APPLICATIONS OF INDUSTRIAL AMMONIA HEAT PUMPS WITH SINGLE SCREW COMPRESSOR TECHNOLOGY

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Abstract: Advances in screw compressor technology have enabled the development of high temperature ammonia heat pumps for use in industrial applications. The balanced axial and radial design of the single screw compressor allows for operation at significantly higher pressures and higher differential pressures than required for industrial refrigeration duty. The high pressure capability of single screw technology, overcomes the mechanical limitations of older screw technology, permitting the conversion of waste heat from a variety of industrial ammonia refrigeration applications into useable heat at temperatures up to 90°C (194°F).

Key Words: ammonia; industrial; natural; efficient; food processing; sanitation; district heat; screw compressor; single screw; twin screw; reciprocating compressor

1 INTRODUCTION

This presentation will illustrate a history of industrial compressor designs and their limitations for operation in heat pump duty, and the design attributes of single screw compressor technology which facilitate its use in high pressure / high temperature applications. The presentation will also highlight a variety of projects utilizing ammonia refrigerant, in which the technology has been applied with several years of operational experience.

1) District Heating: A water source heat pump system
2) Food processing: Providing full use of both the cooling and heating potential of the system
3) Food plant sanitation: Applied as a retrofit to an existing refrigeration system, discharge gas scavenged from host compressors is compressed to higher pressures, and delivers high temperature potable water for sanitation

Recent developments in high pressure industrial compressors provide for the use of ammonia, a natural refrigerant with zero Ozone Depletion Potential (ODP) and zero Global Warming Potential (GWP), while delivering enhanced COP's ranging from as low as 3.0 up to 7.0 or higher, depending on specific application requirements.

2 THE PHYSICS OF AMMONIA IN INDUSTRIAL APPLICATIONS

Ammonia is the most commonly used refrigerant in the food and beverage processing, cold storage and warehouse distribution industries. The qualities of ammonia that make it attractive to these industries include its superior thermodynamic efficiency, high heat transfer properties, and it's low operating suction and discharge pressures compared with many synthetic refrigerants. Although ammonia has a Class B toxicity (occupational exposure limit less than 400 ppm) and Class 2L flammability (ASHRAE 2013), its characteristic odor makes it easily detectable if any system leaks occur. Ammonia is also extensively used in industries outside of refrigeration, such as in agriculture for its application as a fertilizer, and is therefore readily available at a relatively low cost. Ammonia, which is comprised of one nitrogen and three hydrogen molecules, is a natural refrigerant with zero risk to ozone depletion and global warming. Considering the phase-out and adoption of various synthetic refrigerants over the last few decades, ammonia is often considered a “future proof” refrigerant, one that will not come under the pressures of phase-out and the need for replacement due to regulations.

In industrial refrigeration applications, ammonia systems may be designed to operate at evaporation temperatures as low as -43°C (-45°F), at a pressure slightly less than atmospheric pressure, and up to 2°C (35°F), about 5 bar (65 psia). System condensing temperatures may elevate to 35°C (95°F) or 14 bar (195 psia) during the hottest days of summer, but often operate at discharge pressures ranging from 9 to 11 bar (130 to 160 psia) through the majority of the year during cool to moderate outdoor conditions. Industrial ammonia refrigeration systems commonly discharge their heat to the atmosphere through evaporative condensers, and are able to maintain relatively low condensing temperatures and pressures based on an approach to ambient wet bulb conditions.

In food and beverage processing, both cooling and heating is employed. Cooling is applied for food preservation and freezing. Heating is applied for cooking, scalding, blanching, pasteurizing, bottle warming, produce washing and sanitizing. For a heat pump to satisfy these heating loads, it would be desirable to capture and apply the heat extracted in producing a cooling effect, and rather than discharging the heat to atmosphere, discharge the heat into the media satisfying the heating load. The temperature requirements of these heat loads vary by application and by processor, but it’s not uncommon for required temperatures to fall within the range from 54°C to 76°C (130°F to 170°F). Ammonia gas pressures corresponding to these temperatures reveal a range from 23 bar to 39 bar (330 psia to 560 psia). Thus for an ammonia heat pump to achieve these media temperatures, the compressor would need to operate at, or above, the stated pressures.

