DEVELOPMENT OF A WATER VAPOR COMPRESSOR FOR HIGH TEMPERATURE HEAT PUMP APPLICATIONS

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Abstract: A centrifugal water vapor (steam) compressor has been developed for the high temperature range (90-110 °C) for industrial heat pumps in the 100-500 kW range with a 25-30 °C temperature lift per stage. The compressor is based on a high speed gear from automotive turbochargers, thus allowing standard electrical motors for the driveline instead of the usual direct drive with expensive high speed motors. The background for the development is an increased interest for high temperature heat pumps for various industrial applications, in particular in response to the general need of reducing fossil fuel consumption. There is a number of applications for the compressor. It can work as a direct steam generator as an alternative to standard boilers, and if operated in an open configuration along with a number of drying and concentration applications. In a closed configuration it can work as a general purpose high temperature heat pump.

Keywords: Water vapor, heat pump, high temperature, centrifugal compressor, steam generation, drying, concentration

1. INTRODUCTION AND MOTIVATION

The European processing industry is facing a major challenge reducing its carbon footprint. Fossil fuel is extensively used for process heating purposes such as in dryers, evaporators and distillation processes – often in a temperature range of 80-150 °C.

Investigation has shown that about 25 % of the industrial energy use in Denmark can be replaced by properly process integrated high temperature heat pumps. The potential for heat pumping in the industry depends of the possible temperature lift of the heat pump. In the table below the estimated heat pump percentile potential is shown for different temperature lifts and target temperature demands.

Temperature lift Delta T °C	Target temperature demand °C	Estimated COP-value	Heat delivered from the heat pump % of total potential
20	100	11.2	23
	180	13.6	1
40	100	5.6	14
	180	6.8	2
70	100	3.2	35
	180	3.9	25

Table 1: Estimated potential and COP for high temperature heat pumps versus temperature lift and target temperature in Danish industry.

The objective of the project is to develop a cost effective heat pump in the capacity range (200- 2000 kW) for use in process industries in this desired temperature range with a high COP (heat to power ratio). The heat pump should be based on modular units that can be arranged in series and as well as in parallel. By this modular concept, many different applications considering temperature level, temperature lift and capacity can be handled with a rather few standard compressor units. This will make it possible to mass-produce cost efficient compressors.

The most promising working media for high temperature heat pumps application is water vapor due to its excellent thermodynamic properties. Furthermore, water is a natural substance, non-toxic, non-flammable and with zero GWP. Water vapor can outperform other alternatives at higher cycle temperatures. If the efficiency of various compressors is identical, the COP for water vapor will clearly exceed the competing fluids.

If a centrifugal compressor should be used, the requirements would be a rotational speed at approx. 100,000 rpm with a power consumption of approx. 50 kW. Normally, this is out of reach even with permanent magnet high speed motors, magnetic bearings, etc., but if a special planetary gear from an automobile supercharger (Rotrex) can be applied, it could be realized at a relatively low cost.

2. DESCRIPTION OF THE ROTREX PLANETARY GEAR

The Rotrex planetary gear has been developed for automotive superchargers where the rotational speed is in the range 100,000-300,000 rpm. A traditional sprocket gear is very expensive if designed for speeds above 50k rpm. The planetary drive is of the traction type, and a special traction oil developed for the Rotrex drive transfers the torque from the annulus through the rollers to the sun shaft. The planet gear itself has a driving annulus connected to the input shaft. In the center of the planetary drive is the driven sun shaft, which has the impeller fitted with a precise fitting. In the space between the annulus and impeller shaft three rollers transfer the input torque from the annulus.

The annulus has a pre-span against the rollers that again presses towards the spindle. The patented geometry of the gear layout ensures an increased press between the rolling elements proportional to the input torque. Thereby the load and wear of the rolling elements are kept at a minimum, giving the components great durability. At the same time, the noise level is low and the mechanical efficiency above 97% at higher loads.

Developed for automotive use in superchargers, the gear is very cost effective and all the components are made of easy-to-get traditional materials. The gear is scalable from very small to very large units without additional costs for special design. The Rotrex compressor has been used as a boosting device for fuel cells as well as an automotive and industrial application for many years without problems.

