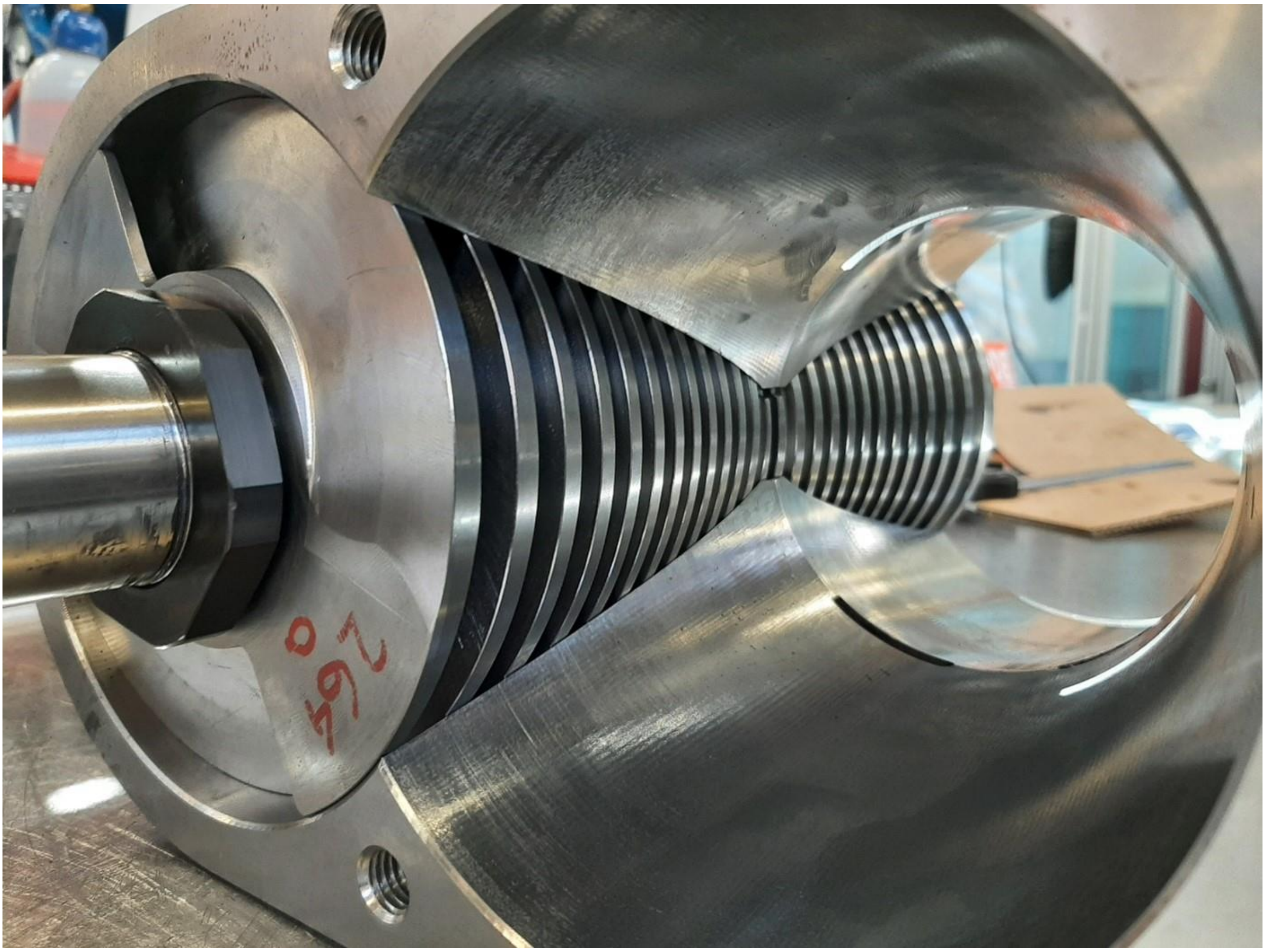

The conical spindle compressor with one of the rotors installed – photo: KRAL

High-Temperature Heat Pump for Tunnel Oven

ELFORSK 352-009

DANISH
TECHNOLOGICAL
INSTITUTE

High-Temperature Heat Pump for Tunnel Oven

ELFORSK 352-009

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Refrigeration and Heat Pump Technology

Prepared in cooperation with
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August 2022
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Summary

The objective of this project was to develop and test a steam compressor that could fit into a heat pump which in turn could meet the requirements for tunnel ovens and spray dryers in terms of supply temperatures in the range of 200°C to 250°C – and thereby replacing gas-fired units.

