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Rotation Heat Pump - Diffusion Bonded Rotor Design

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Abstract

The Rotation Heat Pump (RHP) is based on the principle of compression by centrifugal forces and uses a mixture of noble gases as a working fluid that is neither flammable nor toxic. The core element, the rotor, which previously consisted of individual parts, was replaced in the latest generation by a single block in which heat transfer, compression and expansion take place. This block consists of thin plates with microchannels through which the inert gas mixture flows. These plates are connected by diffusion bonding, creating a block in which almost all the necessary functions are integrated. This system offers the possibility of adapting the thermodynamic cycle to various applications and achieving the greatest possible efficiency through flexible channel routing. This is made possible by the heat transfer during compression and expansion. Different spreads can be achieved at the source and sink, thereby minimizing exergy losses. This design also makes it possible to achieve a significantly higher temperature lift and absolute process temperature compared to the previous system.
This paper shows the concept and system of the diffusion bonded rotor as well as the various possibilities for channeling. In particular, it discusses how the channeling of the microchannels can be designed in order to achieve optimum operation for different applications. Sketches of the thermodynamic cycle show and emphasize the flexibility and should serve as an incentive for the investigation of further application possibilities. Furthermore, the prototypes and rotor blocks built so far will be shown and presented.

Keywords: Rotation Heat Pump; diffusion bonded; high temperature; flexible

1. Introduction

A large share of industrial energy demand is required as heat, De Boer et al [1], often at temperature levels between 100 °C and 200 °C, where conventional heat pump technologies face technical limitations like mentioned in Fleiter et al. [2]. Nevertheless, industrial heat pumps are a key technology for reducing CO_2 emissions by replacing fossil fuels in processes such as drying, pasteurisation, distillation, chemical processing, and district heating. Numerous studies have demonstrated both the significant potential of high-temperature heat pumps and the existing market and technical barriers, particularly related to working fluids, lubrication, and compressor design, Arpagaus et al [3], [4] and [5]. In contrast to conventional Compression Heat Pump (CHP) systems, the heat transfer in a Rotation Heat Pump (RHP) occurs entirely through sensible heat exchange - there is no phase change throughout the process. This results in a higher temperature spread of sink and source which is advantageous for applications with limited thermal capacity while the exergy losses are minimized. Futhermore, the possibility to decouple temperature lift from compressor capacity (since main rotor speed and fan speed can be controlled separately), allows efficient operation at temperatures above 100 °C with high spreads. As a result, the RHP achieves high coefficients of performance (COP) while reducing mass flows and peripheral equipment size. Further details on previous designs of the RHP function, design and also test results and simulations can be found in Adler et al. and Längauer et al. [6-8] and are therefore not discussed here. An example of the Joule cycle is illustrated in Figure 1 below. The approach of using etched plates in combination with diffusion bonding has not been considered in research and development so far. A

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first step is the illustration of possibilities and understanding of designs while in further publications detailed simulations and test results will be presented.

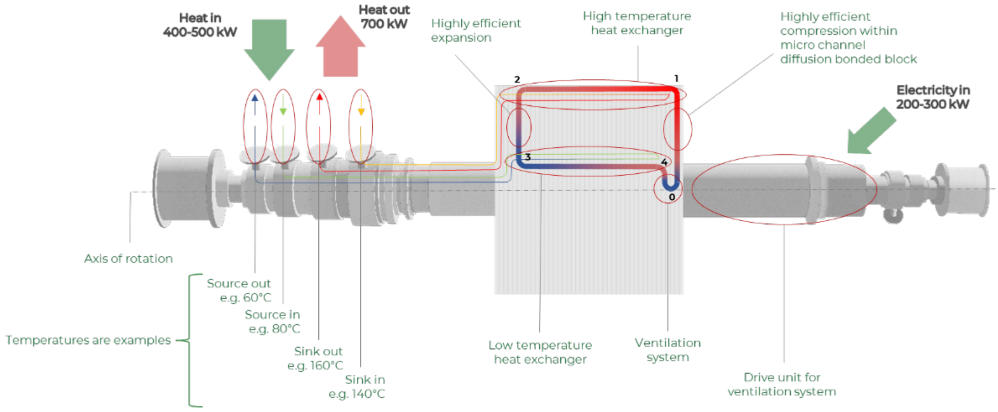

Figure 1. Illustration of thermodynamic process in the DBHE block.

