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Technical Paper #4

Benefit of Ammonia Heat Pump Implementation in the Industry and for District Heating

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Abstract

Over the last 15 years the market for high-temperature ammonia heat pumps has been growing in Europe and now it is also taking off in North America. That period in Europe has yielded many lessons as higher pressure and temperature present new challenges in refrigerant design. This paper explains where heat pump installation differs from refrigeration installation through three case studies of installations in Europe. The favorable thermodynamic properties of ammonia and good system design lead to high efficiency and short payback, which the three cases will describe. With many heat pumps being installed into the district heating market new challenges also arise regarding ammonia handling and safety as the installations are now closer to the public than traditional industrial settings for ammonia refrigeration systems. The paper will describe how these challenges have been overcome. With the phasedown of fluorinated greenhouse gases (F gases), incentives to go for natural refrigerants for these solutions have increased, and as this paper shows financial and environmental incentives to employ ammonia heat pumps are also large.

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Introduction

Industrial heat pump technology has been a known technology for more than 100 years and has been economically viable solution since the 1970s. Nonetheless the widespread uptake of heat pump solutions only started in the last decade. The reason is that burning fossil fuels like coal, oil, or gas is much easier than taking on the bigger investment in a heat pump to save cost in the long run. Most food factories have an abundance of waste heat available from the refrigeration system that can be upgraded with an add-on heat pump. Detailed analysis of the process requirements for heat and cold is necessary to apply the right size buffer tanks so the heat can be used in the process at low cost and high efficiency. Traditionally rejecting all this energy and then using boilers to provide the heating energy was preferred. However, as climate change continues to rise in importance on the global political agenda, major companies are looking to maximize carbon savings, which is where highly efficient heat pumps become an important replacement for boilers. If we can replace fossil fuel heating with heat pumps that only require a small percentage of the heating duty as renewable electricity to become carbon neutral, we will have taken a giant leap toward avoiding a climate crisis.

Ammonia Heat Pump Main Components

Compression Technology

Several compression technologies are currently available on the market, including reciprocating, scroll, centrifugal, and screw compressors. For ammonia applications, the industry typically uses reciprocating or screw compressors (Figure 1). Open-type compressors were preferred in years past, but more recently small screw compressors have also become available as semi-hermetic machines with integrated high-efficiency, copper-wound motors without a shaft seal for chiller applications. This

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development is just one reason natural refrigerants are becoming more accessible in commercial areas.

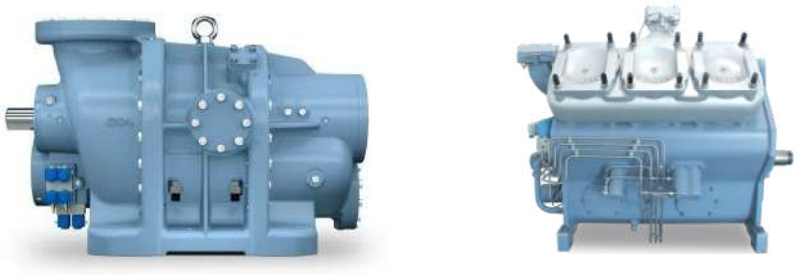

Figure 1. To the left is an ammonia screw compressor and to the right an ammonia piston compressor.

Each compression technology has strengths and weaknesses, so selecting the right compressor is important for getting optimal results from the heat pump installation. For heat pump applications, as for refrigeration applications, the specific running conditions for each project determines the preferred technology.

Reciprocating compressors have a smaller operating envelope relative to differential pressure. For example, high-temperature applications with a low source temperature require two-stage reciprocating compressors, whereas other applications require only a single screw compressor.

High-pressure reciprocating ammonia compressors are limited in capacity to around 580 ft^3/min (1,000 m^3/h), whereas some ammonia screw compressors in operation for heat pump applications have a capacity of more than 5,000 ft^3/min (8,500 m^3/h).

Also worth noting is that according to RTSelect, compressor selection software by GEA Heating & Refrigerating Technologies, reciprocating ammonia compressors increase in volumetric efficiency at heat pump conditions, while screw compressors' volumetric efficiency reduces at the higher evaporation and condensing temperature (Table 1).

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Table 1. Comparison of a Screw Compressor and Piston Compressor Running in Two Different Conditions

		Screw compressor		Piston compressor	
		Chill	Heat	Chill	Heat
Evaporation/ Condensing temperature	°F	14/ + 95	+ 91/ + 158	14/ + 95	+ 91/ + 158
Actual ft^3/min	ft^3/min	1,980	1,815	171	171
Volumetric efficiency	%	94.4	88.4	75.2	85.8

Source: Data from RTSelect, compressor selection software by GEA Heating & Refrigerating Technologies.

