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Ammonia - Steam cascade heat pump for +100˚C steam generation

Kenneth Hoffmann[a*], Michael Bantle[b], Kjetil Evenmo[c]; Vebjørn Nilsen[d]

[a]GEA Heating and Refrigeration Technologies, Unit 9, Conqueror Court, Sittingbourne, Kent, ME10 5BH, United Kingdom
[b]ANEO Industry, Klæbuveien 118, 7031 Trondheim, Norway [c]EPCON Evaporation Technology, Fossegrenda 42, 7038 Trondheim, Norway, [d] Felleskjøpet Agri AS, Nedre Ila 20, 7018 Trondheim, Norway

Abstract

A new innovative high temperature heat pump solution developed by GEA, ANEO and EPCON is presented in this paper: High efficiency and high temperature heat pump for generating steam in the processing industry. By using natural refrigerants ammonia and steam it is possible to ensure the highest possible efficiency without causing any potential harmful damage to the global environment. The heat pump harnesses the heat from the exhaust moist air from the drying process, the air is cooled and dehumidified. It is important to dehumidify the air as a substantial amount of energy is latent energy in the moist exhaust air. Chilled water as low as 20 °C is needed for the energy extraction and a 2-stage ammonia heat pump is used as the first step to generate 85 - 90 °C steam. The dry steam is then compressed to the required steam pressure of 2 bar (around 120 °C) with 4 centrifugal fans in series. This multistage cascade solution gives a high efficiency and minimize the cost by combining two technologies (steam compression and ammonia compression) each operating in the application area where they are the best available technology and hereby achieving a temperature lift of 100K with a heating COP of 3.1.

Keywords: Ammonia, MVR, steam compression, cascade, high temperature heat pump, petfood drier.

1. Introduction

There is an increased focus on decarbonization of industrial processes. The first step in decarbonizations is reducing energy consumption. By closely looking at the whole process and establishing where the quick wins are that, without significant cost, can reduce the primary energy usage. Other improvements are to optimize the heat exchanged within the process and reduce temperature differential across heat exchangers. Many processes are designed for usage of 5 – 10 bar steam (150 °C to 180 °C) for all heating needs even if the temperature needed for the process, is well below 100°C. After energy reduction and optimization, the next step is to establish where waste energy from one process can be used in other parts of the process. This step often leads to installation of heat pumps as the waste energy often are at lower temperatures than required for the process. The many companies who are going through this process often see that most of their heating demand can be met with hot water circuit below 100 °C. This makes the heat recovery easy as it can be provided by standard ammonia heat pumps (preferred refrigerant within the food, beverage and dairy industry). With most of the process heating being decarbonized there is often still some heating demand above 100 °C, which so far have been provided by with either gas fired or electrical boilers. However, this can now be done more efficiently by using natural refrigerant heat pumps (although not ammonia).

Before starting to decarbonize production processes it is important to follow the right strategy. In the pyramid below is shown a sensible approach to decarbonization. The easy and most beneficial gains can be achieved from the bottom of the pyramid, by looking at energy efficiencies in the production. Next step is heat recycling. If the heat demand is large than what can recovered from waste heat the next step is to look for onsite heat generation like solar thermal of geothermal heat. If this is not an option then electrical boilers could

* Corresponding author. *E-mail address:* kenneth.hoffmann@gea.com

be an option and finally the most expensive options of renewable fuels or offsetting emissions, which can achieve the decarbonization but at an added cost making the business less competitive.