A diffusion bonded heat exchanger (DBHE) used in a Rotation heat pump is a compact, high-performance HE to transfer heat between the working fluid and the process media (sink and source). It can withstand very high pressure and temperature conditions. It is manufactured by stacking multiple thin metal plates - stainless steel, nickel-based alloys, or titanium - each chemically etched with microchannels that define the fluid flow paths. The stacked plates are then joined together through a diffusion bonding process, which applies high temperature and pressure under vacuum conditions to create a solid-state metallurgical bond at the atomic level. This is shown in Figure 2.

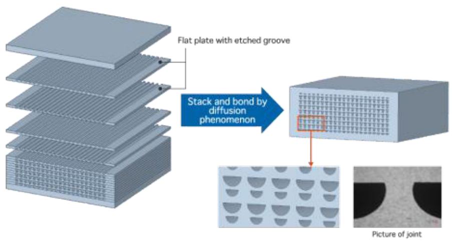

Figure 2. Stacking of diffusion bonded heat exchanger. [10]

Unlike traditional brazed or welded joints, diffusion bonding does not require filler materials. As a result, the final structure behaves as a monolithic component with no distinct interfaces between plates. This provides excellent mechanical strength, corrosion resistance and leak tightness. The compact channel geometry enables very high surface area density, leading to superior heat transfer performance and reduced material usage compared to shell-and-tube or plate-fin designs. Moreover, the high design flexibility allows for customized flow arrangements, including counter-flow, cross-flow, or multi-stream configurations. In summary, diffusion bonded heat exchangers combine high thermal efficiency, mechanical robustness, and compactness, enabling efficient heat transfer even under extreme operating conditions. Their solid-state construction minimizes thermal resistance and potential failure points, offering a long service life and reliable operation in advanced thermal systems. All those advantages make the DBHE the optimal solution for the application in a Rotation Heat Pump like shown in Figure 3.

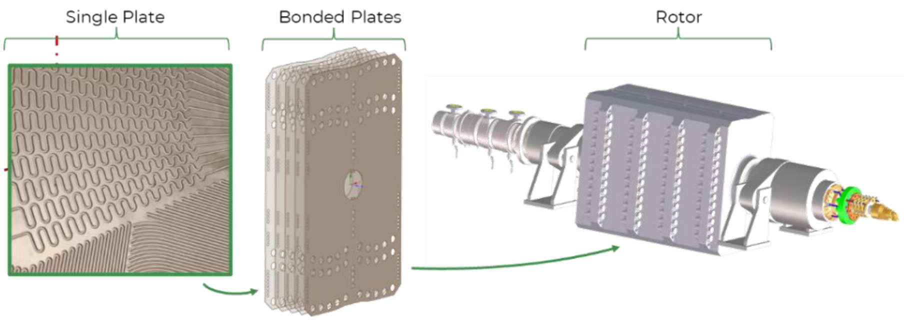

Figure 3. Rotor block built up of single bonded plates and single plate with edged channels.

The operating principle of a Rotating Heat Pump (RHP) and the implemented Joule cycle are based on centrifugal forces. The working fluid - a mixture of noble gases - is contained within a closed pipe system of the rotor. Due to the rotation (current design up to 3500 rpm), the fluid experiences an increase in pressure as it moves toward the outer diameter (0-1). This pressure rise is accompanied by a corresponding temperature increase – which is almost isentropic since the flow losses are very small, allowing heat to be transferred from the working fluid to a heat sink located at the outer area of the diffusion bonded rotor (1-2). After passing through the outer heat exchanger, the fluid is guided through microchannels to a smaller diameter region where the pressure is lower (2-3). At this reduced pressure, the fluid temperature decreases, enabling heat to be absorbed from a heat source via another heat exchanger positioned at this smaller diameter (3-4). A fan is incorporated into the system (0) to ensure continuous mass flow and thus complete the thermodynamic cycle.