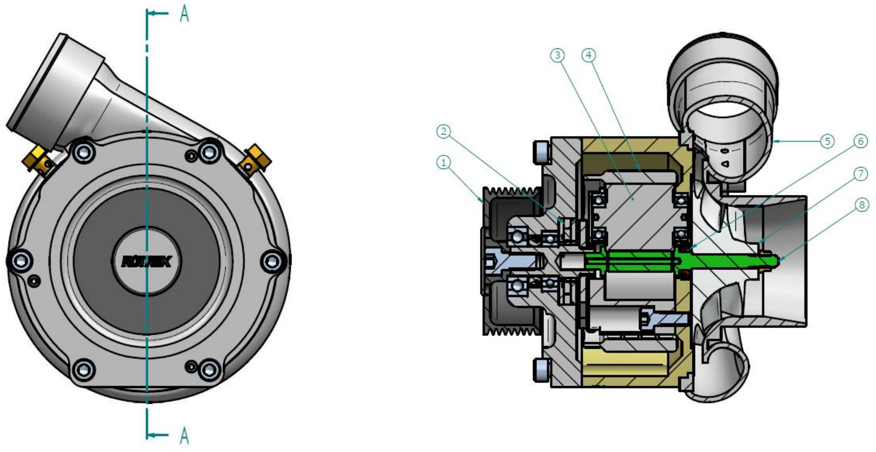

Figure 1: Sketch of the Rotrex planetary gear showing the central impeller shaft, the three rollers and the outer driving annulus.

The difference between compression of steam and air is density, temperature and atomic weight. The shift of working fluid only requires changes to the impeller design and minor changes to the gear itself. The challenging task when compressing water vapor is the sealing between the process steam and the oil lubricated gear. Rotrex is working on this, and a solution has been tested with good results so a seal is expected to be within reach.

3. WATER AS WORKING FLUID

The driving force for the increased interest for water as refrigerant is partly the obvious environmental advantages of water compared to various chemical substances and partly the potential of integrating the equipment directly in the process without any additional heat exchangers. By integrating a compressor or a unit in the process, it is possible to increase process efficiency and simplify the process unit.

There have been successful applications of water as a refrigerant at lower temperatures in the chiller area (ref. 1. -5.). Due to the low pressure and thus the high specific volume, the choice of compressor type is rather limited as very high swept volume is necessary compared to the more traditional working fluids. Turbo compressors have been applied in various configurations as one or more centrifugal stages as well as multistage axial compressors. At higher temperature levels other types of compressors have been introduced, for example Roots type blowers and screw compressors.

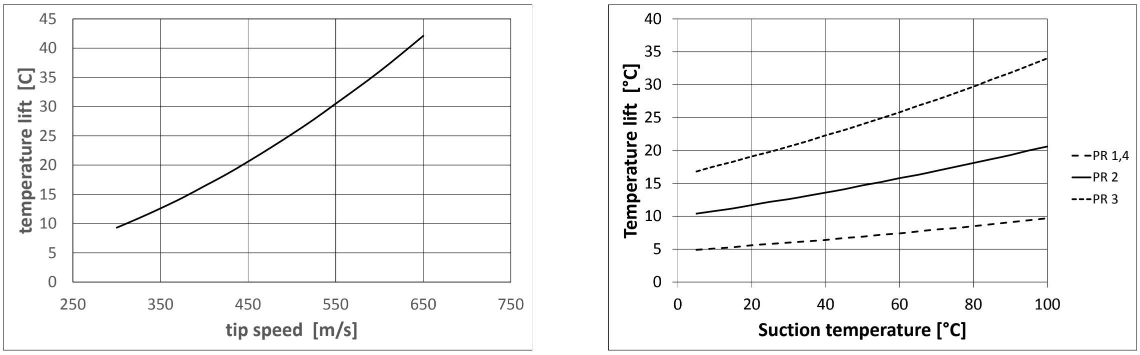

Figure 2: Temperature lift/difference as function of tip speed for centrifugal compressor (left). The properties of water lead to a rather large variation of temperature difference at the same pressure ratio (right).

The advantage of the various turbo compressor types is the relatively compact design that allows high inlet velocities and thus high volume flow at the relative small diameter of the compressor. The disadvantage of using water as working fluid is the relatively low atomic weight of water molecules. The main consequence of the low atomic weight of water vapor is that the temperature lift per stage is relatively small compared to some of the much heavier chemical fluids.