A compressor of the spindle type was designed for a capacity of 130 kW and a temperature lift from 105°C to 230°C with water vapor (steam) as working fluid. Moreover, the compressor was designed with a built-in pressure ratio of approximately 1:20 and water injection for sealing and reducing the discharge temperature.

The geometry of the designed spindles turned out to be too complicated for them to be immediately manufactured by turning on a lathe. It was necessary to use 5-axis machining for the first prototypes.

It also proved quite challenging to assemble the compressor with spindles and insert into an existing housing, especially in terms of finding ways to measure clearance to ensure correct fitment.

Due to time limitations, the manufactured prototype compressor was installed on a recently established test rig at Danish Technological Institute, where a mechanical functionality test and a performance measurement were carried out.

Mechanically, it is a very well-functioning compressor with a low vibration and noise level, and it has a mechanical loss of approx. 6 kW at full speed (8000 rpm) in the current configuration.

In terms of performance, the compressor did not perform satisfactorily without the water injection in relation to the expectations. However, with water injection, the compressor produced a volume flow and pressure rise of several bars, limited by the test rig. The maximum pressure ratio was still lower than the design value, and is probably dependent on the selected tolerance for the distance between the spindle and the compressor housing - a relationship that will be likely to be analyzed and modified in the further development process.

The results of the measurements were very encouraging in that the compressor worked excellently mechanically. The results indicate that initially a rather large clearance was chosen between spindle and housing to be sure that the spindles did not settle or lock on the prototype. If so, a functional compressor is within reach just by varying the clearance. Otherwise, it will be a revision of the spindle design and the water injection design.

Sammenfatning

Formålet med dette projekt var at udvikle og teste en dampkompressor, der kunne passe ind i en varmepumpe, som igen kunne opfylde kravene til tunnelovne og spray tørrere med hensyn til fremløbstemperaturer i området 200°C til 250° C – og derved erstatte gasfyrede enheder.

En kompressor af spindeltypen blev designet til en kapacitet på 130 kW og et temperaturløft fra 105°C til 230°C med vanddamp (damp) som arbejdsmedie. Kompressoren er designet med et indbygget trykforhold på ca. 1:20 og vandindsprøjtning til tætning og reduktion af trykgas temperaturen.

Geometrien af de designede spindler viste sig at være for kompliceret til, at de umiddelbart kunne fremstilles ved at dreje på en drejebænk. Det var nødvendigt at bruge 5-akset bearbejdning til de første prototyper. Så selve fremstillingen af de kritiske spindle komponenter viste sig at være væsentligt mere kompliceret end forudsat.

Det viste sig også at være ret udfordrende at samle kompressoren med spindler og indsætte den i et eksisterende kompressor hus, især med hensyn til at finde måder at måle spillerum på for at sikre korrekt montering – det blev til dels nødvendigt at benytte indirekte metoder..

På grund af de opståede forsinkelser og projektets tidsbegrænsning blev det besluttet af flytte testen fra den oprindeligt planlagte test tunnelovn. I stedet blev den fremstillede prototypekompressor installeret på en nyligt etableret testrig på Teknologisk Institut, hvor der blev udført en mekanisk funktionstest og en ydelsesmåling.

Mekanisk er det en velfungerende kompressor med et lavt vibrations- og støjniveau, og den har et mekanisk tab på ca. 6 kW ved fuld hastighed (8000 rpm) i den aktuelle konfiguration.

Ydeevnemæssigt klarede kompressoren sig ikke tilfredsstillende uden vandindsprøjtningen i forhold til forventningerne. Men med vandindsprøjtning producerede kompressoren en volumenstrøm og trykstigning på flere bar, begrænset af testriggen. Volumenstrømmen og det maksimale trykforhold var stadig lavere end designværdien, og er sandsynligvis afhængig af den valgte tolerance for afstanden mellem spindlen og kompressorhuset - et forhold, der sandsynligvis vil blive analyseret og ændret i den videre udviklingsproces.