The volumetric efficiency of the screw compressors reduces 6% in heat pump operation compared with chill operation, whereas the piston compressor increases 10% in volumetric efficiency at comparable conditions.

In the industry, reciprocating compressors do most heat recovery as they match the capacity and offer better performance than screw compressors. For district heating most cases use screw compressors due to the large capacities offered by this compressor type.

Heat Exchangers

For ammonia heat pump applications delivering up to 203°F, heat exchangers with a minimum design pressure of 870 psi (60 bar[a]) are required. For refrigeration purposes, plate and frame heat exchangers are traditionally used, but availability of plate and frame heat exchangers for ammonia at the heat pump application design pressure is limited. The most common heat exchangers used on the heating side of an ammonia heat pump are shell-and-plate heat exchangers (Figure 2).

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Figure 2. A cut-through view of a plate-and-shell heat exchanger. It offers the high integrity of a fully welded heat exchanger (like shell and tube), but the small footprint and refrigerant charge of a plate heat exchanger.

These are available in a wide range of capacities and pressures, and for ammonia heat pumps using multiple heat exchangers in the heating circuit to optimize efficiency is common. A typical ammonia heat pump has a de-superheater, a condenser, a sub cooler, and an oil cooler (for screw compressor heat pumps), so up to four high-pressure heat exchangers are employed to get maximum efficiency out of the system (Figure 3).

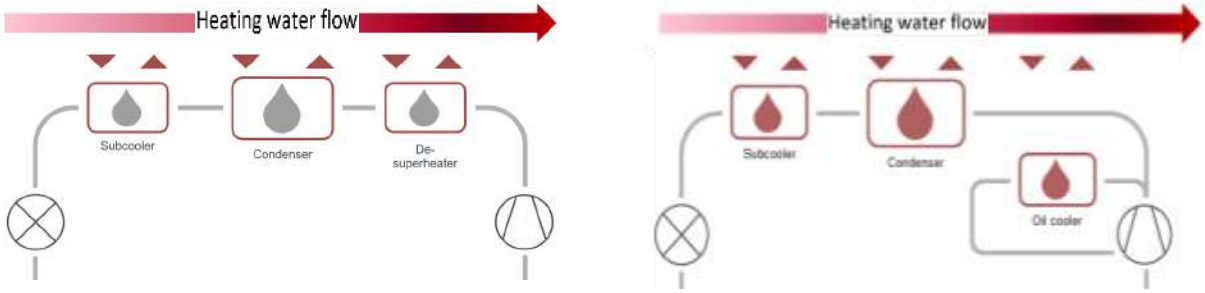

Figure 3. To the left is a typical heat exchanger setup for a reciprocating compressor heat pump, where a high discharge temperature greatly benefits a de-superheater but no oil cooling is available. To the right is a schematic of the water flow through the heat exchangers for a screw compressor heat pump, which features a lower discharge temperature and less superheat energy, but significant heat in the oil cooling circuit.

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Shell-and-plate heat exchanger technology is not commonly known outside the ammonia refrigeration market. The tender specification for large heat pump projects often calls for use of shell-and-tube heat exchangers as this is predominantly the choice for F-gas heat pump manufacturers. Using shell-and-plate heat exchangers has clear benefits such as compactness, low charge, no requirement for service space for tube bundle extraction, etc. Customers must be informed about these benefits to accept alternative heat exchanger solutions.

On the cooling side of a heat pump the selection of heat exchanger depends on the heat source. Many heat pumps installed in the industry use the condenser heat from the refrigeration system as the heat source. For these applications having fully welded heat exchangers is preferable as it minimizes the risk of ammonia leakage out of the system.

For water source heat pumps the selection of evaporator is like refrigeration systems, where plate and frame are most commonly used. If there are particles in the water, shell and tube is preferable and if operating close to freezing a falling film evaporator is an option. These heat exchangers have no special requirements regarding the pressure as standard design pressure can be applied (230–360 psi).

Heat Pumps in Dairies in the United Kingdom and Ireland

In 2008, a dairy in Northeast England was looking to save costs on its fresh milk production line. Fresh milk is a low-margin, high-volume product, so a small savings per gallon can add up to high value. The dairy had installed a 398 TR (1,400kW) ammonia refrigeration plant for cooling down the milk after pasteurization, and it was using 3.14 MBtu/hr (920 kW) of steam (generated by gas boilers) to heat water to 176°F for the pasteurization process (Figure 4). This process is the same for almost all fresh milk dairies across the world.

