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Development of Ammonia-Water Hybrid Absorption-Compression Heat Pumps

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ABSTRACT

In this paper, investigations on the development of industrial high temperature heat pumps are carried out based on the analysis of the current available components. Ammonia-water hybrid heat pumps combine technologies of an absorption and compression heat pump with a mixture of ammonia and water as refrigerant. The functionality of this process was already been proven in the industrial sector using standard components. In this study, currently available components are investigated for utilization in a hybrid heat pump test facility able to operate at elevated high side pressures to achieve exit temperatures on the secondary fluid side of 140 °C to 180 °C. Critical components are identified and discussed based on defined process requirements. Subsequently, an overview of available components enabling process parameters with a high side pressure of up to 60 bar are presented and necessary adjustments for the use in the planned test facility are discussed.
Keywords: Industrial High Temperature Heat Pump, Hybrid Absorption-Compression Heat Pump, Ammonia-Water Mixture.

1. INTRODUCTION

Conti et al. (2016) have stated an increasing energy demand in the industrial sector in recent years with a clear trend for the future. In addition, in various industrial processes large amounts of low grade waste heat are not exploited due to the lack of waste heat utilization. Arpagaus et al. (2018) have found that industrial processes with a large heat demand in the temperature range up to 150 °C and useable waste heat streams in particular have a great potential for high temperature heat pump applications. Simultaneously, the demand for environmentally benign working fluids such as the natural fluids, ammonia and water, become more dominant.
Due to the given properties, hybrid absorption-compression heat pumps (HACHP) with a zeotropic ammonia-water mixture as working fluid provide a good solution for industrial high temperature heat pump applications. The working principle of this system is based on the Osenbrück cycle, which extends a vapour compression heat pump with an additional solution circuit (Osenbrück, 1895). This extension provides the typical properties of HACHP systems such as the attainable high sink temperature combined with high temperature lift and non-constant temperature glide. For this reason, the ammonia-water HACHP concept is interesting for industrial high temperature applications as for instance the utilization of waste heat streams. Furthermore, the functionality of this process in the industrial sector have already been proven by Nordtvedt et al. (2013) using standard available refrigeration components and achieving sink outlet temperatures up to 120 °C.
In recent years, various authors, such as Jensen (2015) and Nordtvedt (2005), have investigated the HACHP system to identify challenges and potentials for the optimization of process parameters. The development was constantly pushed forward due to the increasing interest in the use of ammonia in refrigeration systems and the associated efforts to optimize the components. They determined that the compressor is a dominant constraint on achievable process conditions due to the limitation of high pressure and discharge temperature. In addition, there is a lack of knowledge and experience in operating the system with higher operating parameters. In particular, this relates to the design of the absorber and the expiration of the absorption process at high pressures and temperatures. The focus of this study is therefore to identify available compressor and absorber solutions for the development of a planned HACHP test facility that can operate at high pressure levels and reach sink outlet temperatures of 140 °C to 180 °C.

In the further course, the general functionality and advantages of the HACHP system are presented. In addition, the characteristics and requirements of the planned test facility are discussed. Subsequently, the focus is placed on the identification of critical components to achieve the defined operating parameters. For this purpose, functions and requirements are defined and possible concepts and solutions for use in high temperature operation are demonstrated. Finally, the results of the study are presented and discussed with regard to usability in the development of the planned test facility considering the given requirements.

2. THE AMMONIA-WATER HYBRID ABSORPTION-COMPRESSION HEAT PUMP

This section deals with the description of the general HACHP cycle as well as the discussion of the characteristics and requirements of the planned test facility.