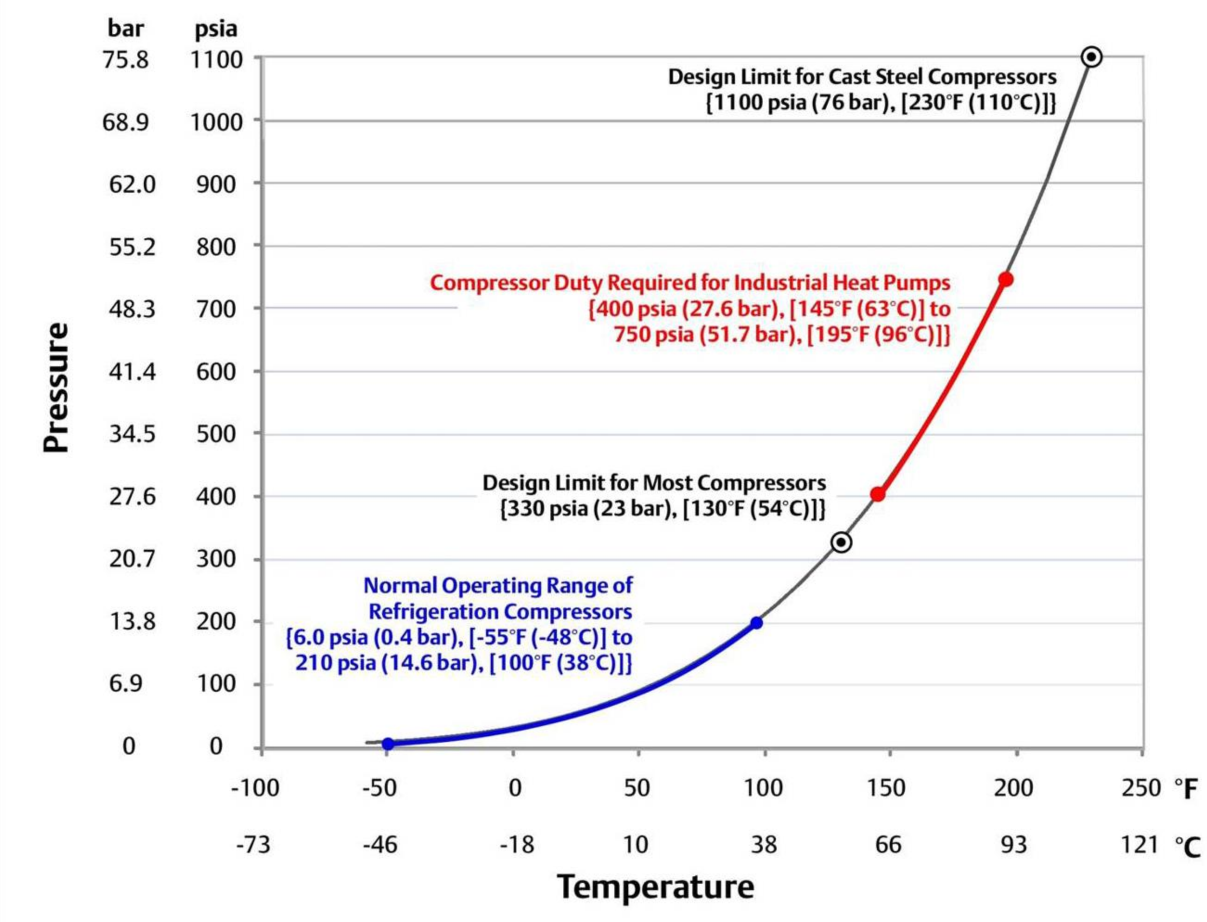

Figure 1. Ammonia Pressure-Temperature Relationship

The most commonly used compressor in industrial refrigeration is the twin screw. Twin screws are inherently subject to axial and radial thrust loads, of which the forces are compounded when operated at the higher pressures required for heat pump duty. The International Energy Agency's (IEA) Heat Pump Centre cites, "Ammonia is not yet used in high-temperature industrial heat pumps because there are currently no suitable high-pressure compressors available (40 bar maximum). If efficient high-pressure compressors are developed, ammonia will be an excellent high-temperature working fluid." (IEA 2008). Thus, most commonly applied compressors in ammonia refrigeration system are inherently limited in their ability to operate at the temperatures required for heat pump duty.