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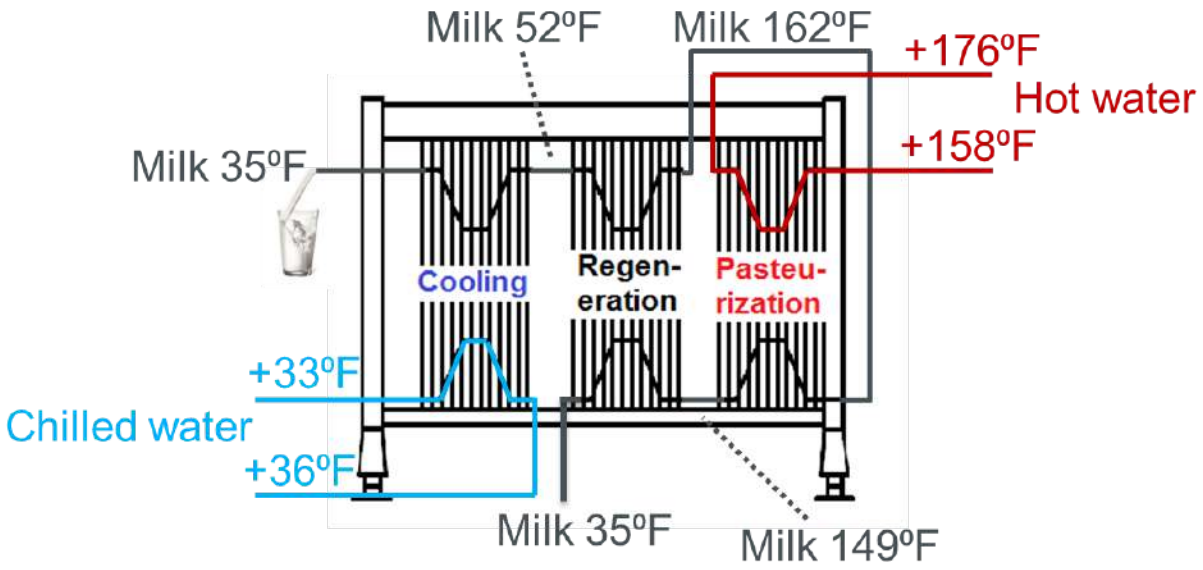

Figure 4. A typical setup for pasteurization with a three-zoned heat exchanger. First the incoming milk is heated in a regeneration area, while the pasteurized milk cools, then the incoming milk is pasteurized with hot water to above 162°F (for fresh milk). After the regeneration area the milk is chilled to a holding temperature of around 35°F using chilled water.

For refrigeration 3 x GEA V1100 compressors were installed with evaporative condensers for heat rejection. At the UK average condensing temperature of 73°F the condenser heat rejection is 5.47 MBtu/hr (1,603 kW) at full load (Table 2).

Table 2. Cooling Coefficient of Performance (COP) of the Refrigeration Plant without the Heat Pump Installed

Compressor	Rpm	To (°F)	Tc (°F)	Qo (TR)	P (kW)	Qc (kW)	COP cooling
3 x GEA V1100	734	23	73	(1,400 kW) 398	203	1,603	6.9

Note that Table 2 indicates a cooling coefficient of performance (COP) of 6.9 for the compressors. The COP is defined as the cooling duty (Qo) in kW divided by

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the absorbed power (P) in kW. The same expression (COP) is used for heat pump installations. In this case the heating duty (Qc) in kW is divided by the absorbed power (P) in kW.

When operating the dairy plant in a traditional way, the dairy uses 203 kW of electricity and 920 kW of steam. There are losses in the steam system (5%–50%), and industrial boiler efficiency is normally between 75% and 85%. For assessment of the site, we have assumed only 20% losses in the boiler and steam system. To get 920 kW of steam energy into the milk requires 1,150 kW of natural gas. Installing a heat pump that uses the waste heat from the refrigeration process enables significant reductions of energy usage. To optimize the heat pump installation, one of the refrigeration compressors is dedicated as a heat source for the heat pump compressors (Table 3). Using this configuration enables us to minimize the heat pump compressors by increasing suction temperature and still have the refrigeration plant operate with floating head pressure for optimum efficiency throughout the year.