2.1. Hybrid Heat Pump Cycle with an Ammonia-Water Mixture as Working Fluid

Fig. 1a shows a simplified representation of the Osenbrück cycle, the most basic HACHP cycle. This basic cycle consists of seven main components: three heat exchangers, a liquid-vapour separator, an expansion valve, a solution pump and a compressor. Throughout the entire heat transfer process with the heat source in the desorber, the ammonia-water mixture is in the two-phase region and the ammonia concentration in the liquid phase decreases. Due to incomplete evaporation, a two-phase mixture leaves the desorber (1). A liquid-vapour separator is applied to separate the phases and ensure that only vapour enters the compressor (2) to be compressed to the high pressure side of the cycle (3). The liquid phase, characterized as weak solution, is sent to the solution pump (4) where the pressure level is increased (5). Then, the weak solution passes through an internal heat exchanger (IHX) to increase liquid temperature and improve overall cycle performance (5-6). After the IHX and compressor, the liquid and vapour streams are mixed which typically results in a liquid-vapour mixture (7). In the absorber, vapour is absorbed into the liquid phase rejecting heat to the heat sink. The ammonia concentration in the liquid phase gradually increases, so that the saturated liquid out of the absorber is called strong solution (7-8). Heat is transferred from the strong to the weak solution stream in the IHX (8-9) before the solution is expanded to the low pressure level (9-10) to return to the desorber.

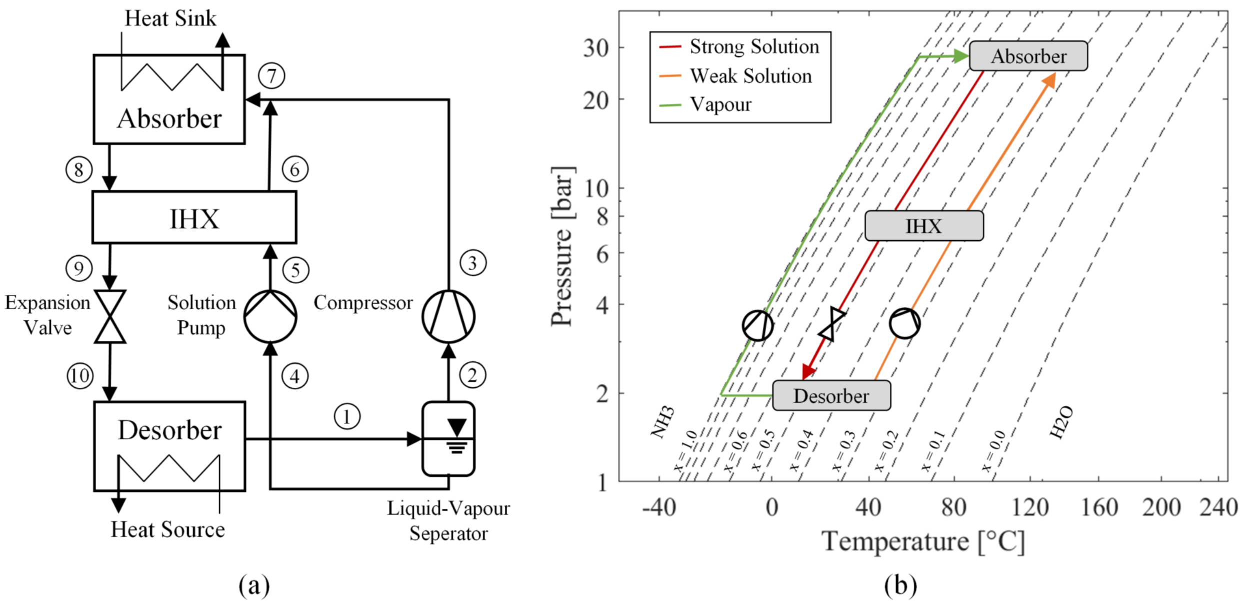

Figure 1: (a) Simplified representation of an absorption-compression hybrid heat pump cycle (b) PTX diagram of saturated liquid for an ammonia-water mixture with hybrid heat pump components