3 INDUSTRIAL COMPRESSOR TECHNOLOGIES USED WITH AMMONIA

Three types of positive displacement compressors are used in industrial ammonia refrigeration and heat pump applications, including reciprocating, twin screw and single screw. These compressors are typically of the open-drive type where the compressor's shaft is external to the frame of the compressor and is rotated by a separate mechanical drive, usually an electric motor. Each type of compressor design and its unique attributes is described herein, along with their potential for use, and corresponding challenges, when applied in industrial heat pump duty.

3.1 Reciprocating Compressors

Reciprocating compressors have been employed in ammonia compression applications since their inception in the 1860's. The basic mechanics of a reciprocating compressor include a piston in a cylinder. Various frame sizes may include from two to sixteen cylinders. Considering each piston-cylinder set, the piston is attached by a wrist pin to a connecting rod which is connected to a crank shaft, as shown in Figure 2. When the crankshaft rotates, reciprocating action of the piston in the cylinder enables compression. The compression cycle includes several steps. Low pressure ammonia suction gas is drawn into the cylinder through a suction valve as the piston moves down, and the gas volume in the cylinder increases. At the bottom of the suction stroke, when the cylinder is at full capacity, the suction valve closes and the piston moves up through the cylinder. The beginning of compression occurs. As the piston continues to travel through the cylinder, the gas is compressed and the gas pressure increases. Compression continues until the pressure slightly exceeds the downstream, discharge pressure of the compressor, at which point a discharge valve opens and the higher pressure compressed gas is pushed out of the cylinder and into a discharge line. The discharge valve closes, the suction valve opens, the piston begins to travel back down through the cylinder, and the cycle repeats.

The differential pressure from suction to discharge, establishes the forces on a reciprocating compressor's internal components. The higher pressure conditions required for industrial heat pump applications must be met with heavier duty and costlier compressor designs, than used for refrigeration. By the nature of the forces in reciprocating compressors operating in refrigeration duty, it's not uncommon for regular annual or biennial preventive maintenance overhauls to be performed. The higher pressure conditions required for industrial heat pumps accelerate the service and maintenance requirements of the compressors, limiting their reliability. The premium cost for heavy duty compressor designs, together with the increased cost and frequency of service and maintenance, can potentially inhibit the economic viability of their use in industrial ammonia heat pump applications.