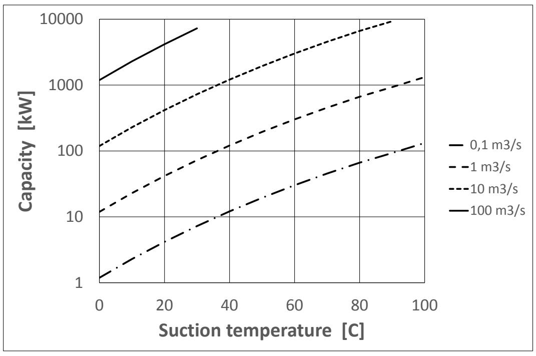

Figure 3: Capacity as a function of the inlet temperature reflecting the huge variation of specific volume and total pressure

The advantage of the centrifugal compressor type compared to the axial compressor type is a relatively higher pressure ratio per stage and well documented design tools, whereas the advantage of axial compressors is a more compact design and potentially slightly higher efficiencies. In general, the diameter of the centrifugal compressor is three to four times the axial compressor diameter for the same capacity and volume flow.

For most of the applications we want as much temperature lift as possible, pushing the tip speed and thus the turbo compressor's mechanical design to the limit and requiring a careful material choice and mechanical design. For most practical designs, the temperature lift or the temperature difference is limited to 20-25 °C when all losses etc. are included. For a number of applications it will be necessary to implement two or three stage solutions, and this is rather straightforward for units with water as working fluid. An intercooler spray system is installed between the two stages, thus limiting the high discharge temperature and improve the overall efficiency.

The actual temperature lift or temperature difference that can be achieved by a given pressure ratio is shown in Figure 2 (right), and the figure shows that the physical properties of water lead to a significant variation relation between pressure ration and temperature difference as the suction temperature increase from 0 to 100 °C. At the same time, the specific volume changes a lot and as a consequence the capacity changes, too. The main consequence of this is that the variations require a specific compressor design at each individual application and temperature range.

Summing up, a unit with water as the working fluid and a suction temperature of approx. 80-90 °C with a capacity of approx. 300-500 kW would require a suction volume flow of approx. 0.3 m^3/s. If the temperature lift should be in the range of 20-30 °C, the tip speed should be in the range of 450-550 m/s which can be achieved with well-known technology.

4. COMPRESSOR DESIGN

The limiting parameter for the Rotrex gear is the torque that can be transferred to the impeller shaft without any significant slip. The overall design values of capacity and pressure ratio must be adjusted to cope with this limitation of the gear.

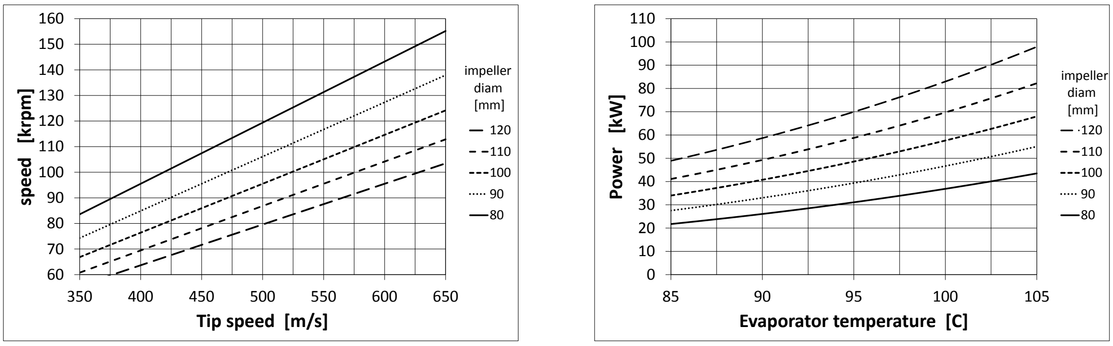

Figure 4: The basic parameters speed, tip speed, power consumption and suction temperature for various impeller diameters

Some very basic parameter studies helped to narrow down the dimensions of the final compressor design, and identified the compromise between how much power or torque can be transferred versus the tip speed, the impeller diameter and thus the design speed.