Table 3. Cooling COP and Power Consumption of Refrigeration and Heat Pump System

Compressor	Rpm	To (°F)	Tc (°F)	Qo (TR)	P (kW)	Qc (kW)	COP cooling
2 x GEA V1100	590	23	61	786 kW 224	87	1,603	6.9
1 x GEA V1100	1,191	23	109	684 kW 194	160	774	3.8
2 x GEA 65HP	1,072	109	181	774 kW 220	146	920	

The two heat pump compressors were added to the system via an interstage vessel, so losses between the condensing temperature of the refrigeration compressor and the suction pressure of the heat pump compressor are minimal. The heat pump

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compressors deliver 180°F hot water (hence the condensing temperature of 181°F). An intermediate water circuit is between the 176 °F hot water going into the pasteurizer and the 181°F coming out of the heat pump, which ensures that any potential ammonia leak into the heating water will not contaminate the milk. Table 3 shows that the total electrical power has increased from 203 kW to 393 kW, so an extra 190 kW of electricity, but the customer has also saved 1,150 kW of gas usage. Based on a gas price of $0.052/kWh and an electricity price of $0.09/kWh and with the plant operating 7,488 hours per year the yearly savings are $307,500 per year (Unsworth, 2011). In addition the carbon savings are significant. When the plant was installed in 2008, the carbon intensity of electricity production in the United Kingdom was 1,190 lb/MWh and emissions from burning gas was 474 lb/MWh, at the time the dairy saved 1,083 tonnes of CO_2 emissions per year. Today, 13 years after the installation, all coal-fired power plants have been decommissioned in the United Kingdom and a significant part of UK electricity is supplied by renewable sources, so the yearly average carbon intensity of electricity is now 400 lb/MWh (2020). As of this writing, the plant has reduced carbon emissions by 1,600 tonnes per year.

In 2019 Aurivo dairies in Ireland made a similar installation for their fresh milk pasteurization process in County Donegal (Figure 5), where they pack 120 million liters of fresh milk per year and are saving $402,500 per year and 400,000 lb of CO_2 emissions per year (*Dairy Reporter*, 2020).

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Figure 5. Installation of 1,200 kW ammonia heat pump at Aurivo fresh milk dairy in Ireland.

London Underground Heat Pump

In 2016, Islington Council in Central London built the world's first heat pump to feed cheap low-carbon heat into a district heating network using the exhaust ventilation air from the London Underground as the heat source. The plan is to continue the development of district heating networks in London and eventually connect all the tower blocks and public buildings like schools, hospitals, and leisure centers. When the heat network has been established, the plan is to try to attract private and commercial owners to sign up to the network also. The heat network will be able to supply environmentally friendly heating at lower cost than burning gas and with zero NO_x emissions, which cause around 4,000 deaths per year in central London (Imperial College London, 2020).

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For this phase of the project (Bunhill 2), a 1,034 kW two-stage ammonia heat pump was installed. The ammonia charge is approximately 770 lb (Hoffmann, 2017). The heat pump consists of a combined evaporator/separator in a fully welded shell. Four heat exchangers are in series in the heating circuit to optimize the performance of the heat pump (Figure 6). First the district heating water cools the de-superheated gas from the low-stage compressor, and then the water is heated in series through the sub cooler, condenser, and de-superheater from the high-stage compressors.