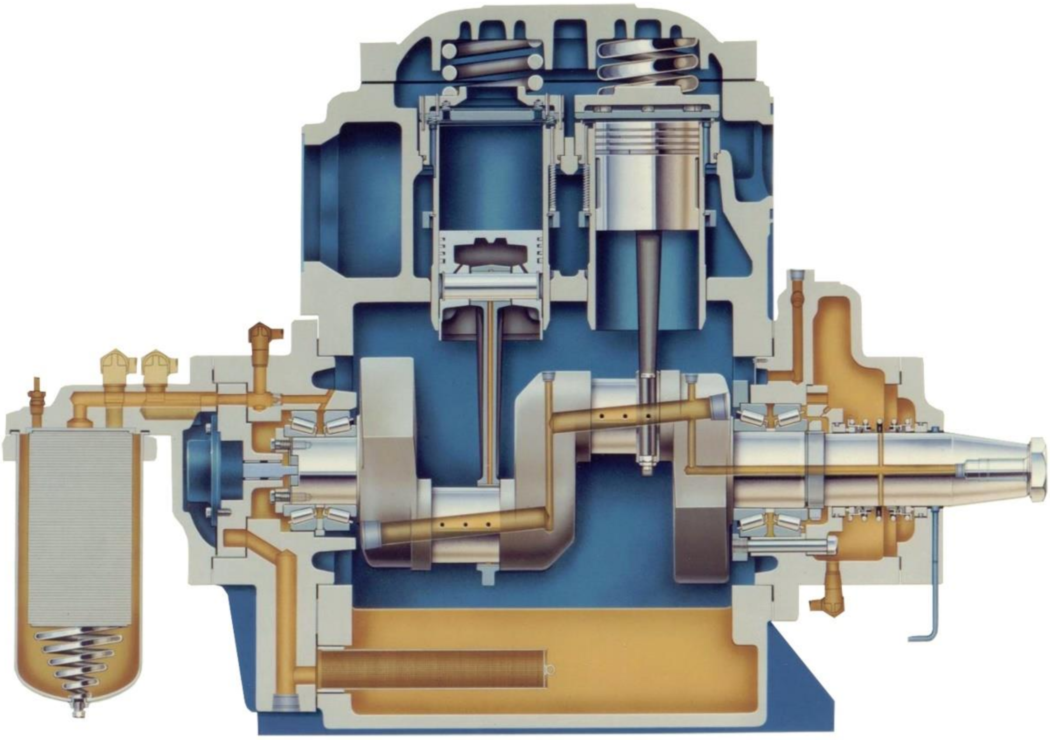

Figure 2. Ammonia Reciprocating Compressor – Section View

3.2 Twin Screw Compressors

Twin rotor screw compressors were patented in the 1930's and adopted into industrial ammonia refrigeration applications in the late 1960's. The basic design includes two intermeshing helical rotors—a male and a female—within a frame or casing. In operation, one rotor is rotated, which causes the rotation of the mating rotor, and together they trap and compress gas. Low pressure gas is drawn into a suction port in the frame at one end of the rotors. The gas is trapped between the annular gaps of the rotors and the casing. As the lobes of the rotors intermesh, the volume of the trapped gas is decreased and the gas pressure is increased. The high pressure gas is discharged through a port in the casing opposite of the suction end of the compressor.

Twin screw compressors were readily adopted into industrial refrigeration applications, because their rotating motion resulted in longer life, lower maintenance and higher reliability than reciprocating compressors. Differential pressures within the compressor exert forces on the rotors and bearings. These thrust forces are exerted in both an axial and a radial direction, as seen in Figure 3. High discharge pressure imparts an axial thrust load on the rotors toward the suction end, which is resisted by the bearings located on the rotors' shafts. As the bearings wear, their ability to withstand the thrust loads diminishes and the risk of bearing failure increases. In the unsupported mid-rotor area of the twin screw compressor, radial thrust loads impart a flexing force on the rotors that can result in rotor deflection. Rotor deflection creates a gap between the rotors which allows pressurized gas to slip, or cascade, to the adjacent lower pressure lobe, reducing the volumetric efficiency of the compressor. In refrigeration duty, typical compressor overhaul cycles may range from 2 to 7 years depending upon actual operating pressure conditions and rotating speed.

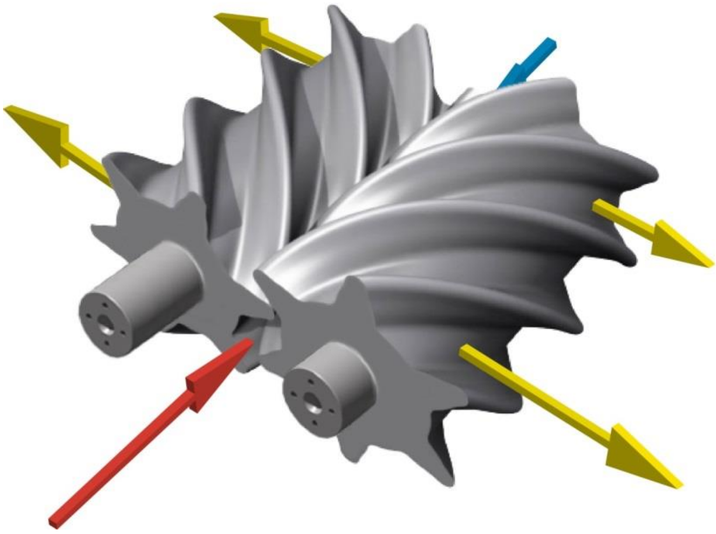

Figure 3. Axial and Radial Thrust Loads Imparted on Twin Screw Rotors

For the higher pressures that exist in industrial heat pump operation, twin screw compressors are fitted with more robust bearings and casing materials. Inherent design limitations can constrain certain models from operating in heat pump duty. Higher differential pressure hastens bearing wear and increases maintenance cycles, limiting their applicability for heat pump operation.