Resultaterne af målingerne var meget opmuntrende, idet kompressoren fungerede fremragende mekanisk. Resultaterne indikerer, at der i starten blev valgt en ret stor afstand mellem spindel og hus for at være sikker på, at spindlerne ikke satte sig eller låste sig på prototypen. Hvis det er tilfældet, er en funktionel kompressor inden for rækkevidde blot ved at variere frigangen. Ellers vil det være en revision af spindeldesignet og vandinjektionsdesignet.

1. Project partners, project process and challenges

The project partners are:

Hamburg Vacuum is the designer and manufacturer of the spindle compressor uHeater. Hamburg Vacuum is generally in close cooperation with R-718 Spindel GbR and in this project also with KRAL [1]. The R-718 Spindel GbR invented the iCooler [2], which is designed to operate on both sides in vacuum and with water only as refrigerant in the range of 0°C to 100°C. The R-718 Spindel GbR holds several patents on the spindle concept for refrigeration equipment. The uHeater increases the application from 100°C to much higher temperatures which means that the uHeater must operate within the pressure range of 1 bar to 25 bar absolute.

CS Techcom is a company specializing in 5-axis machining of prototypes and turbo machinery, and they are the manufacturer of the spindles for the compressor. Moreover, CS Techcom offers turning on lathe, surface treatment, balancing, and 3D measurements as well as assistance and consultancy regarding prototypes and serial production.

Senius (former Flexmatic) is the producer of tunnel ovens, and they are an end-user of the heat pump. Senius could replace the traditional gas-fired energy sections by the heat pump for the baking process. The original idea was to use the Senius test oven as a test rig for the spindle compressor. Due to various delays on the manufacturing of the compressor, the test was relocated to a newly established test rig at Danish Technological Institute to meet the final deadline for the project.

Sanovo is the producer of various types of equipment for the handling and processing of eggs, including a spray dryer to produce egg powder. Sanovo is a potential end-user of the high-temperature heat pump as the temperature level is within the same range for the spray dryer as it is the case for the tunnel ovens.

Danish Technological Institute is an independent R&D institute, and they have been the coordinator and project manager of the project. Their role has among others also been to establish model calculations for the wet compression, the integration of the heat pump, dissemination of the results, and finally, testing of the prototype.

The project process

The project as defined in the application consists of five work packages. The overall purpose of the project is to develop a compressor that can be used in a heat pump which can deliver the temperatures in the 200°C to 250°C level – an interesting temperature range for the applications for tunnel ovens and spray drying plants. Four of the work packages have been completed regarding specifications, compressor design and manufacturing as well as function and performance testing of the compressor. Due to severe time constraints, it was necessary to partially modify the last work package so that the test was carried out on the test rig at Danish Technological Institute instead of conducting the prepared rebuilding of the test tunnel oven at Senius (formerly Flexmatic).

The project process and especially the schedule have had to be adjusted several times, partly because of the Covid-19 pandemic, and partly due to the technical challenges that emerged. Originally, the project was scheduled to be completed on 1 September, 2021, but it was completed on 15 August, 2022.

The essential parts of the project have been completed; a prototype compressor has been designed, manufactured, and tested at a steam test rig, and important knowledge has been obtained both with regards to the compressor and the installation in the tunnel oven.

All project participants have exceeded the budgeted number of hours and expenses, in some cases quite significantly, but they have persisted in completing the project due to the large and promising potential of the technology.

Project challenges

Initially from day to day, the consequences of the pandemic were a drastic decline in orders for all project partners, typically more than a halving of their orders and for some project partners almost a drop-out. This led to a reduction of staff and a strong focus on obtaining new, alternative orders. As the pandemic eased, it led to extraordinary bustle with many new orders combined with difficulties in procuring materials and components. Both phases of the pandemic had the effect that it was a challenge to allocate resources to the project and adhere to the agreed schedules.