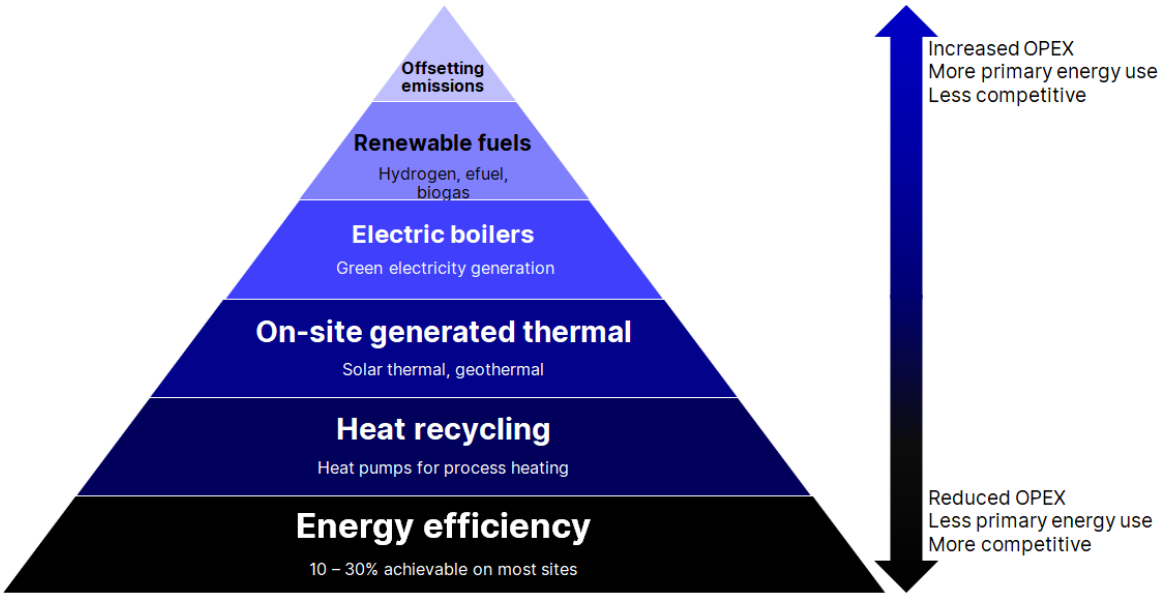

Fig. 1. Decarbonization pyramid.

2. Refrigerants available above 100˚C

Before developing a heat pump solution for delivering temperatures above 100 ˚C, we did an analysis of the available refrigerants for the market. From the table below is a comparison of some of the most common refrigerants considered for heat pump applications above 100 ˚C.

R245 have been around for 20 years and several projects with this refrigerant have been implemented for ultra-high temperature heat pumps (ultra-high = heat pumps delivering more than 100 ˚C). However, R245 have a global warming potential (GWP_{100}) over a 100-year period of 1030. In 2016 the UN countries agreed on phase down of all high GWP refrigerant in the Kigali agreement. Almost all countries have since ratified the agreement and made it local legislation. With a looming ban of high GWP refrigerants it does not make sense to invest in developing solution using these high GWP refrigerants.

R1233zd(E) is one of the new generation F-gasses with low GWP value (<5), This refrigerant has the benefit of being in safety category A1 (non-toxic and non-flammable), which broadens the application area. Unfortunately, the chemical includes Chloride molecules in it structure which is banned in some countries as it leads to ozone depletion (ODP) when released to nature. The ozone depletion is very low for the refrigerant and is registered as having 0 ODP according to UN protocol. The main consideration before applying R1233zd(E) refrigerant is that there now is increased focus on the degradation products of F-gas refrigerants. In Europe long chain Perfluoroalkoxy alkane (PFA) have been banned for several years due to their environmental damage and long life in the nature (also knowns as forever chemicals), but this has led to an increase in use of chemicals which breaks down to shorter chain PFA. These chemicals have proven to be just as damaging to the freshwater environment as the banned PFA, so it is likely that there in the future will be a restriction in the use of chemicals which breaks down to any PFA. One of the breakdown components from refrigerants containing fluoride components are Trifluoroacetic acid (TFA) which is one of the chemicals which is defined as a PFA with short chain fluoride molecules. With these issues in mind there need to a clear efficiency benefit of using these refrigerants with focus on zero leakage system design and a plan for refrigerant recovery at the end of life, to minimize the environmental damage of the refrigerant in the environment.

R601 (Pentane), is one of the hydrocarbons recently identified as suitable for ultra high temperature heat pump applications. With a critical temperature of 196.6 ˚C, it is a suitable refrigerant for delivering hot water or steam above 160 ˚C. This refrigerant has the benefit of being a natural refrigerant with known environmental footprint. When comparing the thermodynamic specifications for the different refrigerants it has been proven in previous papers that R601 offers a higher efficiency than alternative F-gas refrigerants. The main obstacle for a mass implementation of heat pump solutions with R601 is that it is in safety category A3, which is non-toxic but highly flammable. The high flammability will limit the applications where is can be applied.