3.3 Single Screw Compressors

The single screw contains one single main rotor. The main rotor is a cylinder with six (6) threads, or flutes, cut in it. Unlike a twin screw compressor, the threads of the main rotor of the single screw compressors are not helical, meaning that the threads are not cut from one end, to and through the opposite end of the rotor. Rather, as illustrated in Figure 4, each flute is cut through only one end of the rotor cylinder, on the suction end. The threads terminate radially, such that the opposite “discharge” end of the main rotor retains the shape of a solid cylinder. The open end of the grooves allows low pressure suction gas to fill the flutes. In operation, each flute becomes a compression chamber. A series of vent holes, positioned axially through the rotor, oriented parallel to the shaft, and located below the cut of the flutes, allows low pressure suction gas to reside at both ends of the rotor. The pressure of the suction gas exerts a force in an axial direction on the main rotor. Since low suction gas pressure resides at both ends of the compressor’s main rotor, the balanced net axial force on the main rotor of the compressor results in long bearing life.

Two star gate rotors intermesh with the main rotor. The star gate rotors are identical in shape and are positioned opposite of each other, across the diameter of the main rotor. The main rotor’s rotation causes the intermeshing star gate rotors to rotate. As a tooth of the gate rotor enters a flute of the main rotor, the tooth serves to “close the gate”, and trap the gas in the flute. As the tooth travels through the flute the trapped gas is compressed to a smaller volume and higher pressure.

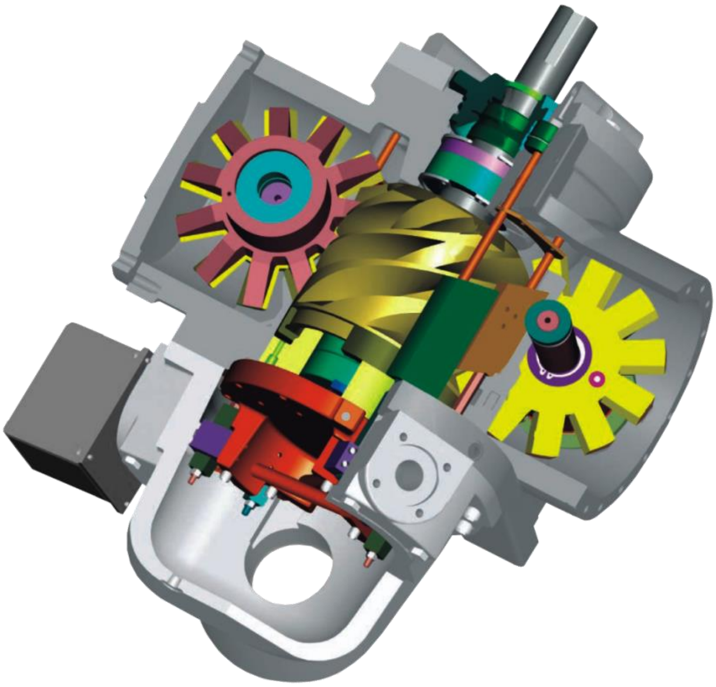

Figure 4. Single Screw Compressor Internal Components

Of the six main rotor flutes, three are engaged in compression on the top half of the compressor, and the opposing three flutes are simultaneously engaged in compression on the bottom half of the compressor. The gate rotor on one side of the main rotor is inverted relative to the gate rotor on the opposite side of the main rotor. The gas that enters the flutes on the top half of the compressor is compressed by the gate rotor on one side, and the gas that enters the flutes on the bottom half of the compressor is compressed by the gate rotor on the opposite side. A casing wrapped around the main rotor encloses and traps the gas in the main rotor's flutes. High pressure compressed gas is discharged from the casing's diametrically opposed triangular shaped discharge ports, out of the side of the compressor, in a radial direction. The radially opposed star gate rotors, and radially positioned discharge ports, result in no net radial load on the main rotor, delivering long bearing life.