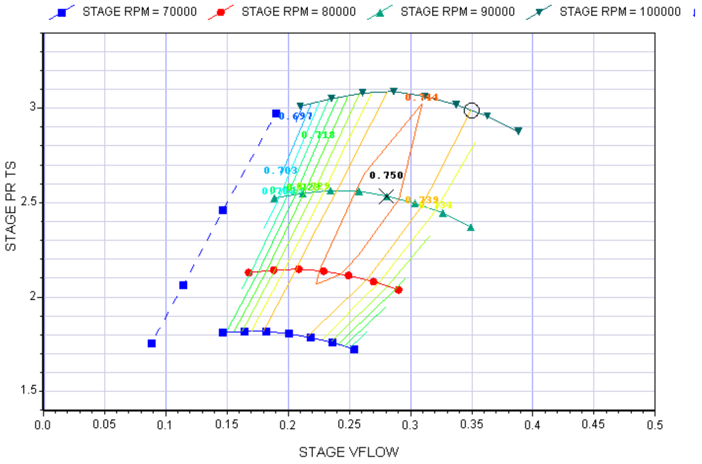

Figure 5: Predicted compressor map (volume flow is m^3/s)

The largest gear that is used as basis for the prototype can transfer in the order of 50 kW at approx. 100.000 rpm, which exceeds the boundaries of direct drive high speed motors with rather expensive magnetic bearings, permanent magnets, etc. It is the real advantage of this gear that such specifications can be realized at relatively low costs.

A high-level commercial code was used for the final detailed compressor design. The code consisted of both a 1D correlation, a model based prediction tool and a full 3D geometry generation and CFD code for detailed geometry design. A number of parameter studies were performed with the 1D code, for example the influence of impeller blade exit angle on pressure ratio, hub tip ratio, speed, etc. For example, the blade exit angle decides the trade-off between high pressure ratio and high efficiency. In our case, high pressure ratio was given priority at the expense of efficiency, leading to almost straight impeller blade outlet angles.

The majority of the overall compressor design is performed with this code and the predicted map for the final design choice is shown in Figure 7. The design values are an impeller diameter of 110 mm, a design speed of 95000 rpm, a design volume flow of 0.3 m^3/s and a blade exit angle of 10 degrees.

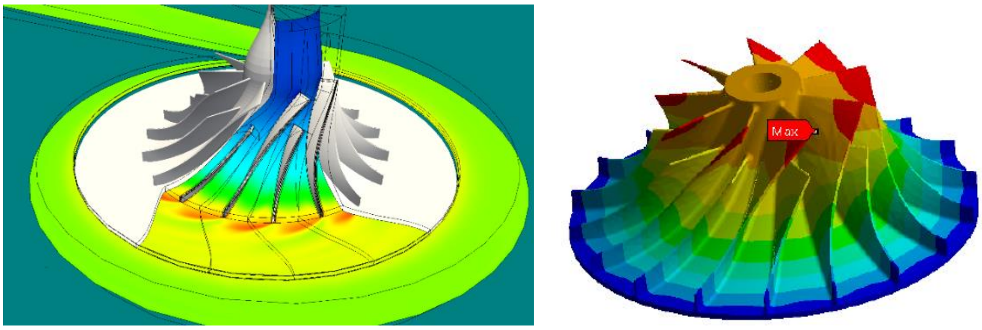

Figure 6: An example of CFD calculations showing the total pressure distribution (left) and an example of FEA analysis showing total displacement at design speed.

Diffuser and volute design have a great influence on the stall limit and the total conversion of dynamic pressure to total pressure. In general, there is a trade-off between the stall limit and the peak efficiency. In our case the larger stall limit was more important than a high peak efficiency, allowing the compressor to work at a number of different applications and even allowing the same geometry to be used in serial coupling with one compressor on top of one or two compressors for a temperature lift of approximately 50 °C. A linear diffuser is added to the volute in order to reduce loss of dynamic pressure in the condenser.

Figure 7: The final compressor prototype compressor including the Rotrex gear (left)

The final 3D detailed design was performed by means of the commercial CFD code. Some of the results are shown in Figure 6: CFD results of total pressure distribution and FEA results of total displacement due to centrifugal forces. The mechanical design of the Ti impeller was pushed to the limit and the high peak stress level required a careful design.

Figure 8: The prototype compressor installed with a standard 50 kW electrical motor, pulley and belt drive

5. TEST RIG DESIGN

Prior to this compressor development, a test was performed at Haldor Topsoe's test facility with a smaller compressor in the Rotrex program without any modifications due to the change of working fluid. The results of these tests are published in (6.)