Compared to previous designs of the RHP the advantages of using the diffusion bonded rotor design are the smaller footprint, higher efficiency, increased output temperatures. The following comparison,

Figure 4 shows the previous design of the RHP consisting of single components like heat exchanger, pipes, structures, shaft in contrast to the new compact DB design.

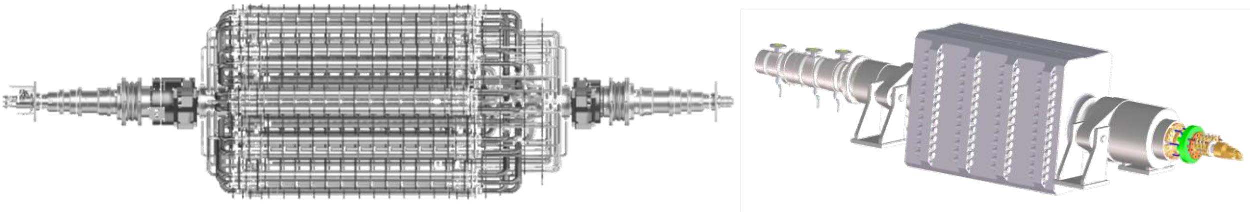

Figure 4. Comparison of previous RHP design (left) with new DBHE block design (right).

2. Possible sheet designs

The following two examples of possible sheet designs will discuss how different arrangements of the water and gas channels will affect the thermodynamic process. Since the routing of the channels is very flexible, optimal conditions for various processes, while obtaining very low exergy losses, can be achieved. The calculation method for the thermodynamic cycle is similar to the method for the previous design (Figure 4) and can be done by different approaches which are mentioned in Längauer et al. [11]. Essential for the temperature lift are still the rotational speed and the differences in diameter as well as the properties of the working fluid.

2.1. Process Description “Isothermal design”

The isothermal design is intended to provide an isothermal heat transfer during the compression of the working fluid. Every gas channel which connects the ports e.g. Port 1.1 and Port 1.2 transfers heat to the water while the gas is still compressed. The gas would be heated up during the compression if there would not be

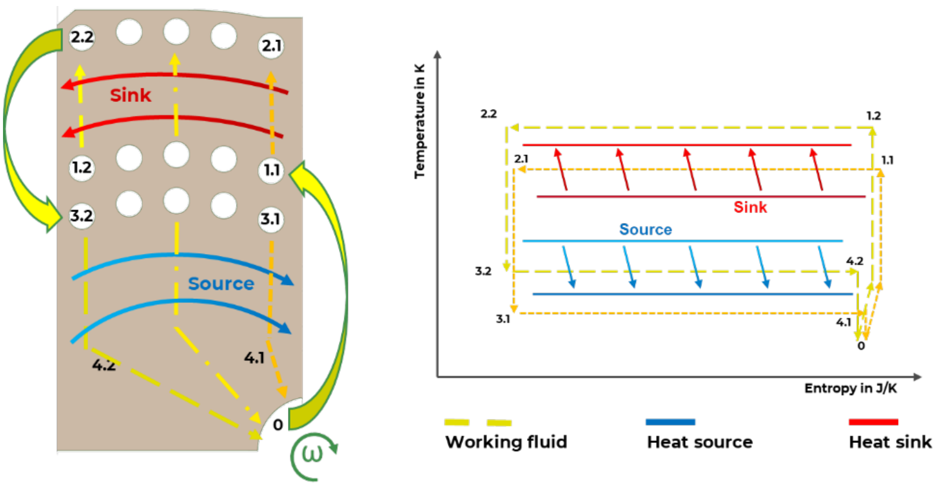

Figure 5. Illustration of design and thermodynamic process for “Isothermal design”

any heat transfer. The temperature increase of the water is generated due to the higher temperature of the outer channels e.g. connecting Port 1.2 and 2.2. The available surface of the plate is used as much as possible for arranging gas channels and transferring heat from the gas to the process fluids. The thermal capacity with this design is maximized. Figure 5 and the following description should give an overview of the thermodynamic process:

Compression (0–1.1)

The gas is compressed due to centrifugal forces as it moves outward in the rotating system.