Fig. 1b shows a pressure-temperature-concentration (PTX) diagram of saturated liquid for an ammonia-water mixture including main components and flows of a hybrid heat pump cycle. This representation illustrates the overall functionality and properties of the system, not the actual compression paths. As mentioned by Jensen et al. (2014), the HACHP system has two additional

degrees of freedom compared to conventional vapour compression systems. This ensures the high flexibility and adaptability of the operating parameters to given boundary conditions.
Based on the simplified cycle (see Fig. 1), authors such as Nordtvedt (2005), Kim et al. (2012) and Jensen (2015) examined various process modifications. These include additional components, such as further heat exchangers or circulation and cooling circuits. This allows the system to be further adapted and improved, but complexity has also increased. The following properties and advantages of the system were claimed:

- The ability to vary the composition of the working fluid and circulation ratio increases the flexibility of the system and makes it easier to adapt to temperature fluctuations and heat capacities. By controlling the ammonia concentration of the weak solution, various operating conditions can be achieved and the operation improved.
- Compared to conventional vapour compression heat pumps, which use pure ammonia as the working fluid, higher sink temperatures can be achieved at relatively low discharge pressure.
- Occurring temperature glides due to the use of a zeotropic working fluid during the absorption and desorption process can be adapted to the gliding temperatures of heat sinks and heat sources. This reduces the irreversibility of the system and allows a high temperature rise with comparatively high COP for many operating conditions, and in particular for waste heat applications.

2.2. Characteristics and Requirements of the Planned Hybrid Heat Pump Test Facility

As previously discussed, there is an increasing interest in utilizing waste heat streams of industrial processes using high temperature heat pump applications. The focus of recent years has been on developing and improving existing cycles and components. In addition, the numerical analysis of Jensen (2015) has extensively investigated the potential and requirements of the HACHP system for achieving sink outlet temperatures above the current limit of around 120 °C.
The aim of developing the planned HACHP test facility is to increase the achievable outlet temperatures on the secondary side up to 140 °C to 180 °C and to optimize the system by taking advantage of the developments and improvements of recent years. In addition, the optimization of process parameters and components should be possible. To achieve these goals, the following characteristics are defined for the planned test facility:

- The components of the system must be designed and selected to operate at high temperatures and high pressures to achieve the desired sink outlet temperature.
- In order to test and optimize various operating conditions, it must be possible to vary the weak solution composition as well as the heat source and heat sink temperatures.
- To test and optimize different components of the HACHP cycle, the respective connections of the components must be designed interchangeably.
- In order to ensure the necessary flexibility of the system, auxiliary equipment and measuring instruments must have a sufficiently wide range to cover all possible operating conditions.
- The mass and energy flows must be regarded as relatively small, since it is a laboratory test facility.

Due to the ammonia-water mixture as the working fluid and the desired operating conditions, additional requirements such as material compatibility and oil-free operation are placed on the system:

- When designing the system and selecting the components, attention must be paid to material compatibility. All wetted parts must be made of ammonia-compatible material. Ammonia and hydrous ammonia are fully compatible with materials such as iron, steel, stainless steel and aluminium, but cause corrosion problems in contact with copper, zinc and copper-based alloys (Stene, 2008).
- The oil-free operation of components such as the compressor is desirable to keep the system and in particular the heat exchanger free of lubricant oil. Especially high temperatures and the possible water content in the vapour stream make the oil separation more complex and expensive. The incomplete separation results in lubricating oil in other components of the system, such as the heat exchanger, which affects the heat transfer properties (Zaytsev and Infante Ferreira, 2002).

3. INVESTIGATION OF COMPONENTS FOR USE IN HYBRID HEAT PUMPS

This section is focused on critical components in the design of the planned test facility to achieve the defined characteristics and requirements. Based on Jensen (2015) and Nordtvedt et al. (2013), the compressor for the compression of the ammonia vapour is a critical component of the HACHP system and leads to limitations for the achievable operation parameters. Another critical component is the absorber for the absorption process at the planned high pressure and temperature level, as there is a lack of knowledge and experience for these operating areas. In the further course, the functions and requirements for these components are defined and possible concepts and solutions for use in the planned HACHP test facility are presented and discussed.