R718 (water), have been proven to be a very efficient refrigerant and with a critical temperature of 373.9 ˚C, it is suitable for heat pumps delivering more than 200˚C water or steam. It is non-toxic and non-flammable and no environmental impact of the refrigerant. The main issue is the high boiling point at atmospheric pressure of 100 ˚C with the correlated high-volume flows in vacuum application as well as the high superheat generated during compression. An analysis of the food, dairy and beverage industry have shown that heat sources in general are below 100 ˚C, so steam compressors will have to operate in vacuum and with steam in vapor phase below 100 ˚C, there is a requirement for compressors with a large volume flow.

Table 1. Comparison of refrigerant types suitable for +100˚C

Refrigerant	R1233zd(E)	R245	R601	R718
Molecular structure	CHCl=CH-CF3	CF3CH2CHF2	CH3-3(CH2)-CH3	H2O
Molar weight	130.5	134.0	72.15	18.0
Boiling point at 1.013 bar (°C)	18.3	15.14	36.1	100.0
Critical temperature (°C)	165.6	154.0	196.6	373.9
Critical Pressure (bar)	3.57	3.65	3.37	22.1
Heat of vaporization @ 120 °C (kJ/kg)	123.1	112.4	268	2202.2
GWP100 (CO2=1)	<5	1030	11	0
ODP	0.00034	0	0	0
Lifetime in atmosphere (days)	10 – 40	~2800		-
Occupational Exposure limit (OEL) (ppm v/v)	800	300	2000	1.000.000
Safety group (ASHRAE 34)	A1	A1	A3	A1

3. Heat pump application

Industrial food processes like sterilization, high temperature pasteurization or drying requires more than 100 ˚C heat supply. Outside the food industry there are more processes requiring higher than 100 °C steam like paper, pulp, chemicals etc. for many of these processes it is possible to provide the heat by heat-recycling as the heat added in the front end of the process in most cases can be recovered later in the process. In food processing where pasteurization or sterilization is needed, you will most likely have a refrigeration plant which is used to cool the products after it has been heated and the refrigeration plant reject waste heat to ambient in the process, this heat can via a heat pump be upcycled to the right temperatures for the process. For drying facilities there is not always a refrigeration plant as the drying process removes the moisture content from the product, which gives the product a long shelf life without the need for keeping it refrigerated. For drying processes, you often have large amount of waste heat in the exhaust air, as the air used for drying is collecting the moisture and being heated up across the product. By cooling the air below the dew point sufficient energy can be recovered to recycle the heat and use the exhaust air as the heat source for providing steam for the drying process.

In the diagram below is shown a schematic of a typical pet food pelleting process. The energy flow for pet food pelleting is very similar to a spray drying process. The pellets are formed by mixing the ingredients with process steam and pressing them into their final shape. Hereby the product/pellets are moisturized and heated. In the next process step the pellets are cooled and dried in counterflow with cooling air. The air becomes moist and warm in the process. This exhaust air is used as heat source for a the heat pump and the sensible as well as the latent heat is transferred into the ammonia heat pump. The 2-stage ammonia heat pump system generates low pressure steam at 85 °C. The steam is then compressed via 4-stage centrifugal fans to the required steam pressure for the mixing process of 2 bar.