On the technical side, the production and assembling of the prototype has been far more challenging than expected. The compressor is inspired partly by a vacuum pump and partly by a water pump, but in contrast to both, it has been necessary to change the cylindrical shape of the spindles to a more conical shape to achieve a compression of the steam. This change in the outer diameter proved to complicate the expected manufacturing process by turning on a lathe so much that the method eventually had to be completely abandoned. Instead, CS Techcom succeeded in finding a method where the complex shape of the critical components was produced by 5-axis machining, a more resource-intensive process.

During the next step of incorporating the manufactured spindles in the compressor housing itself at KRAL, a partner with HV proved to be very demanding. It was necessary to install and control the spindles with very small tolerances, both radially and axially, and not least to develop measurement methods which were made more difficult due to the variable outer diameter. As it turned out, there was contact between the two spindles at the assembly, and 0.1 mm of one spindle set was machined twice before it was possible to rotate the compressor without contact between the two spindles.

Due to the uncertainty on the timing for the assembling of the compressor, the prepared rebuild and construction of the test tunnel oven at Senius were put on hold after all the preparations, calculations, and procurement of most components had been completed. The completion of the conversion of the test tunnel oven was estimated to require four to six weeks of work. Thus, the delay in the assembling of the compressor until the end of June 2022 ultimately meant that it was impossible to complete the test at Senius.

Instead, the tests were conducted at Danish Technological Institute where it was possible to use a test rig for steam compressors, which was completed at the end of May 2022.

2. Introduction

The ongoing electrification of the process industry as part of the green transition is slowed down by the lack of commercially available technical solutions at temperatures above 100°C. In particular, the temperature range from 150°C to 250°C is important for a significant part of the process industry, and the electrification of the industry requires development of suitable heat pumps for the relevant applications.

This project will help to fill this gap and contribute to the situation where appropriate hardware is available for the process equipment manufacturers. In this case, especially manufacturers of tunnel ovens and spray drying plants, but also industrial dryers from laundries and the like, will be able to benefit from this project. The capacity of the heat pump is rather low, in the order of 150 kW, which in particular makes it suitable for direct process integration. The basic concept is scalable, and the expected range of capacities might be in the range of 100 kW to a few MW.

The heat pump is based on the combination of water (steam) as refrigerant and on a geometry known from vacuum pumps and water pumps. The use of water as a refrigerant ensures the environmentally optimal choice and in addition, steam is well-known in the process industry. Technologically, there are similarities with a screw compressor, but the special spindle geometry allows for significantly higher pressure-ratios and, thus, greater temperature lifts. Therefore. for the project partners, the technology is much more applicable for the heat pump application than the screw compressor principle.

3. Tunnel oven

Tunnel ovens are widely used in applications in all kinds within the food industry, not only for baking bread, cakes, and biscuits, but also for baking liver pate, pizza, prepared meals etc. Outside the food industry, tunnel ovens are for example used to dry items after washing and after painting. Tunnel ovens are also used by other industries, for instance manufacturers of plasterboard sheets.

Danish manufacturers of tunnel ovens are world leaders, so there is a very large export share; 90 - 95% of the production. The tunnel ovens are typically built in 6 m modules which are assembled into a baking line. A baking line can be 50 - 80 m long. Typically, three to six of these modules are so-called energy modules where the air is heated, and the baking takes place.

The temperatures are mostly in the range of 150°C to 250°C, but requirements vary from about 100°C to 300°C. The air is predominantly heated by means of gas firing, and the air is recirculated in the individual modules. Part of the air is vented to regulate the humidity, and it is replaced by fresh outdoor air.

The service life of the plants is generally very long, typically decades, and in the vast majority of cases, the tunnel oven is a key element in the production. Thus, in most cases, the plants are in operation around the clock, all year round. Even though the energy costs for production may make up a smaller percentage of the costs of the final product, the many operating hours could provide a significant saving on an annual basis, and thus a financial margin for investment.