3.1. Compressor Solutions for use in Hybrid Heat Pumps at High Temperature Operation

In the HACHP system, the compressor takes over the compression of the ammonia vapour after the liquid-vapour separator from the low pressure to the high pressure level (see Figure 1). As inlet condition for the ammonia vapour at the compressor inlet, a pressure of approximately 2 bar and a temperature of 60 °C are assumed. In addition to the general requirements for components for use in the planned test facility with ammonia-water mixture as working fluid, further requirements are defined based on the desired operating conditions for the compressor used. In order to achieve a high temperature lift and outlet temperatures on the secondary side of 140 °C to 180 °C, a high discharge pressure and pressure ratio are required. For this purpose, the compressor must withstand a discharge temperature of at least 180 °C. According to Neskå et al. (1998), operation with normal lubricants should be possible for discharge temperatures up to 180 °C. Due to the design and properties of the system, it is possible that the ammonia vapour contains a low water content. Therefore, the compressor must be resistant to small amounts of liquid in the vapour stream during the compression.

The investigations of Arpagaus et al. (2018) and other authors have shown that various compressor concepts and solutions are possible for ammonia vapour compression in high temperature heat pump applications. Based on the higher pressure ratios that can be achieved and the smaller swept volume compared to dynamic compression systems, positive displacement compressors, such as the piston and screw compressor, have been identified as promising approaches. Possible concepts and solutions for the compression are presented below.

A basic solution for the compressor system is the compression in one compressor stage. This is possible for pressure ratios and inlet conditions in the appropriate range, depending on the compressor selected. To achieve higher pressure levels with increasing inlet conditions and discharge temperature, the modification of the process cycle as well as the further improvement of the compressors are suitable solutions.

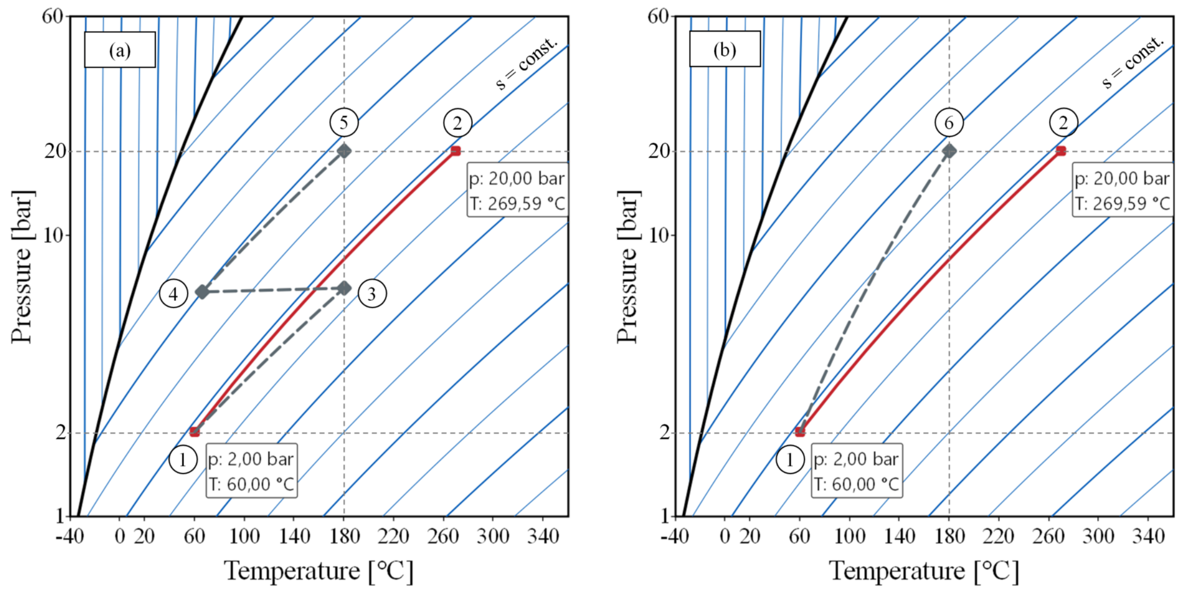

Figure 2: Log p-T diagram of pure ammonia including an isentropic compression compared to (a) two-stage compression with intercooling and (b) one-stage compression with cooling and liquid injection