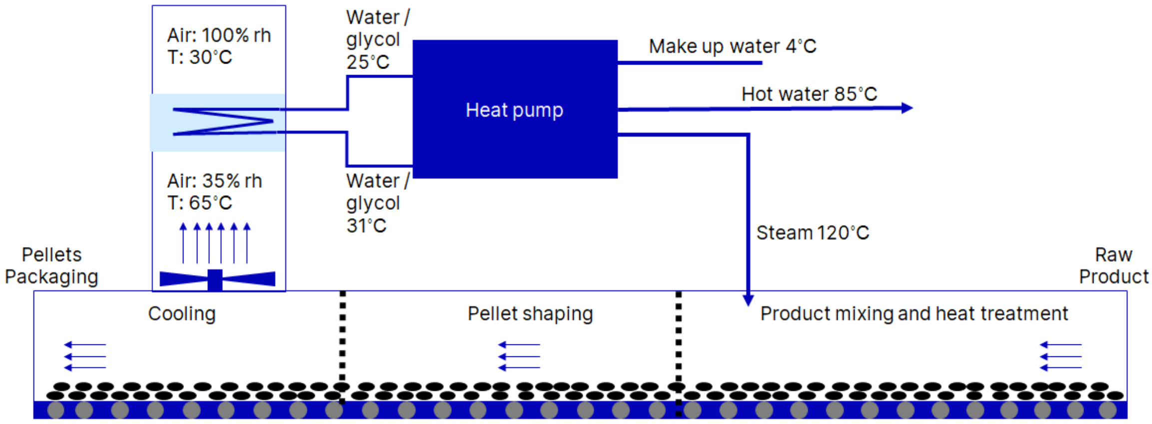

Fig. 2. Schematic of the process to which the heat pump is applied

4. Heat pump design

The pelleting process requires 2000 kg steam per hour at 2 bar (120 ˚C). As the steam is injected into the product, no steam is recovered, and all the steam needs to be generated from the make-up water, which is entering the heat pump at 4 ˚C. The factory also needs hot water at 85 °C for other consumers, which they would like the heat pump to provide in addition to the steam demand. The heat source is via a water circuit in the exhaust air stream. The heat exchanger in the exhaust air is designed for a water temperature supply temperature of 25 ˚C and return temperature to the heat pump of 31 ˚C. With an evaporation temperature of around 22 ˚C for the heat pump and steam delivered at 120 ˚C, it is close to 100K temperature lift, for this to be economically attractive the efficiency of the heat pump needs to be best in class.

To achieve highest possible efficiency of the heat pump system, different heat pump configuration has been considered.

1. Purely steam compression
2. Low stage: Single stage ammonia heat pump. High stage: steam compression
3. Low stage: Two stage ammonia heat pump. High stage: steam compression

4.1. Purely steam compression

There are different compression technologies available for steam compression, however there are large differences in the efficiency of these compression systems. For lower pressures (below 2 bar), the centrifugal turbo compressors have proven to offer the highest efficiency with an isentropic efficiency around 80-85% for the compressors. The centrifugal turbo compressors offer 9 – 10K temperature lift per compression stage for their standard range. There are centrifugal compressors on the market which almost double this temperature lift in a single stage. However, for smaller capacities the cost per kW is not economical for compressors with higher temperature lift and it is more affordable to have 2 compressors with smaller temperature lift. For a project of this size and temperature lift it is necessary with 11 – 12 MVR turbo compressors for the most efficient steam only system. Due to the cost and space requirement this solution was discarded.

4.2. Low stage: Single stage ammonia heat pump. High stage: steam compression

Low stage ammonia piston compressors have an isentropic efficiency of 88% at the chosen design point. Ammonia piston compressors is a price competitive solution with a small footprint and high efficiency. Figure 3 shows the application area for the GEA ammonia piston compressors. The graph shows that at an evaporation temperature of 22 ˚C it is not possible to condense above 80˚C this will give a steam evaporation temperature of 76 ˚C and the compressor will be operating on the limits of its operation area. For delivering steam at 120˚C, we would require 6 or 7 centrifugal compression stages, to lift the steam temperature from 76 ˚C to 120 ˚C. With the operational limitation in mind a 2-stage ammonia heat pump was considered.

4.3. Low stage: Two stage ammonia heat pump. High stage: steam compression

With a two-stage ammonia compression cycle it is possible raise the suction temperature of the high stage ammonia compressor, so it no longer operates at the limits of the application area. This also gives more flexibility of the suction temperature of the steam compressors. The steam evaporation temperature was set at 85 ˚C, with the ammonia heat pump able to increase this to 90 ˚C. This flexibility will give valuable information regarding heat pump design for future projects.