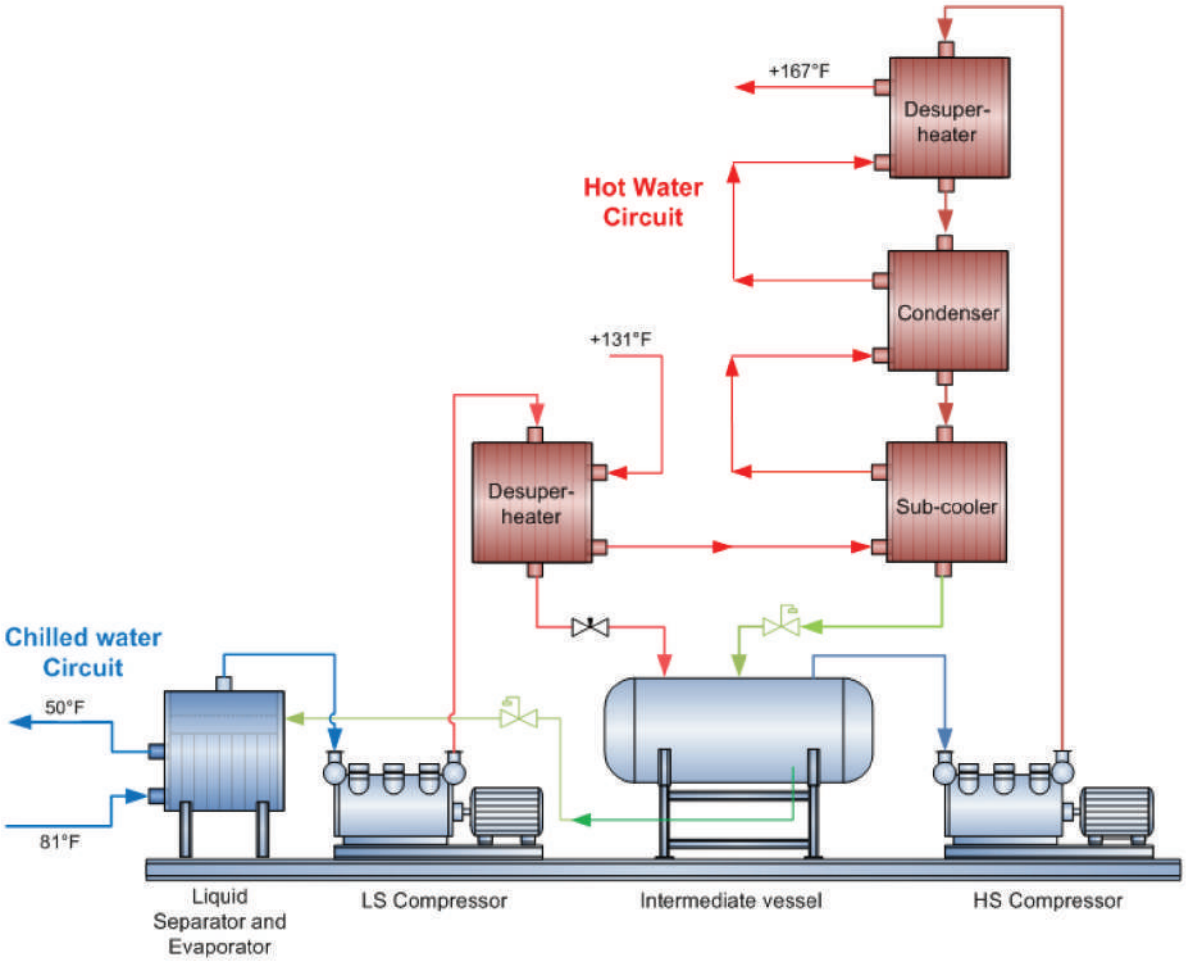

Figure 6. Simplified schematic of the ammonia and water circuit of a high-efficiency heat pump.

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The design criteria for the heat pump are based on heating water returning at 122°F and supplied at 167°F. The air cools from 75°F to 57°F in the cooling coil with water at 55°F/46°F. At these conditions, the total cooling duty is 222 TR (780 kW), the absorbed power of the three compressors is 369 BHP (275 kW), and the heating duty is 1,034 kW giving a heating COP of 3.7. The heat network needs a higher temperature in the peak of winter, so the heat pump is designed to supply heating water up to 176°F (Figure 7). On the cooling side the ventilation air coming out of the underground can also vary. In the peak of summer, it can be 86°F and in the winter, it can drop to 68°F. It rarely drops below 68°F. When the tube started operating in the 19th century it was cool underground, but due to inadequate cooling and ventilation, the generated heat from the people and friction from the train operation have heated up the whole network 18–25°F since it began operation.

