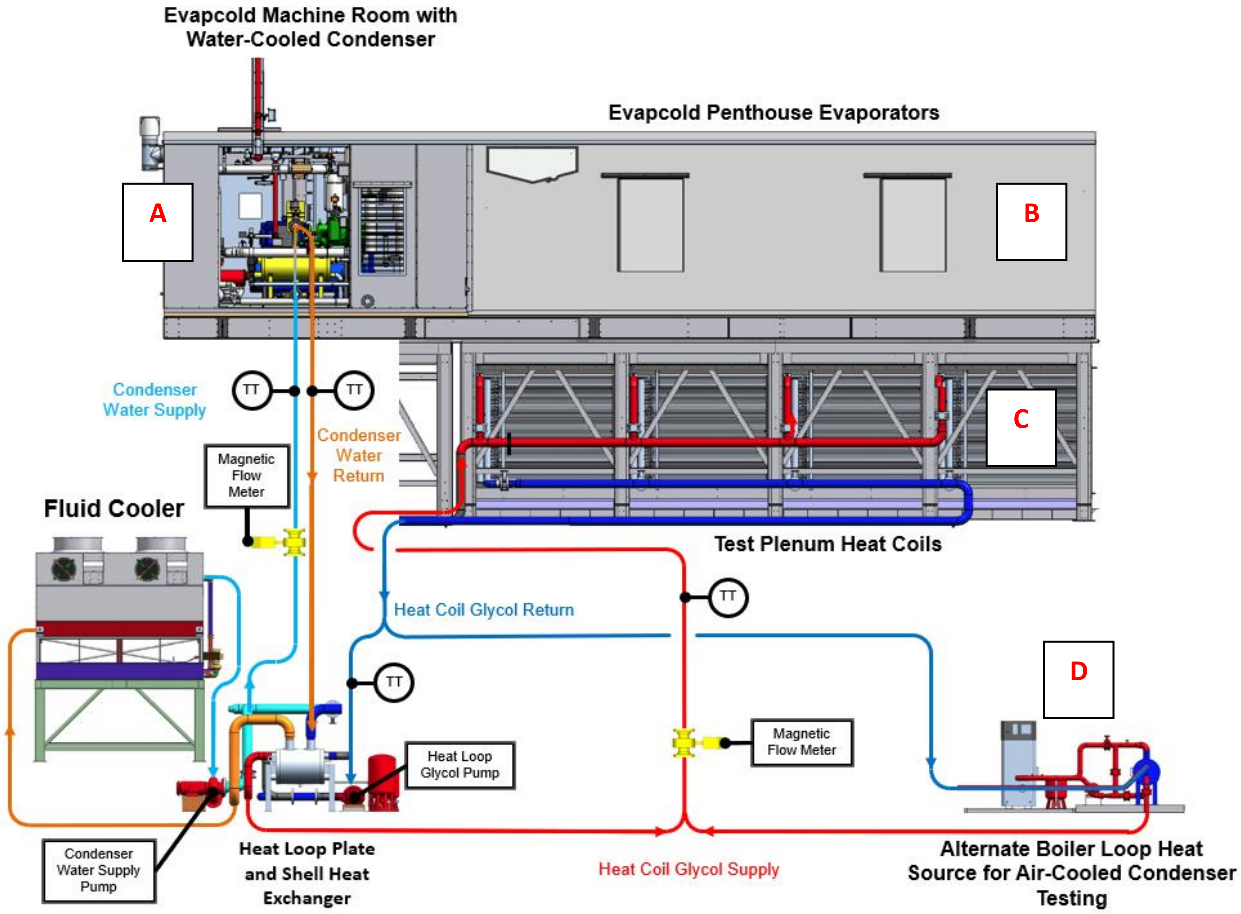

Figure 2: Packaged Ammonia Refrigeration System Test Stand

The only limitation of the test stand is the ability to control ambient temperature conditions. This is less of an issue with water-cooled condensing systems for several reasons. First, it is easier to maintain the minimum condensing temperature of the system through water supply temperature and flow rate manipulation at low ambient temperatures. Additionally, the water-cooled plate and shell condenser usually has less charge than an equivalent air-cooled condenser and is located in the temperature-controlled machine room. However, air-cooled condensing systems are more influenced by the ambient conditions for the opposite reasons. The air-cooled condenser is outside and directly affected by the ambient temperatures. Furthermore, air-cooled condensers generally require more surface, volume and charge due to lower heat transfer coefficients compared to water-cooled condensers. These factors add to the challenge of ultra-reliable operation over the wide range of real-world conditions. In order to evaluate air-cooled condensing systems thoroughly, a low temperature environment needed to be created to evaluate system operation.