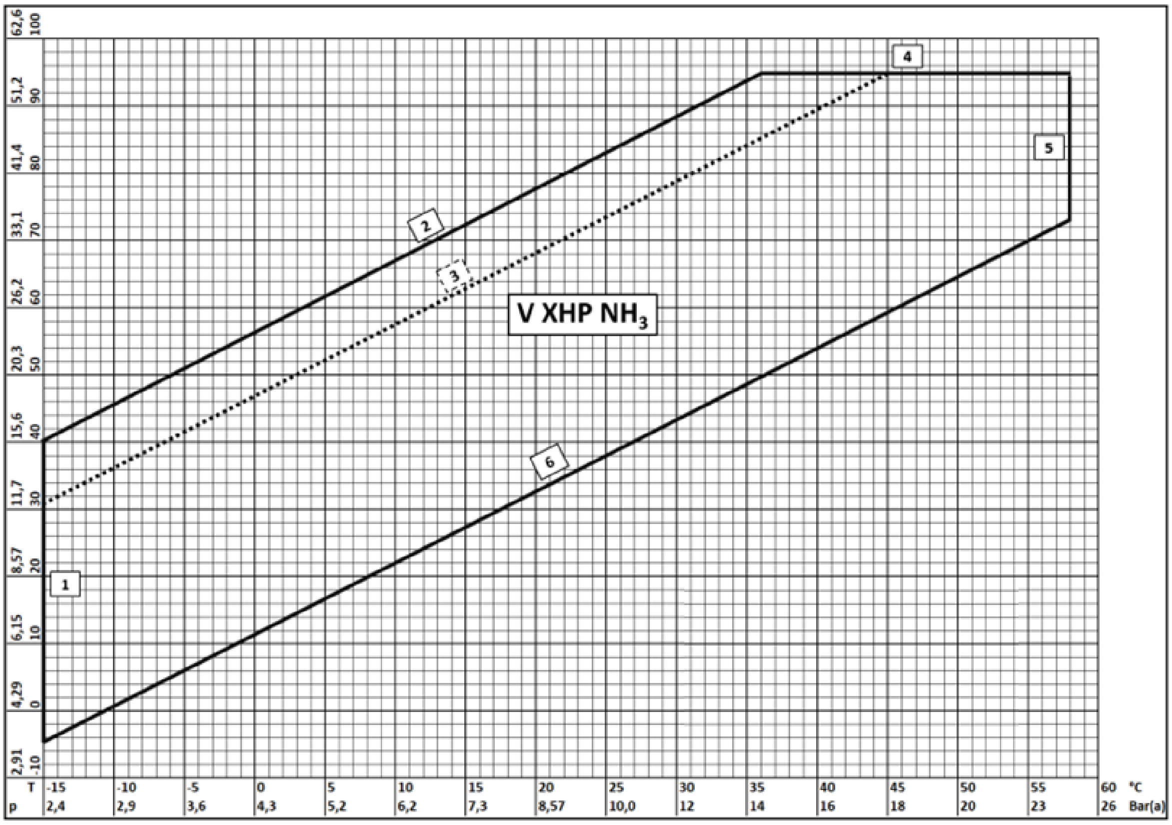

Fig. 3. Application area for the VXHP compressor range, the limitations are: 1: minimum evaporation temperature, 2: maximum discharge temperature at full load when superheat is 0K, 3: discharge temperature with some cylinders disengaged, 4: maximum condensing temperature, 5: maximum evaporating temperature, 6: minimum pressure ratio

4.4. Heat pump system description

The heat pump is designed with a low stage screw compressor operating from +22 ˚C to +45 ˚C. The chilled water circuit is designed for 25 ˚C / 31 ˚C flow and return temperature. If the exhaust air has a higher moisture content or higher outlet temperature, it will be possible to extract sufficient heat with higher chilled water temperatures and approving the efficiency of the heat pump. The absorbed power of the low stage compressor reduces with approximately 2% per degree higher suction temperature. If it is possible to operate at 5K higher suction temperature it reduces the absorbed power with approximately 10% or 15 kW. The screw compressor will need a small amount of oil cooling to ensure sufficient lubrication ability. A high oil temperature will result in a lower viscosity and provide less lubrication, which can lead to increased wear of the compressor. Around 20 kW of oil cooling is provided by the chilled water circuit. Alternative ways of doing the compressor cooling were considered, like thermosyphon oil cooling or liquid injection into the discharge of the compressor. Each solution gives more heat recovery, but are also more difficult to operate, so as this is a trial installation, the system which is easiest to control have been chosen for the oil cooling circuit.