Heat Transfer Inner Channel (1.1–2.1)

In the channel closest to the axis of rotation, heat is transferred at a constant temperature.

Heat Transfer Outer Channel (1.2–2.2)

In the outer channel, where the temperature level is higher, heat is also transferred at a constant temperature. The water temperature of the sink increases from channel 1 to channel 2 due to crossflow over the gas channels.

Expansion (2.1/2.2–3.1/3.2)

After heat transfer at high temperature, the gas expands to points 3.1 and 3.2. These correspond to different temperature levels resulting from the different radii within the system.

Low-Pressure Heat Exchange and Final Expansion (3.1/3.2–4.1/4.2–0)

At points 3.1 and 3.2, the gas enters the low-pressure heat exchanger area, where it undergoes isothermal expansion to points 4.1 and 4.2. The gas then continues to expand toward the center (point 0).

Fan (Point 0)

At point 0, a fan is located to ensure the continuous mass flow of the working fluid within the system.

2.2. Process Description "Parallel flow design"

In the following "Parallel flow design" the heating up of process media is realized in a different way compared to the "Isothermal design". Instead of keeping the working fluid at a constant temperature level the increase of pressure is used in two ways. On the one hand side the increasing of pressure and temperature is used to transfer heat to the process fluids and on the other hand side there is also a temperature increase to get the temperature spread of sink and source. So not all of the temperature gain due to the rotation is used to heat up the water side, also a temperature increase is desired to provide the spread of sink and source. This method is used for the sink side as well as for the source side. While at the sink the temperature increase is used on the source side the temperature decrease is used in both ways – heat transfer and providing spread. The advantage compared to the "Isothermal design" is that each port and channel are seeing the same thermodynamic cycle. This results in very stable conditions for the entire system and very good flow distribution between the ports and channels. Also, it allows to control the temperature spread and lift by just moving the inlet and outlet ports to a lower and higher radius. The drawback of the system is that this design does not use the maximum possible surface area of the plate which results in a reduced thermal capacity due to less channels which can be arranged. The following Figure 6 and process description will illustrate and analyse the process in detail:

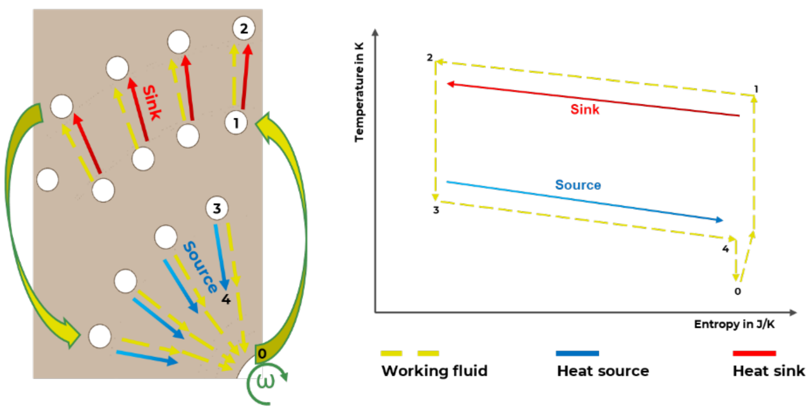

Figure 6. Illustration of design and thermodynamic process for "Parallel flow design"

Compression (0–1)

The gas is compressed due to centrifugal forces as it moves outward in the rotating system. This compression is very efficient and almost isentropic since the flow losses are very small.

Heat Transfer (1–2)
The water/process fluid and gas are guided parallel to a higher radius while heat is transferred from the gas to the water but also the temperature is increased for both.
Expansion (2-3)
After heat transfer at high temperature, the gas expands to points 3. Thus, it expands to lower pressure and temperature levels. This expansion is almost isentropic since relative flow velocities and losses inside the system are small.
Low-Pressure Heat Exchange and Final Expansion (3–4)
The water/process fluid and gas are guided parallel to a lower radius while heat is transferred from the water to the gas but also the temperature is decreased for both.
Fan (Point 0)
At point 0, a fan is located to ensure the continuous mass flow of the working fluid within the system.