Low Ambient Temperature Testing

Evapco's first packaged low charge ammonia refrigeration system prototype was tested in the Low Temperature Environmental Test Chamber normally used for testing fin and tube evaporators. This chamber is not large enough to test larger penthouse packages routinely tested on the test stand. Fortunately, Evapco found a supporting partner in Creative Thermal Solutions, Inc. (CTS) to test larger packaged low charge ammonia refrigeration systems utilizing air-cooled condensing. CTS adapted one of its buildings to accommodate indoor testing of a full-scale air-cooled condensing packaged penthouse refrigeration system at extremely low ambient conditions similar to the Low Temperature Environmental Test Chamber. A representation of the unit in the chamber is shown in Figure 3 and an image of the air-cooled condenser installation in the test chamber is shown in Figure 4.

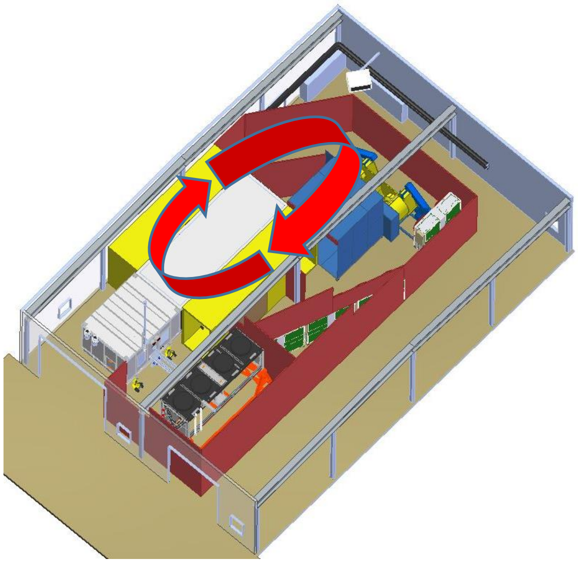

Figure 3: Model of Low Ambient Test Chamber for Air-Cooled Condensing Packaged System Testing

Figure 4: Condenser Installation in Low Ambient Test Chamber

The entire building was insulated to maintain a -23 °C [-9 °F] ambient temperature. The fans in the penthouse circulated the air through an isolated tunnel. Within the tunnel, air passed through the evaporator coils where heat was rejected, through an AMCA style nozzle wall for airflow measurement and finally through a set of heat coils where heat was added back into the air. Measurements on the circulated air and refrigeration system provided accurate load calculations for efficiency and CoP calculations. Additional testing was performed to evaluate startup and shutdown sequences for reliable operation.

Observations from Testing

The first packaged low charge ammonia refrigeration system prototype became the benchmark for understanding the need for and importance of ultra-reliable operation. Focused on reducing charge to the lowest possible level and eager to bring something new and innovative to the refrigeration industry, new technologies and innovations were implemented in the design. Unfortunately, some of the new packaged technologies and innovations attempted in the original prototype were discovered through testing to only be effective for limited operating conditions. Introducing a low charge product with limited reliability and flexibility to operate over the range of conditions known to exist in a traditional refrigeration facility would have been detrimental to the public’s perception of packaged low charge ammonia refrigeration systems. It became clear that starting with a more conventional system design and observing how this system would be affected by the dynamic nature of the smaller packaged system was prudent. Testing this air-cooled condensing system prototype in the Low Temperature Environmental Test Chamber also validated the need to test multiple units at a wide range of load and ambient conditions.

Lastly, another important discovery was made during testing of the first prototype. While rarely mentioned or even suggested, commercialism of product thermal capacity and energy use exists at various levels in the refrigeration industry supply chain. This commercialism is routinely accepted and accounted for through safety factors and conservative “rules of thumb” when calculating loads. This is an obstacle when designing and developing a fully rated product line of packaged refrigeration systems. The design of the first prototype fell short of achieving the expected thermal capability due to the inability of components to achieve 100% of the stated capacity. Reliable and consistent startup and shutdown sequences were also not achieved. Validating the capability of each component became necessary to understand how to adjust manufacturer’s claimed performance in order to determine capacity of the packaged system as a whole. Because of strong supply chain relationships, the information obtained from testing was shared and discussed with component manufacturers.

Once the above obstacles were overcome, the operation of prototype systems became more reliable. However, we identified other obstacles, primarily at part load and low ambient temperature conditions. These obstacles included oil temperature control, compressor differential pressure control, freezing effects for water-cooled condensing systems, and liquid ammonia management.