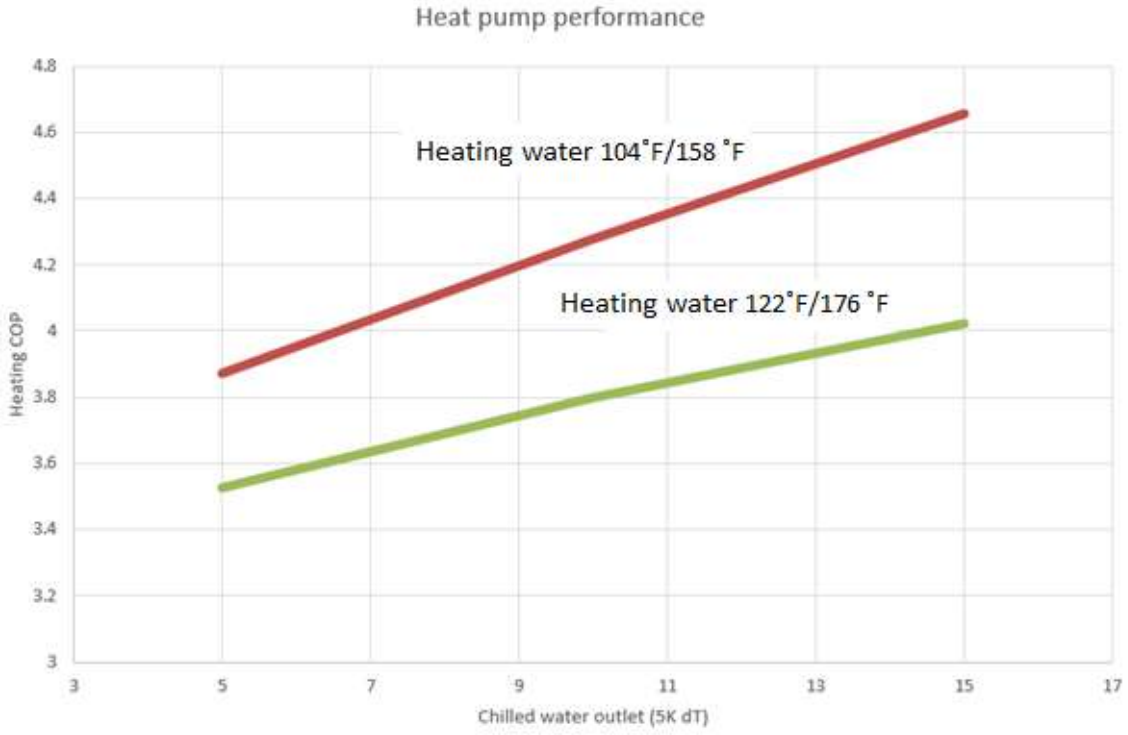

Figure 7. Illustration of the performance of the London Underground heat pump. The green line (122°F/176°F) is the performance at the time of installation. The council aim to optimize the heating network over time and lower the flow and return temperature and eventually achieve the performance illustrated by the red line (104°F/158°F).

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The heat pump has one low-stage piston compressor and two high-stage compressors. The low-stage compressor provides enough cooling capacity to generate 1,000 kW heating capacity. The minimum part load of the system is 25% of the design capacity—both low-stage and high-stage compressors have VFD motors for optimised performance at part load.

Heat Source

From other air source heat pumps, we are accustomed to the air-cooled evaporator blocking up with ice, which can be overcome by defrosting the coil. In this case defrost is unnecessary as the temperatures are much above 32°F, but an issue remains with the cooling coil blocking up. The air is extracted from the underground to ambient at ground level. A (780 kW) 222 tons of refrigeration water–cooled cooling coil is mounted in the airstream with a reversible fan extracting 70 m3/s. Most of the year the air from the London Underground will be cooled before being vented to atmosphere. On warm days, the airstream is reversed and chilled across the cooling coil before being vented into the underground tunnel. The London Underground has experience with this type of installation from other parts of London where the air is chilled before venting to the underground tunnels. The air quality from street level differs significantly from air extracted from the underground. The underground air has a high metal content (Transport for London, 2014), whereas the air quality on busy London streets is mainly (around 80%) NO_x and PM10 and PM2.5 from exhaust and brakes from cars, busses, and trucks (Chetan Lad, 2016). To avoid the coil being blocked by the pollutants, a wide fin spacing was chosen (four fins per in.). Based on the London Underground's experience from other sites and tests made with the cooling coil the coil will need to be cleaned every 6–12 months.

To avoid ammonia potentially leaking from the air-cooling coil and being vented into the underground, there is an intermediate water loop. The heat pump cools water that is circulated in the cooling coil in the ventilation shaft.

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Ammonia Absorber

The ammonia heat pump is installed at street level on the corner of a busy London street. To avoid any harm to people the extract air from the plant room will be rejected above the roof of the nearby 18-story block of flats during normal operation. When the plant is serviced (some ammonia smell can be expected) or an ammonia alarm is set off, all the ventilation air will be passed through a carbon filter, which absorbs all the ammonia leaving 0 ppm of ammonia in the air after filtration. We have investigated other options, but no other solution can offer 100% removal of the ammonia in the air. Water scrubbers and acid-based scrubbers reduce the ammonia content in the air below dangerous levels, but they do not completely remove the ammonia from the air, and with a large population in the area with no knowledge of ammonia safety levels, any prevailing ammonia smell could cause panic. Although the ventilation air is rejected at the highest level, taller buildings are under construction nearby, so having zero ammonia content in the ventilation air is important.

The absorption material used is a carbon-based pellet, with an additive to improve the ammonia absorption properties. In our test we found that that material can absorb up to 5.6% ammonia. For the project in London, the absorber quantity is selected based on 4.6% ammonia absorption capacity. Therefore, installation of 17,600 lb of absorbent material would be required to absorb the 770 lb of ammonia in the heat pump (Figure 8). This could have been mitigated by selecting a design with independent ammonia circuits for the low stage and high stage, which would have more than quartered the ammonia content per circuit to less than 150 lb, thereby reducing the size of the absorber equally.