The new compressor was initially tested at the Rotrex test rig with air as a working fluid. Afterwards, it was installed at the same location as the previous smaller compressor, in parallel with the existing steam ejector as part of the Haldor Topsoe process equipment.

The new design with the titanium impeller and the capability to meet higher pressure ratio has also been initially tested at Haldor Topsoe's test facility. The new steam compressor is shown on the test rig in figure Figure 9 (left site) together with a smoothed compressor map transformed when test data from air is transformed to operation on steam (right site). So far, an initial test has been carried out.

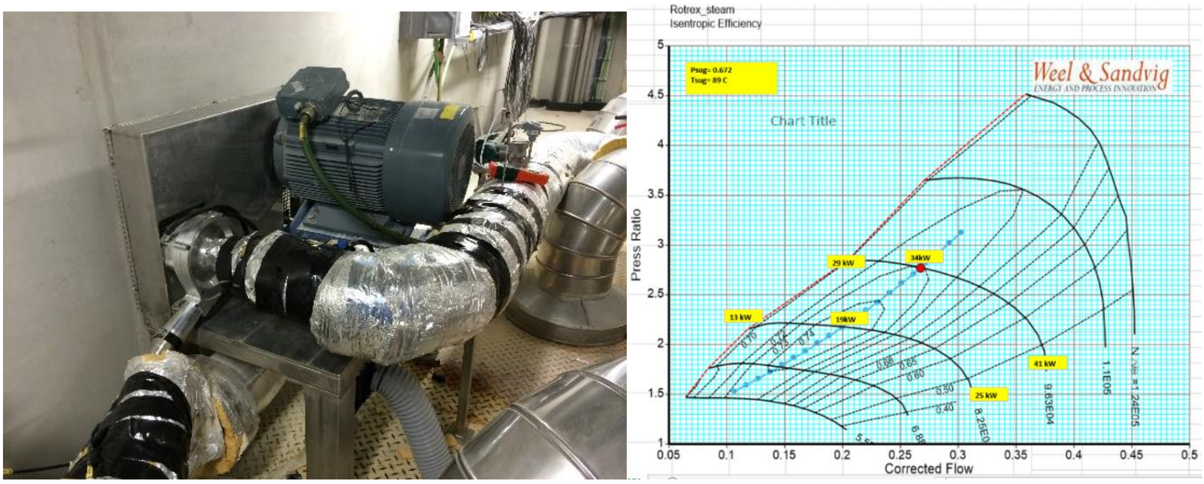

Figure 9: The new compressor displayed at Haldor Topsoe's test rig (left site) and a smoothed compressor map transformed from test data on air to steam (right site)

6. APPLICATIONS

The new heat pump concept has the potential to be used in many different applications to reduce primary energy consumption. For many industrial applications a temperature lift above 30 K is required for balancing the investment costs and the operational costs. To accomplish a higher temperature lift, a two-stage configuration with compressors arranged in a serial coupling as shown in figure 10 can deliver temperature lifts between 25 and 50 K. The three stage configuration can deliver a temperature lift up to approx. 75 K (ref. 6. - 8.).

Figure 10: Compressors set up in parallel combined with serial coupling to match required capacity and temperature lift (pressure ratio).

The basic requirements for some of the applications where a high temperature heat pump can be used are:

- Evaporation plants (temperature lift 10-20 K, direct)
- Distillation columns (temperature lift 30-60 K, indirect)
- Drying (temperature lift 50-70 K, indirect)
- Process integration. Source steams composite from multiple sources (temperature lift 20-70 K, indirect)

As an example, one possible application is timber drying. Timber is dried as a batch process with a typical drying profiler versus time as shown in Figure 11.

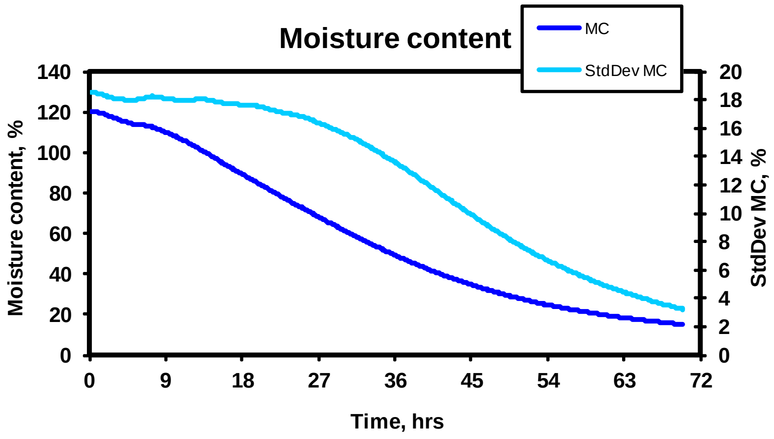

Figure 11: Typical drying profile for a timber drying kiln.