Compressor Differential Control – Hot/Cold Starts

Particularly challenging to the reliable operation of packaged ammonia refrigeration systems is compressor differential control for hot and cold starts. The most adverse hot start occurs during initial commissioning of the cold storage warehouse or after long term shut-downs. Commissioning can occur during the hottest days of summer when suction and discharge pressures are very high due to high temperature differentials across the evaporator and high condensing temperatures due to high ambient temperatures. Additionally, commissioning is most often conducted under part-load operation which takes time to reduce suction temperature and pressure. This situation was replicated during laboratory testing when the compressor cycled off failing to achieve differential pressure and sufficient oil pressure before the time delay expired. This scenario was overcome by closing the compressor suction valve to artificially reduce the suction pressure and increase the differential pressure. As the room temperature reduced, the suction valve was opened or bypassing load.

It was observed during testing that cold starts pose more difficult challenges than hot starts. Low ambient temperatures significantly lower the ammonia condensing temperature. Consequently, this reduces the saturation condensing pressure and differential pressure below the minimum required for compressor startup and operation. In a water-cooled condensing system, the cooling fluid temperature can be managed to a minimum temperature or flow reduced to allow the ammonia condensing temperature to increase to satisfy the compressor differential pressure requirement.

Oil System Control

Oil temperature control is vital to the proper operation of the system and the longevity of the compressor. Excessive oil temperatures can lead to premature compressor bearing and compressor shaft seal failures. These particular packaged ammonia refrigeration systems do not include oil pumps. Oil flow is generated from the pressure differential created between the compressor discharge and suction pressure. Therefore, maintaining compressor differential is essential to the proper operation of the compressor oil system.

During normal operation, controls are in place to ensure the required compressor differential is maintained including discharge pressure control based on condenser water control, suction temperature control based on compressor speed or on/off cycling, and oil differential pressure control safeties.

However, oil temperature control for water-cooled systems is different than air-cooled condenser systems. In this case, the oil cooler in a water-cooled packaged refrigeration system is integrated with the plate and shell condenser. Oil temperature can be easily maintained by controlling the water temperature or flow rate from the open or closed-circuit cooling tower through tower fan speed, pump speed or bypass.

The oil cooler in an air-cooled packaged refrigeration system is a thermosyphon plate and shell heat exchanger. Challenges with startup were encountered during low ambient conditions when oil is cooler than normal operation. To provide reliable startup under these conditions, a 3-way valve was implemented to allow mixing of the oil during start-up operations. The 3-way valve also allows better control and balancing of oil temperatures. The hot oil then travels to the heat exchanger and is cooled. The cooled oil returns to the compressor and recycled to maintain a constant acceptable oil operating temperature.

Cold start operation is more complicated for an air-cooled condensing refrigeration package. Oil temperature and compressor differential pressure control issues at start-up are driven by the over-performance of the air-cooled condenser at very low ambient conditions. Reducing condenser oil surface, modulating condenser fans and regulating ammonia gas flow were all discovered in testing to be viable means of countering air-cooled condenser over-surface at low ambient conditions.

In addition to the oil temperature and compressor differential pressure control issues of a water-cooled system, liquid migration during shutdown of an air-cooled condensing system becomes another issue. Large temperature gradients can occur between the air-cooled condenser located outside, the components of the machine room located in a heated space and the evaporator coils subject to the room application temperature. As a result, liquid ammonia can migrate to different locations reducing liquid volume in vessels needed for pump operation. Therefore, vessels and other components must be sized to contain the varying charge levels in the system and require an increase in the overall system charge to ensure ultra-reliable operation.

Several control schemes were tested to maintain the required compressor differential and appropriately manage the liquid ammonia. Interestingly, different control components and control schemes could be employed for different room application temperatures. Isolation of the ammonia within the system is also a consideration. Precautions must be taken to prevent hydrostatic isolation.

Referring to the first prototype tested in the Low Temperature Environmental Chamber, as the ambient temperature was reduced and heat load was removed replicating part load low ambient operation, system operation from start-up to shutdown became more erratic. This was attributed to inadequate liquid ammonia management. The air-cooled condenser was subjected to the ambient temperature, the compressor and vessels were in a machine room that is heated to maintain a minimum temperature and the penthouse was exposed to the cold storage / process temperature. As a result, liquid ammonia migrated out of the machine room to colder locations of the system. It was concluded that managing where the liquid is in a packaged system is very important. Vessels and systems must be sized to contain the various charge levels through start-up, operation and shutdown at all possible load and ambient conditions. The testing at CTS revealed additional information that different methods of ammonia migration control could be implemented effectively depending on the room application and ambient temperatures.