3. Specifications of RHP based on DBHE

This section provides an overview of the specifications of the Rotation Heat Pump featuring the diffusion-bonded rotor design. Compared to previous versions, the new design offers a significantly smaller footprint and improved efficiency, achieved through advanced rotor and heat exchanger technology. Additionally, the temperature lift has been increased due to the higher centrifugal forces made possible by the upgraded design. The maximum temperature lift is limited by the mechanical stress that the material can endure. However, with the potential use of materials offering higher tensile and yield strength, further increases in performance will be achievable in the future. Overall, the new rotor already demonstrates significantly enhanced performance compared to previous versions. The following Table 1 and Figure 7 show the specs and visualization of the system.

Table 1. RHP K7.3 specification with diffusion bonded rotor system

Dimensions (W x L x H)	1,5 x 6 x 2,5 m
Nominal thermal capacity	700 kW_{th}
Max. electrical power demand	100-330 kW (400 V, 50Hz)
Working medium	Noble gas mixture (He, Ar, Kr, Xe) GWP=0, ODP=0, non-flammable, non-toxic
Hydraulic connection	H2O / DN80
Supply temperature	Up to 200 °C
Temperature lift	Up to 100K (measured source out to sink out)
Heat source cooling	Up to 40K
Efficiency	Up to 65% (calculated Carnot-efficiency)

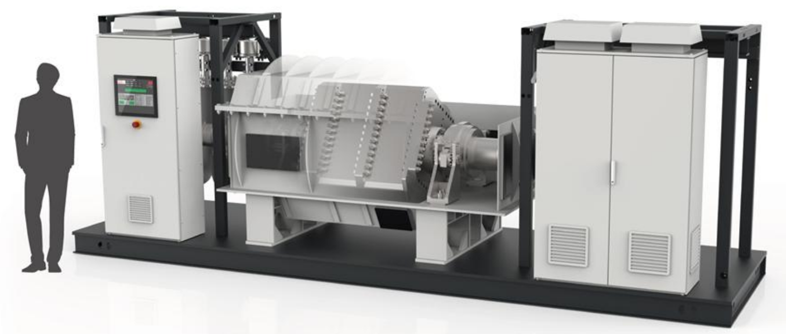

Figure 7. RHP system with diffusion bonded rotor including electrical cabinets

4. Conclusion

The integration of a diffusion bonded heat exchanger (DBHE) into a Rotating Heat Pump (RHP) represents a significant technological advancement in compact, high-efficiency thermal systems. The DBHE's monolithic structure - achieved through the diffusion bonding of microchannel plates - ensures exceptional mechanical robustness, thermal conductivity, and corrosion resistance, all while minimizing leakage risks. Its design enables efficient heat transfer under extreme temperature and pressure conditions, making it ideally suited for the centrifugal operating environment of the RHP.

In the RHP system, the DBHE effectively manages the thermodynamic processes governed by centrifugal forces and the Joule cycle. Through precise microchannel design, the heat exchangers facilitate both isothermal and parallel flow configurations, each offering distinct advantages in terms of thermal capacity, temperature control, and flow stability. The isothermal design maximizes surface utilization for superior heat transfer, while the parallel flow design enhances uniformity and control across the system's ports and channels.

Overall, the RHP equipped with a diffusion-bonded rotor demonstrates a remarkable combination of compactness, efficiency, and reliability. Its noble gas working medium ensures environmentally friendly operation with zero GWP and ODP. The design achieves high temperature lifts and efficiencies of up to 65% of the Carnot limit, highlighting its potential as a scalable, high-performance solution for industrial heat recovery and process heating applications. With future improvements in material strength and bonding technology, even greater operational pressures, temperatures, and efficiencies can be realized, further solidifying the DBHE-based RHP as a next-generation heat pump technology.

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