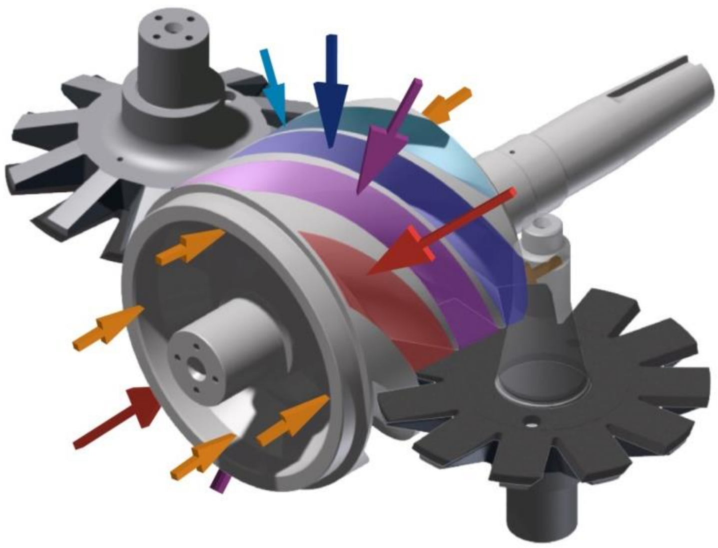

Figure 5. Balanced Axial and Radial Thrust Loads on Single Screw Rotors

Because of its inherent balanced design, single screw compressor technology has been employed in open loop high pressure gas compression applications for more than twenty years. Recently, the potential for its use in high pressure heat pump applications was realized. To accommodate the higher pressures of the ammonia gas in heat pump duty, the tensile strength of the compressor frame is increased to contain the gas at the required pressure duty, through the use of various high strength materials such as nodular iron and cast steel. Yet because the internal forces remain in axial and radial balance, as shown in Figure 5, even at high discharge pressures, the bearing life and reliability of single screw compressors has resulted in significant market acceptance and adoption in industrial ammonia heat pump applications.

4 INDUSTRIAL AMMONIA HEAT PUMP APPLICATIONS

4.1 District Heating

A city in Norway draws heat from its adjacent fjord to supply most of the city’s 90°C (194°F) hot water heating needs with an ammonia heat pump using single screw compressors. The heating capacity of the system is rated at 14 MW and is considered the world’s largest high temperature natural heat pump.

The heat pump system is comprised of three independent two-stage single screw ammonia sub-systems. Each sub-system includes a sea water chiller, two single screw compressor units, desuperheating heat exchanger, condenser, subcooler, and economizers. Heat is sourced from the adjacent fjord at a water temperature ranging from 6°C to 8°C (43°F to 46°F), and the water is returned back to the fjord at 2°C to 4°C (36°F to 38°F). Cold 60°C (140°F) water returning from the city’s district heating loop is heated to 90°C (194°F) in the city’s heating plant and distributed to consumers throughout the city. Most of the heat supplied from the heating facility is provided by the heat pump system. Supplemental heat is added to the district heat loop by natural gas boilers during the coldest months of the heating season.