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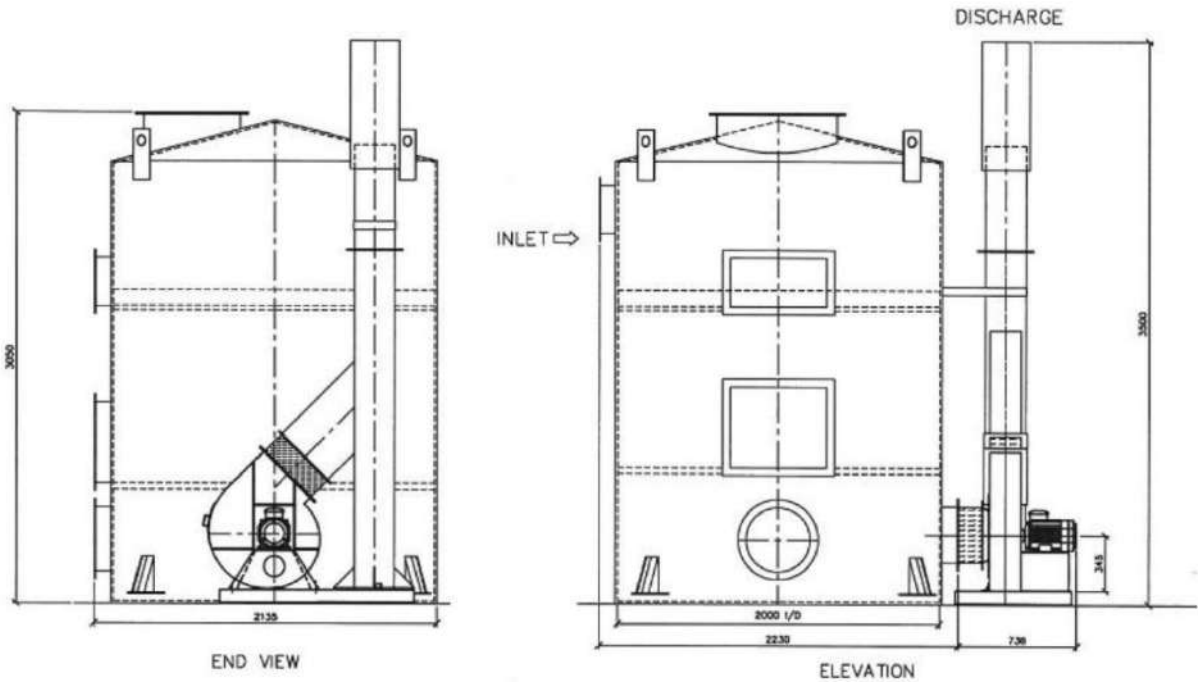

Figure 8. Drawing of the absorber vessel holding 17,600 lb of carbon pellets, through which the ventilation air passes.

Malmö District Heating Heat Pumps

In a world of phrases such as "environmentally friendly," "sustainable," and "natural," Swedish district heating is using innovative technology to meet regulations and set quite high efficiency standards. In 1980, the Swedish town of Malmö installed its first district heating heat pump plant. However, in 2012 when the Montreal Protocol banned the synthetic refrigerant used in the plant (R22), the plant was decommissioned. In November 2017, the second generation was up and running after one year of preparation.

E.ON, one of the world's largest investor-owned electric utility service providers, installed four ammonia heat pumps, each with just more than 34 MBtu/h (10 MW)

heating capacity next to the sewage treatment and waste incinerator plant in the Malmö harbor area (Figure 9). The heat pump system extracts nearly 8,500 TR (30 MW) of heat from the sewage water and adds 10 MW of electrical power to generate 136 MBtu/h (40 MW) of heating.

Figure 9. Four 10 MW heat pumps installed in Malmö, Sweden.

The sewage water temperature varies between 54°F and 64°F depending on the season. The cleaned sewage water was previously returned to the sea, but now it passes through the heat pump evaporator and is chilled 6K before being returned to the sea. By harvesting the heat from the wastewater, which has a higher average temperature, the plant is running with better efficiency than if it had been using sea water (-15% efficiency) or ground source water (-10% efficiency).

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As the sewage water is not constant throughout the year (more after rainfall) or during the day (more in the morning), a large reservoir for the sewage water was built, which was ready a year after the heat pump was installed. By evening out the sewage water flow the yearly energy output from the heat pumps has increased from 110 GWh to 170 GWh.

Although the sewage water is taken at the end of the cleaning process, particles of organic material remain in the water. To avoid these blocking up the evaporator, a fine filter (2 mm) is installed, and the tubes in the shell-and-tube evaporator are cleaned daily, using a ball cleaning system, without stopping the heat pump. Efficiency improves 2%–3% after each ball cleaning of the tubes.