Efficiency

After achieving ultra-reliable operation and the resulting ammonia charge that supports it, attention is directed to optimizing CoP. The packaged low charge ammonia refrigeration systems discussed in this paper utilize screw compressors which are commonly chosen for cold storage warehouse designs based on tonnage, low saturated suction conditions, operational flexibility and convenience for incorporating into a compact design. Several options can also be employed to improve efficiency part-load operation. Through testing, a combination of both speed and slide valve control was identified to yield better CoP's at part load operation as shown in Figure 5. Multiple packaged systems on a refrigeration facility can provide improved efficiency and additional energy savings by cycling off when room conditions are met.

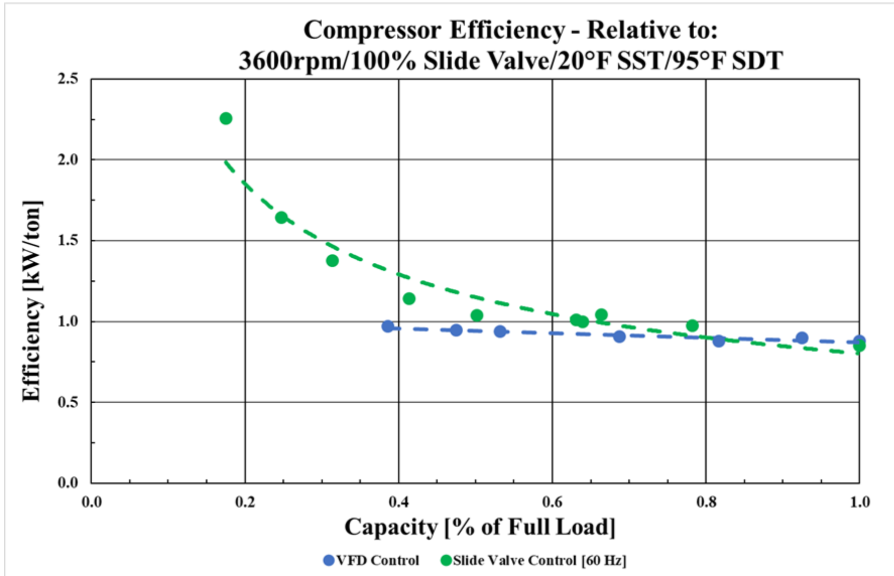

Figure 4: Compressor Efficiency - Speed and Slide Valve Control

At lower saturated suction temperatures, compressor efficiency can be increased by utilizing an economized cycle improving CoP 5-10%. The trade-off of using an economized cycle for CoP improvements is the need for an additional vessel which increases ammonia charge. The additional vessel and increased ammonia charge is generally not warranted at higher suction temperatures since an improvement like this is not realized to this extent.

Another consideration for improving the CoP of the system at part load operation is implementing speed control on the evaporator fans. However, not all applications can operate with reduced fan speed due to air throw and minimum required air changes based on product cooling requirements. How the fan speed is controlled as well as how multiple packaged refrigeration systems are arranged on the facility greatly influences this opportunity.

There are some key energy efficiency advantages of multiple packaged low charge ammonia systems, distributed systems, compared to central machine room systems. Distributed system packaged units eliminate the energy-consuming piping pressure drop of long piping runs common with traditional central machine room systems. Typical piping runs for central machine room systems can add up to 2 °C to 3°C [3° to 5°F] to the saturation temperature from system pressure losses, forcing the central machine room compressors to operate at lower suction pressures to overcome the losses and consuming additional energy.

Distributed system packaged units allow the refrigerant suction temperatures to be matched precisely and continuously to each individual room temperature, allowing each room to operate as efficient as possible, versus a traditional central machine room system that is typically limited to only 2 or 3 "house suction" temperatures, which serve many rooms and many room temperatures.

Distributed units commonly have variable frequency drives included as standard for compressor control allowing this primary energy user to operate very efficiently (Fig. 4). The smaller compressor motors in Distributed Systems, versus central plant motors, allow VFD's to be more commonly and cost effectively applied. VFD's can also be provided with the evaporator fans and condenser fans as well.

All of the above provide the ability for a facility to have a supervisory control system that provides complete energy management at the point of use. Built-in software available in some Distributive Systems, in conjunction with a supervisory control system, can provide very efficient energy management.