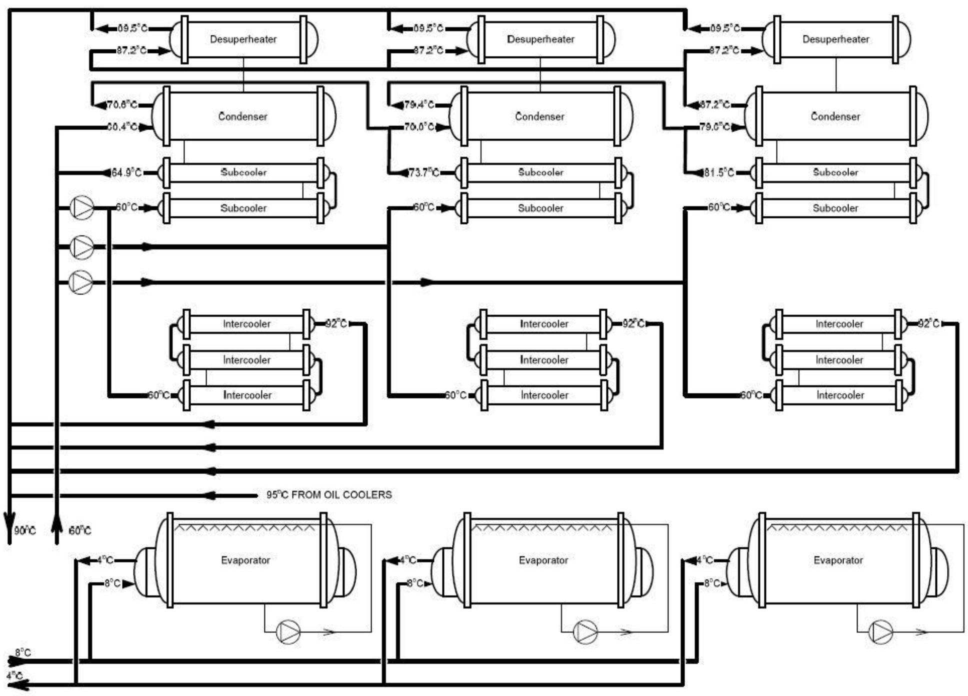

Figure 6. Ammonia District Heating Heat Pump-Source and Load Water Piping (Pearson 2010)

The evaporators extract heat from the seawater into the ammonia heat pumps. Heat from the ammonia sub-systems is transferred to the city's district hot water loop through multiple heat exchangers in a stair step fashion, as shown in Figure 6. The first heat pump loop raises the water temperature from 60°C to 70°C (140°F to 158°F); the second loop heats it to 80°C (176°F), and the last loop heats the water to 90°C (194°F). The first stage compressors increase ammonia vapor pressure from 4 bar (60 psia) to approximately 24 bar (350 psia), and the second stage single screw units compress the gas up to 52 bar (750 psia).

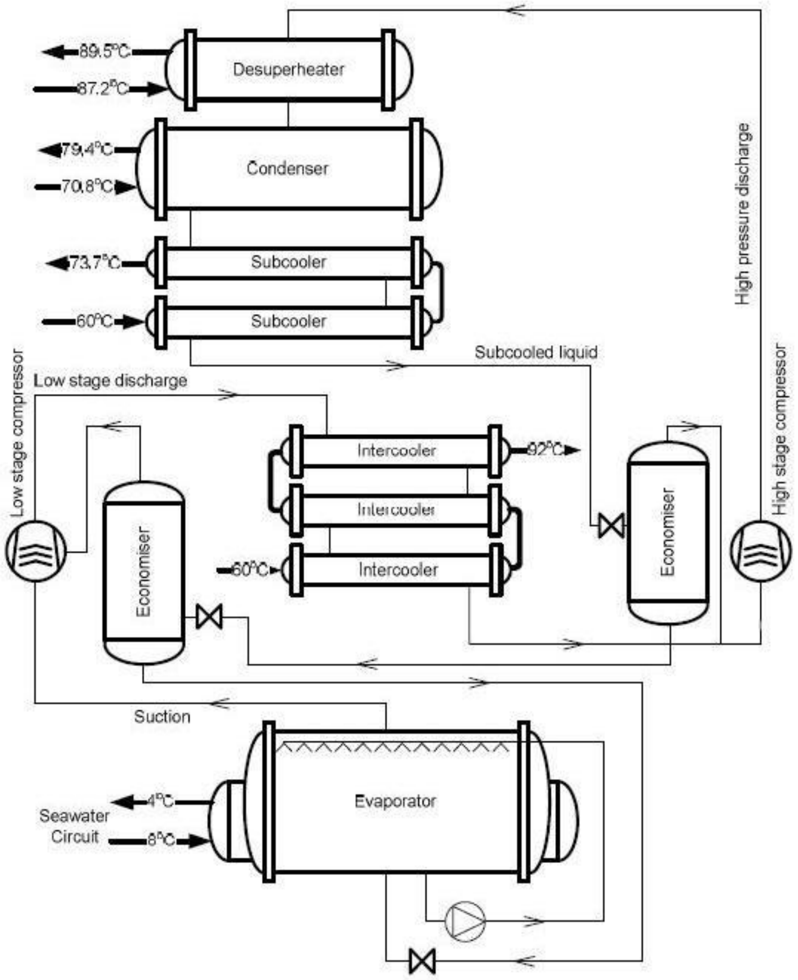

Figure 7. Ammonia District Heating Heat Pump - Ammonia Piping Schematic (Typ. of 3) (Pearson 2010)

Several objectives for the district heating system included a desire for the highest possible coefficient of performance, with a technology that required low annual operating and maintenance costs, and a system that employed a natural refrigerant, if possible. Ammonia was one of the few refrigerants that could meet all of the city's efficiency and environmental requirements. Although the ammonia based industrial heat pump operates at pressures up to 52 bar (750 psia), performance improvements were estimated to be more than fifteen percent higher than a heat pump using R-134a, the alternative refrigerant that was considered for the project.