The chilled water circuit is also connected to the oil-cooler on the reciprocating high stage compressor. It is not necessary to have oil cooling of the high stage compressor during normal full load operation, but during part load it might be necessary. Both ammonia compressors are using the same oil.

The evaporator is a plate and frame in stainless steel AISI316L, in combination with the low charge separator it gives a good performance at variable working conditions. After the discharge from the low stage compressor the superheated discharge gas is injected into an open separator vessel below the liquid level in the separator to ensure the gas temperature in the vessel is not superheated. The saturated gas from the low stage screw compressor is compressed in the high stage piston compressor. The high stage compressor is a 6-cylinder high pressure compressor which is able to condense at up to 95 ˚C. It will be operating between the suction pressure of 45 ˚C and the saturated discharge pressure of 89 ˚C. The superheated refrigerant is condensed in a AISI316L stainless steel plate and frame cascade condenser/evaporator. Low pressure (0.58 bar) steam is evaporated in the cascade condenser/evaporator. Due to the large volumetric difference of liquid water and water vapor, 30% of the water entering the heat exchanger at the bottom is exiting the heat exchanger at the top together with the steam bubbles. To separate the water from the steam a separation tank is installed. The dry steam is compressed through 4 stages with centrifugal fans to the desired end pressure of 2 bar steam (120 ˚C). On the inlet side of the centrifugal fans is liquid injection to control the superheat of the discharge steam.

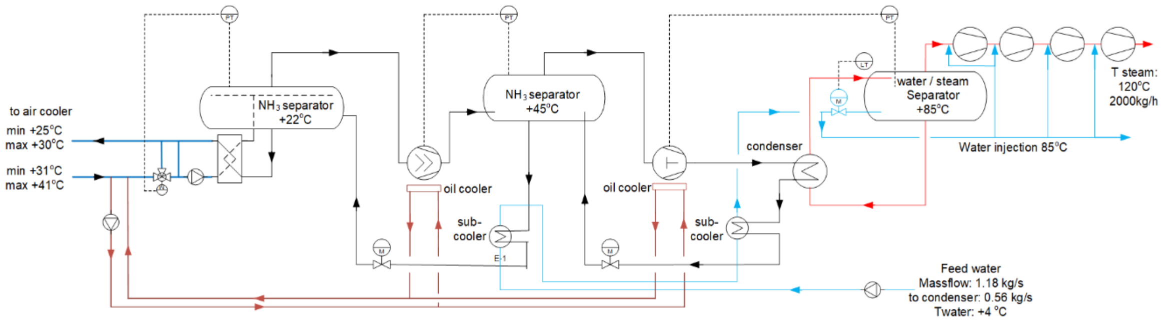

Fig. 4. Flow diagram for the complete heat pump system with both the ammonia compression heat pump and the mechanical vapor compression part.

4.5. Steam generation

With an ammonia design pressure of 60 bar and steam evaporating at 0.56 bar, it is important to select the right heat exchanger for exchanging energy between ammonia and water. Several different types of fully welded heat exchangers were considered. On figure 5 is shown 2 different solutions. The solution to the left has the heat exchanger plate pack within the water/steam separation vessel. This ensures practically 0 kPa pressure drop, which helps with the efficiency, however, there is concerns about potential deformation of the plates within the vessel, as there is no frame support at the end of the plate pack and with a pressure inside the plate pack of 60 bar, it seems like a high risk. To the right is a fully welded heat exchanger with a separation vessel on top of the heat exchanger, this gives a compact design suitable for the required water and ammonia pressures without any risk of leakages. The steam generated from the heat pump is injected into the product, so it is required to have fresh water through the heat exchanger, which for this installation raised concern regarding corrosion of the shell of the heat exchanger as the water would be in direct contact with the carbon steel shell. There was also concern regarding scaling of the heat exchanger, which can be solved by descaling the heat exchanger, but for heavy lime scale it might be necessary with a mechanical cleaning of the heat exchangers which is not possible with the fully welded plate and shell design. It was concluded that these type of heat exchangers are more suitable for closed water circuit systems, which is only fed by recirculated water and a small amount of ionized make-up water.