Figure 12 shows two options for heat pump integration in a timber drying kiln. To the left a heat pump retrofitted to a conventional “air dryer” and (to the right) a super-heated steam kiln drying process. For the conventional kiln drying process, the heat pump circulation fan consumes about 20 kW and the compressor consumes about 84 kW when delivering 446 KW heat to the drying chamber. The total COP value is about 4. In the super-heated steam drying kiln drying concept the COP value can reach above 7.

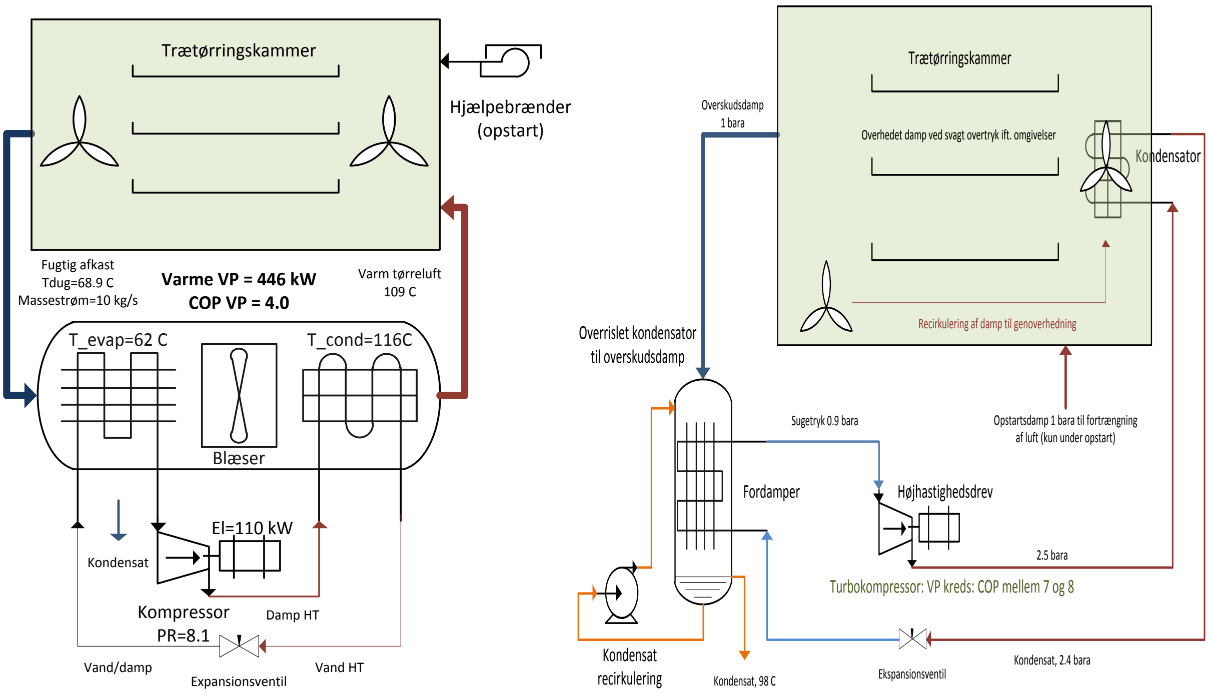

Figure 12: Heat pump integrated in a timber drying kiln. Left: Conventional drying in air. Right: Drying in super-heated steam

7. CONCLUSIONS & FUTURE

A novel high efficiency high speed turbo compressor for high temperature heat pumps with water vapor as a cycle media has been constructed and initial tested. The potential for using new high temperature heat pumps in the industry is enormous and can be a very important cost effective way to reduce energy consumption and carbon dioxide emissions. A limited number of different compressor sizes and design are necessary to cover the large variation in the physical properties of water in combination with the various process specifications.

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