4.2 Food Processing

A confectionary production facility in the United Kingdom was looking to its heating and cooling systems as a way to reduce the environmental impact of its operations.

The production facility relies on large refrigeration systems for both chocolate manufacturing and storage and distribution. Refrigeration is needed to cool chocolate, while heat is needed to separate the chocolate from the shaping molds. The site planned to convert their heating system from a central coal fired steam generation plant to one that uses natural gas, and to convert their cooling plant from an R-22 refrigeration system to a new industrial system that uses ammonia.

Site engineers desired the use of the natural refrigerant ammonia for the new refrigeration system, the highest coefficient of performance possible, and a technology with low annual operating and maintenance costs. They also wanted to capture as much waste heat as possible to minimize the need for gas fired equipment. Initial consideration for the new cooling system was to install four (4) twin screw ammonia compressors. Site compressor selection shifted from twin screw to single screw type following the recognition that single screw compressors were able to meet the simultaneous cooling and heating process needs of the plant's operation.

A self-contained ammonia heat pump system delivers both cooling and heating benefits to the processor, providing chilled glycol at 0°C (32°F) and hot water at 60°C (140°F) using heat extracted from the cooling process, and single screw compressors. The heat extracted from the chilling processes is elevated to a level that provides 60°C (140°F) hot water for process heating and sanitation needs from a single stage system. It is estimated that the ammonia heat pump solution has cut process utility costs at the site by over $394,000 per year (Pearson 2011), and the reduction of gas combustion has reduced CO_2 emissions by over 1.1 million pounds per year

4.3 Food Plant Sanitation

A major food processing plant in the USA employed an industrial ammonia heat pump to capture the waste heat from the existing refrigeration system to heat water for their sanitation needs, in lieu of the gas consumed by their previous system. The heat pump's heat is sourced from the highest ammonia gas pressures in the refrigeration system (Figure 8). The heat pump elevates an average of 640 liters/min (170 gallons/minute) of continuous potable water flow from 16°C (60°F) city water temperature up to the 63°C (145°F), required for their wash down needs, and with performance at a 5.3 annual average COP.

Site engineers adopted the inherent high pressure capabilities of single screw compressor technology to achieve the high temperature water required for their needs. The ammonia heat pump solution (Figure 9) has reduced the user's heat energy costs by over $250,000 each year and saves fourteen million gallons of water per year because of the reduced load on the plant's evaporative condensers (Gladis 2012).

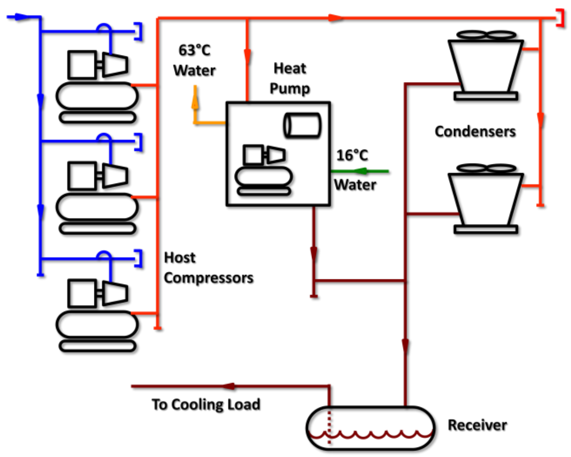

Figure 8. Scavenging Type Heat Pump System for Food Plant Sanitation

Figure 9. Single Screw Heat Pump System for Food Plant Sanitation

5 CONCLUSION

Ammonia has long been recognized as a premium refrigerant for industrial applications due to its high efficiency, low cost and environmental benefits. But the use of ammonia as a working fluid in high temperature ammonia heat pumps has been constrained by the limitations of industrial compressor technologies.

With a growing knowledge of the inherent high pressure capabilities of single screw technology, its use in industrial heat pump applications is gaining acceptance. Application results continue to reflect high heat pump performance with satisfactory reliability, reinforcing the benefits of single screw compressor technology's inherent balance design.

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