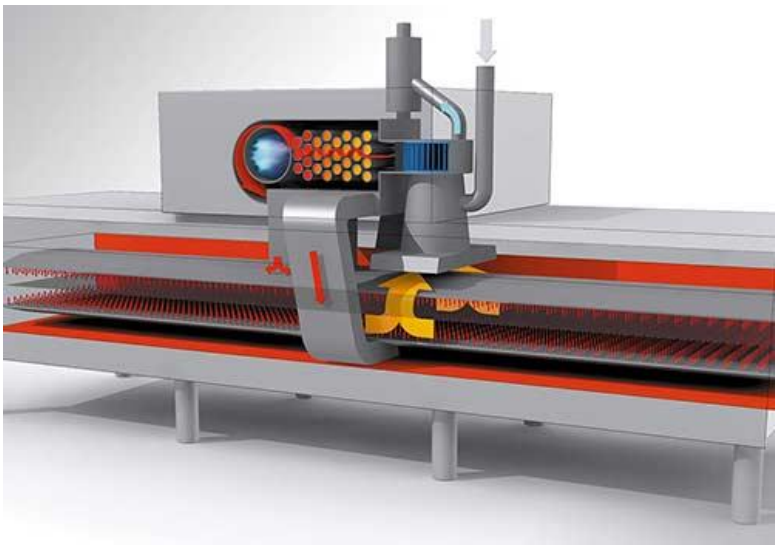

Figure 1: Typical configuration of gas-fired tunnel oven with recirculation (Senius).

Figure 1 shows an example of the basic design of a so-called energy unit, an individual section of a complete tunnel oven production line (Figure 2) where the air is recirculated and heated in this section. A conveyor belt with the products runs through the oven, where heated air is led to the baking section via a series of nozzles above and below the conveyor belt. The air velocity in the nozzles is relatively high to increase the heat transfer coefficient for the heating of the product. The products typically release water during the baking process, and the cooled humid air is returned to the heating unit at the top of the section. The humidity is controlled by bleeding humid air and replacing it with less humid outside air which is subsequently heated. The heating is typically done by a gas burner which heats the air by means of a heat exchanger. However, some processes can use the resulting flue gas directly. A production line, e.g., for cookies, consists of a number of sections in addition to the baking sections themselves. It can be cooling sections, sections for different finishing of the products (e.g., chocolate), etc. Depending on the product, there will be different designs and lengths of a production line, and typically three to six of these will be energy units.

If a heat pump is to replace the gas-fired heating, it is necessary to consider which heat source can be used as the heat source is not an external supply but must be found in the process. In principle, there are two options, either by condensing the humid air (as for example in a household dryer) or by cooling the product and conveyor after the baking process. The advantage of condensing the water content is that the section becomes an independent, self-contained unit, and the disadvantage is that the temperature of the heat source can be quite low depending on the relative humidity in the return air from the baking section. The advantage of using the cooling of the product and the conveyor belt as the heat source would be the high temperature of the heat source while the disadvantage may be the distance to the heat source. There may be up to 50 - 60 m to the end of the production line. In either case, COPs in the order of 2 to 3 in average for the full production line are to be expected.

Figure 2: Sections of tunnel ovens combined to a production line [3].

Figure 3 below shows a situation where the humid return air from the baking (1) is used as the heat source for the heat pump. After an optional internal heat exchanger, the return air is cooled down to a temperature close to the dew point (2), and in the evaporator, the air is further cooled to the dew point, and part of the water in the air is condensed (3). The dry, cooled air is heated in the internal heat exchanger close to the return air temperature (4), after which the condenser heats the dry air even more, typically 50 - 70°C above the return air temperature (5). If there is a need for additional heating, it is possible to use an electric heater (6) which is also used when starting up the unit.

If cooling is used as the heat source, the internal heat exchanger will not be relevant, and the evaporator will be supplied directly from the cooling air, which comes from the rear sections of the production line.

Market research has been done on the total market for bakery equipment [4], and it is stated that the total market in 2023 is expected to be 11.4 billion USD, of which a significant part will be the production lines themselves, including tunnel ovens (estimated at 1.2 billion USD globally). Thus, it is a large market with a very large potential, not least because the developed heat pump can be used as a retrofit on the approximately 5000 globally existing tunnel ovens.