Heat Network

The heat pump has been integrated into the district heating network to work with the nearby waste incinerator plant. The return water from the city comes to the waste incinerator plant at around 122°F, where the flue gas economizer heats it to around 131°F before it enters the heat pump where it is further heated to 151°F. The water then returns to the waste incinerator plant where it is further heated to the required temperature for the heating network, which can vary depending on the heating demand from 167°F to 203°F (Figure 10). The heat pump is designed to deliver heat up to 176°F, but will rarely deliver temperatures greater than 162°F.

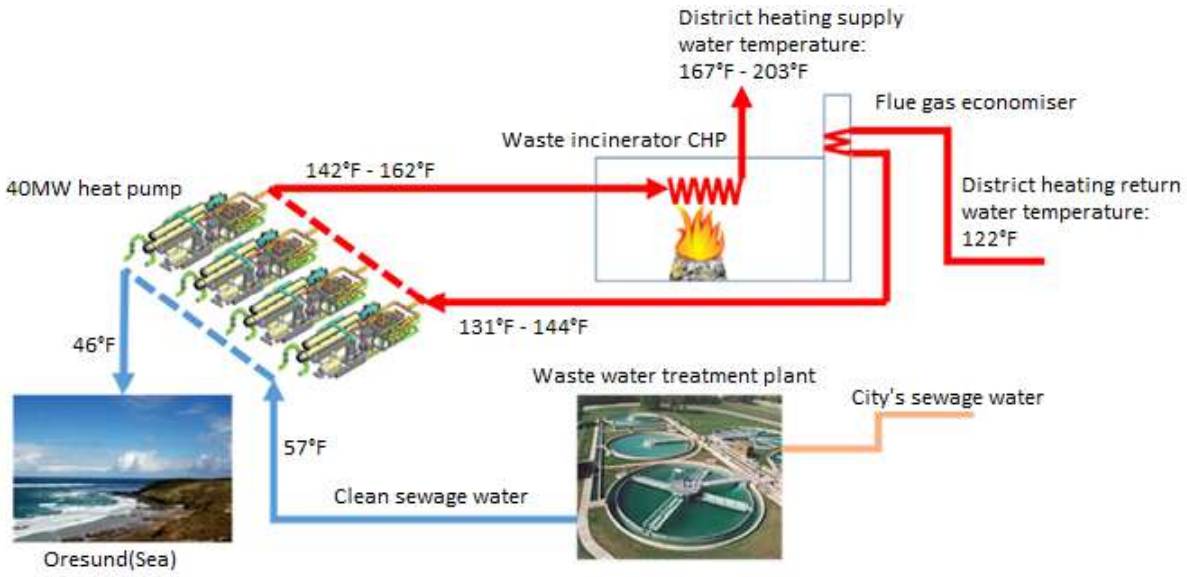

Figure 10. Schematic of the water flow through the heat pump. The sewage water is first cleaned before the heat pump and afterward pumped into the sea. The heating water comes back from the city and is heated in the flue gas economizer and then heated by the heat pump before it returns to the waste incinerator plant where it is heated further from the waste heat to the desired outgoing temperature.

By replacing heating traditionally done by gas boilers the district heating network saves more than 50,000 tons of CO_2 per year. Many other cities aim to decarbonize their heating systems over the coming years and remove NO_x from the local environment. Many other Nordic cities have already installed high-efficiency heat pumps to combat local and global pollution, and more will surely follow globally in the coming years. By using ammonia heat pumps, the City of Malmö is not only swapping from fossil fuel to electrically driven heating, it is also doing it in the most efficient way. Today delivering heat up to 203°F is possible (Ammonia21, 2021) with a heating COP greater than 3.0 using an ammonia heat pump, which is more than 20% better than F-gas competition.

In the future when all heating has moved from fossil fuel to electrically driven heat generation green electricity production will be unable to fulfill this growing demand.

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To achieve a match between the available electricity and renewable heating installing the most efficient system today is important.

Conclusion

Ammonia heat pumps are suitable for many applications. Industries with combined cooling and heating needs are the most obvious application because payback of the investment is the shortest. However, many other applications also exist such as in industries where there is no cooling demand but plenty of waste heat. Many cities are also looking into decarbonizing the heating of homes, as replacing fossil fuels not only reduces the carbon footprint, it also reduces NO_x emissions, which are a major health problem in large cities.

Heat pump installations have also advanced from being purely based on payback, as demand for decarbonization is increasing, leading to ever increasing temperature demand. Many customers now ask for heat pump solutions up to 203°F hot water, which is possible with today's ammonia heat pumps.

As with refrigeration, ammonia is not competitive for small domestic systems, but the upper size of ammonia heat pumps has few limits. So far, the largest installed is 136 MBtu/hr (40 MW), but with modular design even larger ammonia heat pump installation are achievable.

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