Fig. 2 shows the isentropic compression (1-2) of pure ammonia in a log p-T diagram from the previously defined input conditions (1) to a freely defined pressure of 20 bar (2). A discharge temperature of almost 270 °C is achieved. Due to the relatively low density and specific heat capacity of ammonia in the superheated vapour phase, the discharge temperature occurring during compression is comparatively high (Stene, 2008). In the ideal case, this is far above the indicated maximum temperature and is even higher for the real compression due to irreversibility. This leads to many problems, such as chemical decomposition of the working fluid, carbonization of the lubricant and collapse of seals (Jensen, 2015). In addition, high discharge temperatures reduce the COP of the HACHP system.
Jensen (2015) discussed different process modifications to achieve the desired pressure rise by holding the discharge temperature in an acceptable range for the compressor. The first possible modification, as shown in Fig. 2a shows a two-stage compression (1-5), whereby the gas is cooled down again after reaching a temperature of 180 °C by an additional IHX (3-4). This two-stage compression can provide a higher pressure level and sink temperature, as the discharge gas temperature is reduced during the compression process. The investigation results have shown, that the option of an additional IHX installed behind the contained IHX caused the lowest cost increase and the highest discharge gas temperature decrease (see Fig. 1).
Another promising concept is the use of a liquid-resistant compressor with the implementation of an injection of the strong solution before or after the IHX. Fig. 2b shows a possible one-stage compression with cooling and liquid injection during the compression process (1-6). The injection can take place on various tasks and can be used for seal cooling and for lowering the discharge temperature through the compression. Zaytsev and Infante Ferreira (2002) investigated the various effects of the additional injection of ammonia-water mixture into the compressor. In general, the liquid injection has positive influence of the compressor volumetric and isentropic efficiency. On the other hand, the liquid injection leads to various challenges due to the complexity of the evaporation processes during the compression. However, oil-free compressors with liquid injection capable of achieving the desired parameters are not readily available.
All approaches have individual advantages and challenges for use in HACHP systems at high temperature operation. Table 1 gives an overview of the previously mentioned and discussed advantages and challenges of the different solutions for the ammonia vapour compression.

Table 1. Overview of solutions for the ammonia vapour compression

	Single-Stage	Multi-Stage	Liquid Injection
Advantages	Lower installation costs	Possible intercooling	Oil-free operation
Challenges	High discharge temperature	Higher complexity	Evaporation process

3.2. Absorber Solutions for use in Hybrid Heat Pumps at High Temperature Operation

Jung et al. (2014) identified the absorber as one of the most significant components in the HACHP system. As mentioned by Nordtvedt et al. (2013), the operation of the hybrid heat pump cycle with ammonia-water as zeotropic mixture leads to large non-constant temperature glides during the desorption and absorption processes. In the absorber, the ammonia concentration in the liquid phase increases due to the absorption of the vapour. The saturation temperature of the mixture decreases from the inlet to the outlet of the heat exchanger due to the considerably lower boiling point of ammonia compared to water. During this absorption process, heat is transferred to the coolant on the secondary fluid side.
For the use of an absorber for the absorption process in a HACHP system, various requirements for the properties of the heat exchanger are defined. In addition to the general requirements, such as the minimization of size and pressure losses, the suitability for the given operating parameters must be considered for use in the planned test facility. Based on Kang et al. (2000), a high area density [m^2/m^3] of the heat transfer surface combined with a high overall heat transfer coefficient is required to achieve a compact size of the heat exchanger. Furthermore, the generation of a good mixture of the vapour and liquid phases and the complete and continuous wetting of the heat transfer surfaces are important.
For the construction of the absorber, different heat exchanger types and absorption modes are available. Previous work has used tube and shell as well as plate heat exchanger types with different orientations and flow directions. Based on Kang et al. (2000), the falling film and bubble absorption

modes were recommended for use in HACHP systems. In the further course, possible solutions and concepts will be presented and discussed.