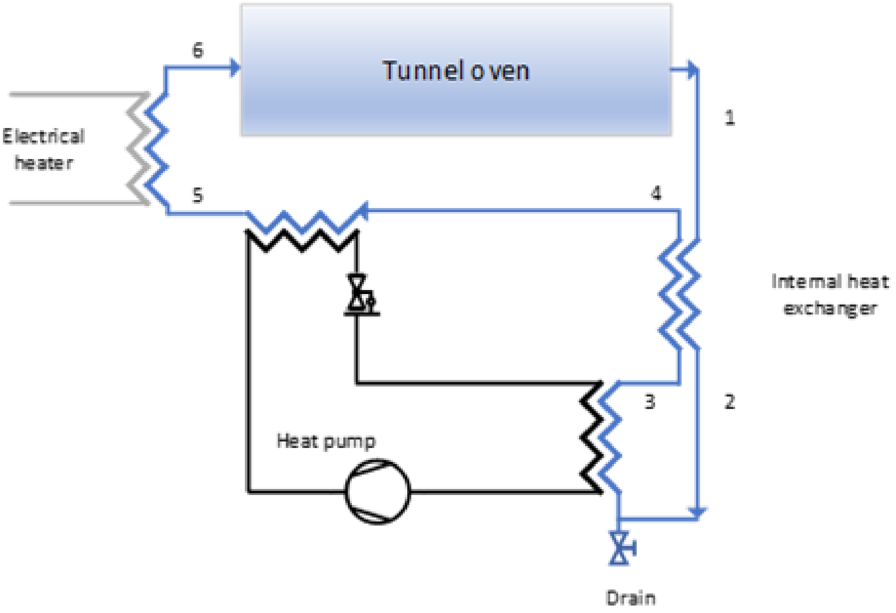

Figure 3: Potential integration of heat pump in tunnel oven operation as energy unit.

4. Spray Drying

Spray drying is a unit operation which is an even more widespread method both in the food industry as well as non-food industry to dehydrate liquid to a powder for increased shelf life and easier handling. The process is used to convert a liquid product into powder, grains or granulate - either for further processing or for direct use. The capacity and temperature variations for this type of plant are significantly greater than for tunnel ovens. The value of the market for spray drying equipment is estimated at 5.4 billion USD in 2023, [5], [6], which is four times the market for tunnel ovens. The industry is well-established and the entire drying theory and the description of plant and function are described in a number of textbooks, e.g. [7], [8], [9].

In general, the most common temperature range for spray dryers is roughly the same as for tunnel ovens, so the heat pump developed for tunnel ovens can just as well be used for spray drying plants. This also applies to the plant from the project partner Sanovo, which supplies plants for drying a variety of products as described in [10]. The design of the plants is atypical in that the spray direction is horizontal, as illustrated in Figure 4, instead of the more common vertical spray towers.

In a spray dryer, water from the product evaporates by means of heated air. The heating of the air is traditionally done by gas firing (Figure 5), and the (dry) warm air is cooled and humidified by the evaporation. Often, the humid air is led out to the environment and replaced by outdoor air which is subsequently heated as illustrated in Figure 6. In some cases, some heat recovery is established through a heat exchange between the exhaust air and the inlet air.

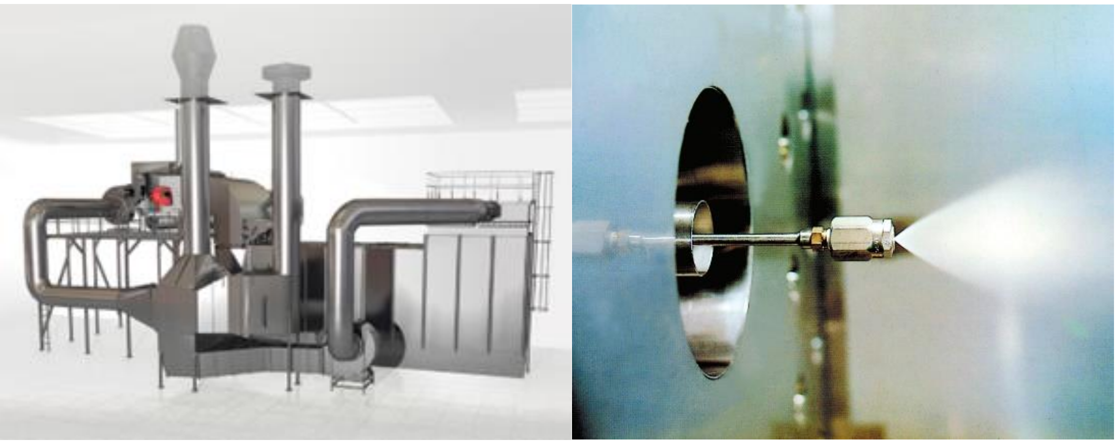

Figure 4: Sanovo spray dryer plant (left) with horizontal spray distribution (right).