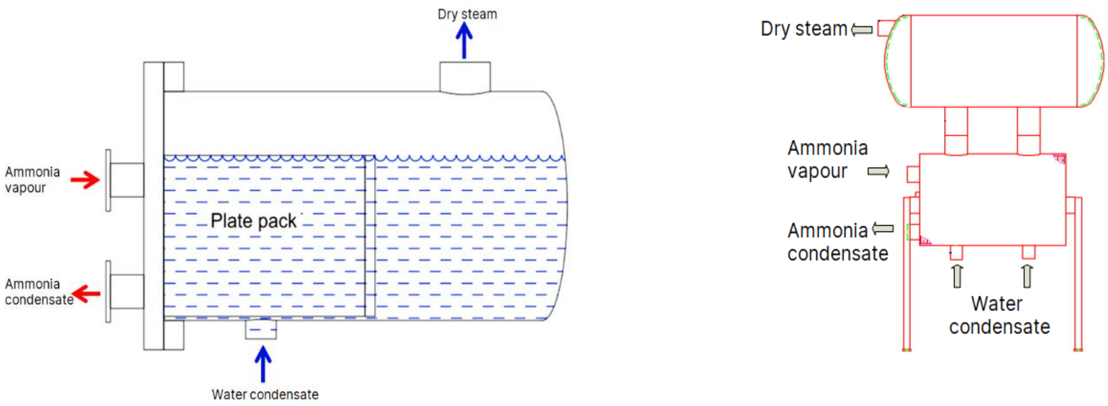

Fig. 5. 2 different heat exchangers for ammonia to water/steam cascade heat pumps

For this project a plate and frame heat exchanger were selected. The plates are welded together on the ammonia side and has gasket between the plates on the water side. This design also add further safety to the system as a potential failed welding of the plates will not leak ammonia into the water system and potential contaminate the products. The pressure drop on the water side is 4 kPa at full load operation, at the low-pressure operation (0.56 bar) this is equal to 1.5K temperature drop.

4.6. Cascade Steam Compression

The steam supplied from the Ammonia heat pump is further compressed to the required steam pressure of the process by a multi-stage Mechanical Vapour Recompression system (MVR-HP). For the MVR system vertical arranged high pressure centrifugal fans (so called MVR compact fans) are used. The MVR fans are characterized by a relative moderate pressure increase which results in a temperature increase of approximately 10K per stage. Since the process requires a steam pressure of 2 bar it is required to install 4 pcs MVR fans in series in order to increase the pressure from 0.56 bar (85 °C) to 2 bar (120 °C).
The compact fans are vertically arranged machines which are equipped with a frequency controlled direct drive and a high-speed motor. Depending on the operational requirements the MVR fans are rotating at up to 13.000 rpm.

Using water-steam in heat pump applications has in general two disadvantages compared to traditional refrigerants. The first is the high volumetric flow at low pressure applications, however this is compensated by the integration of MVR fans in this case. The second is the relatively high superheated steam temperature during compression, which is a consequence of the thermal properties of steam. Due to the 4-stage compression stages, hence moderate pressure ratio each stage, the steam flow is de-superheated by direct water injection. The injected water is hereby evaporated and is cooling the steam back toward the saturation line of the steam. The amount of injected water is controlling by the degree of de-superheating. The production process requires a certain amount of superheat, which is controlled by the water injection in the last stage. The total amount of injected water for the design condition is 150 kg/h and is increasing the amount of supplied steam.