Minea and Chiriac (2006), for example, used a horizontally arranged shell and tube heat exchanger with a falling film for their investigation of the HACHP system. In this case, the weak solution slides as a thin film on the outside of the horizontal tubes from top to bottom. The ammonia vapour fills the free space and is absorbed into the liquid film with the release of heat to the coolant in the tubes. They mentioned that the driving force for the absorption and amount of mass transfer are related to the ammonia vapour pressure and concentration as well as the composition of the liquid and mass transfer resistance.

An et al. (2013) investigated a vertical plate heat exchanger with bubble absorption mode. Here, the weak solution and ammonia vapour entered the absorber at the bottom and flow to the top with the coolant in counter-flow direction from the top to the bottom. They found that the absorber internal pressure has more effect on the coolant temperature difference than the geometric conditions. In addition, the absorber aspect ratio of the length to the gap between the plates has more effect on the overall heat transfer coefficient than the ratio of the width to the gap.

Due to the investigations carried out and the results obtained, the plate heat exchanger type is increasingly being used for HACHP applications. The ammonia-water mixture can flow downwards as in a falling film type of absorber or upwards as in a bubble type absorber. Jung et al. (2014) stated, that the plate heat exchanger is able to transfer heat very efficiently during the absorption process due to the large surface area and corrugated plates. The plates can be pressed with different shapes to increase the turbulence, fluid distribution and surface area. Because of these capabilities, the design can be much more compact compared to shell and tube heat exchangers. In addition, the plate heat exchanger type can provide a high heat transfer coefficient, good wettability and mixing of the liquid and vapour phases. Figure 3 shows a schematic representation of a plate heat exchanger with falling film and bubble absorption mode. The specified flow directions can be varied depending on the application.

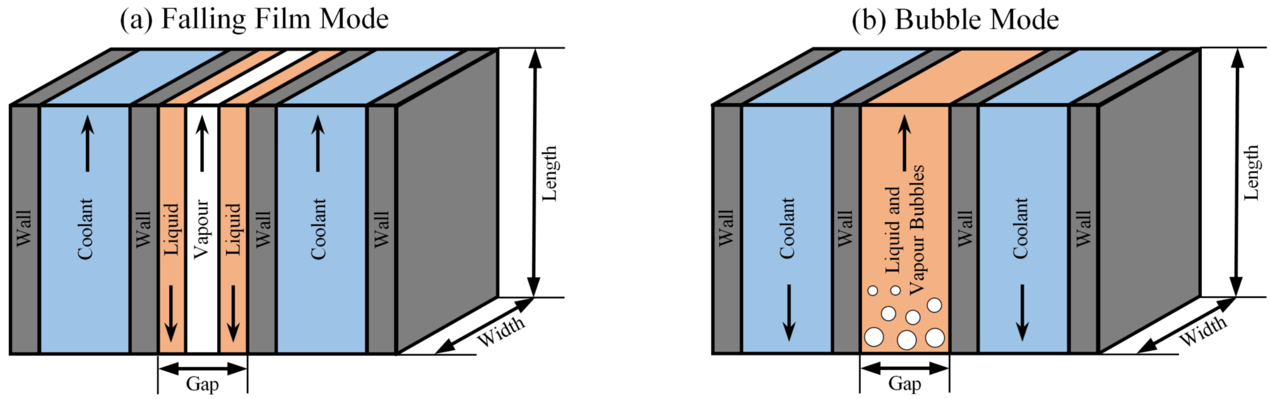

Figure 3: Representation of a plate heat exchanger with falling film and bubble absorption mode