Closing Comments

Ammonia is a very efficient and environmentally-friendly natural refrigerant. Evapco is committed to developing product lines that support its continued safe use. Bold claims exist in the refrigeration market for packaged ammonia systems that operate at miniscule amounts of ammonia. However, claims only of low charge are meaningless without ultra-reliable and efficient operation and meeting stated thermal and energy use capability. The purpose of this paper is to **educate the refrigeration industry on the challenges surrounding <u>ultra-reliable, efficient, fully rated</u> packaged low charge ammonia refrigeration system design and present capability information gathered through extensive testing**.

Table 1 below is a sample of the capacity and metrics for the packaged low charge ammonia refrigeration systems tested and developed at the time of this paper. These numbers are reflective of systems that:

- Will operate reliably at all load and ambient condition;
- Comply with the design requirements of IIAR-2; and
- Are fully rated

As expected, systems utilizing air-cooled condensing require more ammonia and consumer more energy per ton of refrigeration and have slightly lower CoP's than water-cooled systems at full load. However, note that the values for water-cooled condensing systems do not account for external heat rejection equipment including cooling towers and pumps. At some off-peak conditions, air-cooled condensing systems can be as or more efficient. In comparing water-cooled condensing recirculated liquid systems to DX systems, the charge is higher for about the same efficiency and CoP. However, comparing these numbers to a conventional central machine room refrigeration system design is impractical since accurate load calculation is nearly impossible to definitively know the actual tonnage capability of the system. As mentioned previously, significant safety is typically included in traditional system design to account for unknown heat loads and component capability commercialism that also clouds the true system operating capacity. Conventional central machine room refrigeration systems are estimated to require 15-30 pounds of ammonia per ton of refrigeration so there is clearly a significant charge reduction in packaged ammonia refrigeration systems. In addition, multiple packaged refrigeration systems can also offer improved efficiency and redundancy. Most importantly, when designed appropriately and tested thoroughly, packaged ammonia refrigeration systems will provide ultra-reliable operation.

Table 1: Package Low Charge Ammonia Refrigeration System Metrics

System Type	Cond Type	Room Temp	Average Metrics at Maximum Capacity						
			kW	[TR]	kg/kW	[lb/TR]	kW/kW*	[hp/TR]*	COP*
LCR-LR-P-SC	Air	Low	211	[60]	1.06	[8.2]	0.74	[3.5]	1.4
LCR-LR-P-SC	Air	Med	246	[70]	0.90	[7.0]	0.52	[2.5]	1.9
LCR-LR-P-SC	Air	High	264	[75]	0.69	[5.4]	0.45	[2.1]	2.2
LCR-LR-P-SC	Water	Low	211	[60]	0.70	[5.4]	0.43	[2.0]	2.3
LCR-LR-P-SC	Water	Med	317	[90]	0.54	[4.2]	0.30	[1.4]	3.4
LCR-LR-P-SC	Water	High	352	[100]	0.41	[3.2]	0.22	[1.0]	4.6
LCR-LR-P-DC	Water	Low	211	[60]	0.70	[5.4]	0.46	[2.2]	2.2
LCR-LR-P-DC	Water	Med	371	[105]	0.54	[4.2]	0.29	[1.4]	3.5
LCR-LR-P-DC	Water	High	352	[100]	0.42	[3.3]	0.27	[1.3]	3.6
LCR-DX-P-SC	Water	Med	317	[90]	0.36	[2.8]	0.30	[1.4]	3.3
LCR-DX-P-SC	Water	High	352	[100]	0.25	[2.0]	0.22	[1.0]	4.5
LCR-C-SC	Water	Med	454	[129]	0.11	[0.9]	0.28	[1.3]	3.5
LCR-C-SC	Water	High	475	[135]	0.11	[0.8]	0.25	[1.2]	3.9
LCR-C-SC	Water	Med	1125	[320]	0.10	[0.8]	0.24	[1.1]	4.2
LCR-C-SC	Water	High	1382	[393]	0.08	[0.6]	0.18	[0.9]	5.5

LCR ≡ Packaged Low Charge Refrigeration
SC ≡ Single 100% Compressor
DC ≡ Dual 50% Compressors
LR ≡ Recirculated Liquid Penthouse
DX ≡ Direct Expansion (DX) Penthouse
C ≡ Chiller
*Water-cooled condensing systems do not include cooling tower fans or pumps for heat rejection.

Research and development will continue with respect to packaged low charge ammonia refrigeration systems including direct expansion (DX) systems and expanded use of air-cooled condensing systems. New concepts and innovations are being developed that, when applied to these first-generation low charge packaged systems, will improve the metrics illustrated above promoting the continued and expanded safe and efficient use of ammonia.

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