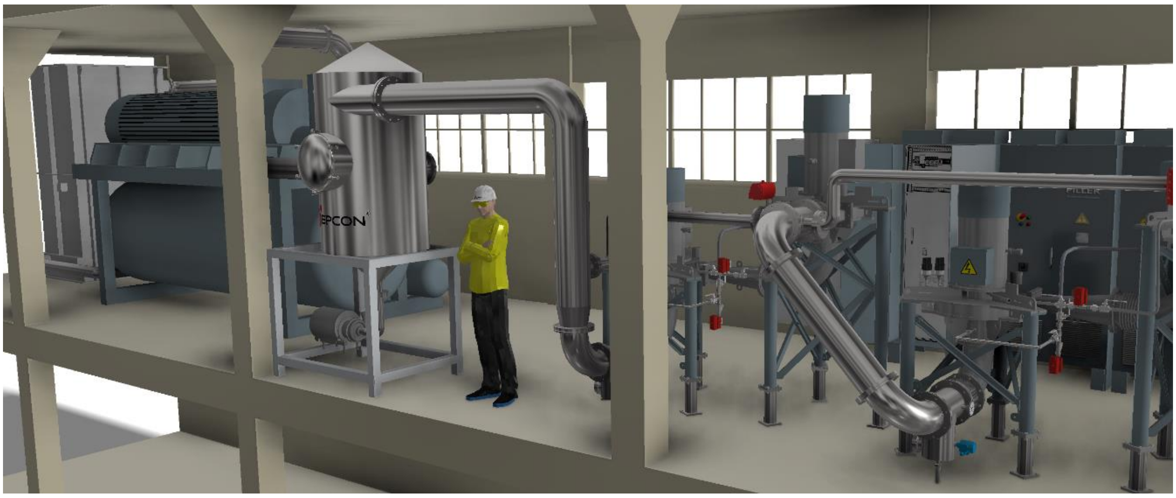

Fig. 6. Preliminary drawing of heat pump installation with ammonia heat pump to the left and steam compression to the right.

For the presented case the efficiency and energy saving potential must be based on the combined energy consumption of the two heat pumps systems and the total amount of delivered energy:
The combined COP considered in this case is the pre-heating of the feed water and the evaporation at low pressure and the required energy to increase the steam pressure to 2 bar.
The total thermal capacity of the system is 1880 kW and consist of approximately 1464 kW for steam generation (equals 2 ton/h of process steam) and 416 kW preheating of feed from 4 °C to 85 °C. The electric power is defined as the shaft power of to the compressors. Auxiliary equipment is not included in the calculation.

Table 2. Heat pump performance

Heat pump performance		
Absorbed power		
Ammonia screw compressor (22 °C to 45 °C)	kW	158.6
Ammonia piston compressor (45 °C to 89 °C)	kW	212.1
4 x MVR steam compressors (85 °C to 120 °C)	kW	189.0
Total shaft power	kW	559.7
Total power (including electrical losses)	kW	601.8
Heat output		
Steam generation	kW	1464
Heating water 4°C -> 85°C	kW	416
Total heat output	kW	1880
Performance		
Shaft COP steam generation only	n/a	2.6
Shaft COP including water heating	n/a	3.4
Heat pump COP (including electrical losses)	n/a	3.1

To produce 2 ton/h of process steam the COP of the Ammonia heat pump is 4.5 and for the water compression is 7.5. This gives a combined COP of 3.1 for the total system for the steam production by the heat pump system from moist air.

The operational time of the system is estimated to be 5000 hours per year for the production site. Hence the system will deliver around 9.40 GWh of thermal energy per year. The alternative energy source is an electric steam boiler with an estimated 90% efficiency. The primary energy consumption for the heat pump solution is hence 3.03 GWh. per year while the boiler would need 10.4 GWh. or fossil; this gives more than 70% energy saving for the production process.

5. Summary and Conclusion

This project has led to a thorough evaluation of different refrigerant and heat pump technologies for providing steam at 120 °C for a commercial petfood manufacturer. Although several refrigerants are available for the temperature range, none of them offer the same longevity, flexibility, and efficiency as the chosen ammonia / steam combination. The chosen technologies are readily available on the market but have for the first time been combined to create a heat pump with a temperature lift from heat source to heat sink of close to 100K. Being able to reduce the energy usage from 10.4 GWh per year for electrical boiler to 3.03 GWh for the heat pump is key to the project being a success. Through the operation of the heat pump further optimization is expected for generating the best-in-class ultra-high temperature heat pump for the future.

6. Acknowledgements

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