One of the major challenges in using plate heat exchangers for two-phase applications is to ensure good distribution at the inlet and mixture of liquid and vapour over the entire length of the absorber. Because of the easier distribution of the vapour phase, the bubble absorption mode has an advantage over the falling film. In addition, the falling film is susceptible to solvent flow instabilities, which can significantly affect absorption and heat transfer rates (Kang et al., 2000). Table 2 gives an overview of the previously mentioned and discussed advantages and challenges of the different solutions for the absorber design and ammonia absorption mode.

Table 2. Overview of solutions for absorber design and ammonia absorption mode

	Plate Heat Exchanger	Falling Film Mode	Bubble Mode
Advantages	Compact design and good mixing conditions	Low pressure drop and high heat transfer coefficient	High absorption and heat transfer rate
Challenges	Distribution of the mixture	Solvent flow instabilities	Distribution over total length

4. RESULTS AND DISCUSSION

Based on the defined characteristics and requirements of the planned HACHP test facility and the corresponding requirements for the identified critical components, available solutions on the market were investigated. The investigation has shown that the compressor for the ammonia compression is the main constraint to achieve higher process parameter such as the high pressure and temperature level.

Ahrens et al. (2019) conducted a study focusing on available ammonia compressors for HACHP systems in high temperature operation. The results have shown, that various solutions from different manufacturers are currently available on the market. However, to the best knowledge of the author, the available compressors do not achieve the defined requirements for the use in the planned hybrid heat pump facility. It is not possible to operate at high pressure and to achieve exit temperatures on the secondary side of 140 °C to 180 °C. For the development of the planned hybrid heat pump test facility, modifications of the system must be considered. Possible adjustments have already been discussed and may include the division of the compression process or the integration of additional cooling options.

The investigation on the absorber has shown that various solutions are currently available on the market. Plate heat exchangers can be used with the presented absorption modes. The use of both methods by subdividing the absorption process is also possible, as described and used by Nordtvedt (2005). Overall, the available solutions can be operated at the required pressure and temperature levels. Based on these results, the planning and operation of the planned test facility is possible, although the achievable efficiency of the absorption process and heat transfer may not be optimal. In addition, the lack of knowledge and experience for the absorption process and the design of the absorber for the planned operating areas can be improved.

For the further development of the HACHP test facility, the examination of a solution for the ammonia compression is the major challenge. Despite this fact, the design and operation of the absorber should be possible in an acceptable range. Overall, the development of the planned test facility can help to expand knowledge and experience in design and operation and to support the further development of the components.

5. CONCLUSIONS

The aim of this study was the identification and evaluation of suitable components for the development of a planned ammonia-water hybrid absorption-compression heat pump test facility. At the beginning, the general functionality and advantages of the HACHP system were presented. In addition, the characteristics and requirements of the planned test facility were discussed. Subsequently, the focus was placed on the critical components identified to achieve the defined operating parameters. Here, the compressor for the ammonia compression and the absorber for the absorption process at high temperatures and pressures were identified as possible limitations. For this reason, functions and requirements were defined and possible concepts and solutions for use in high-temperature operation were presented and discussed. Finally, the results of the study were presented and discussed with regard to usability in the development of the planned test facility considering the given requirements.

The investigation has shown, that due to the increasing interest and use of ammonia for industrial heat pump applications, a growing range of compressors with high pressures up to 60 bar is available on the market. The use of currently available compressors is not possible without adjustments due to the special requirements for use in the planned test facility. For the absorber, a general use of the available solutions under the given conditions should be possible. However, design and efficiency may not be optimal due to lack of experience in the planned operating area. In general, experience in the operation and improvement of main components as well as the entire cycle can be gained by developing a HACHP test facility.

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