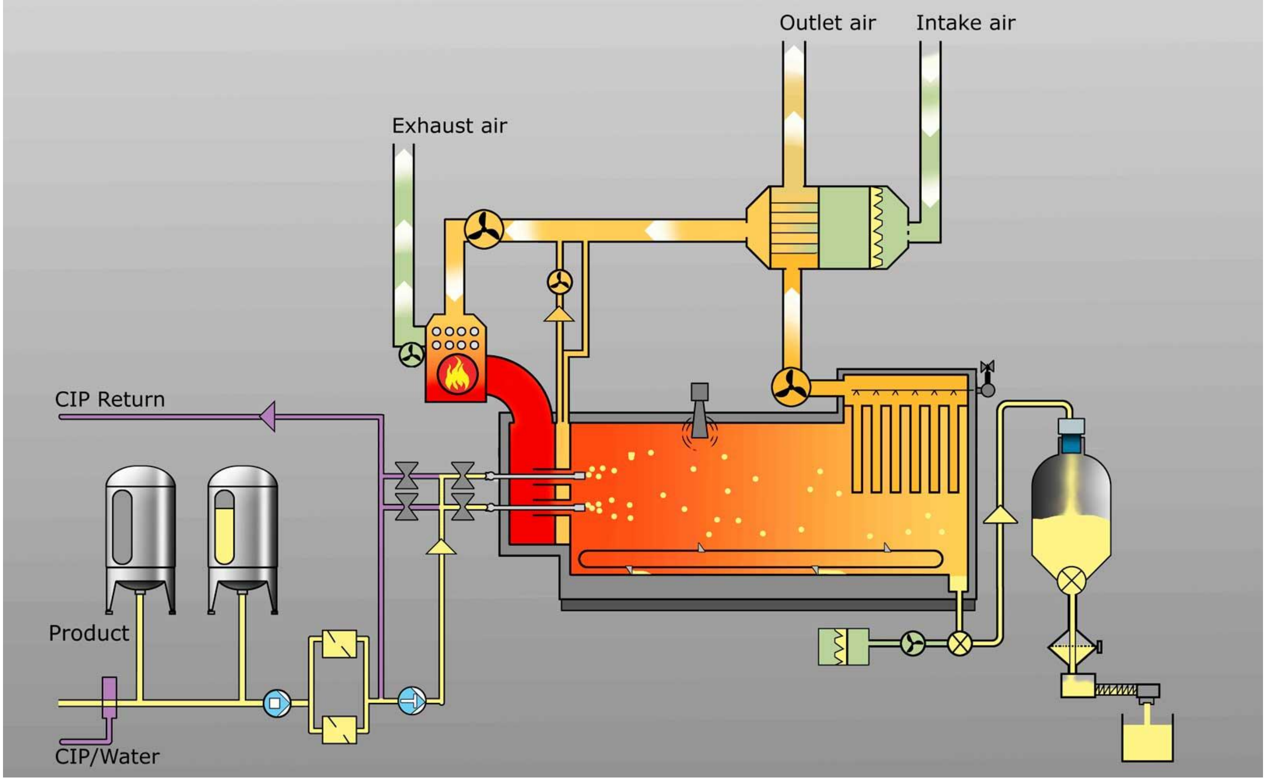

Figure 5: Sketch of Sanovo spray dryer operation with gas-fired heating of the air and heat recovery by heat exchanger between outlet and inlet air.

A heat pump can be integrated directly between the exhaust air and the incoming air so that the entire cooling and heating is handled by the heat pump - optionally with an internal heat exchanger as seen in the tunnel oven in Figure 3.

If the air can be recirculated, then, the dehumidification can take place by means of the evaporator. The evaporator cools down the air to the dew point and drains some of the water after which the dry cold air is heated in the condenser and returned to the spray dryer as illustrated in Figure 7. Thus, the heat pump can in principle be integrated in the two types of systems according to the same general principles - of course with adaptation to the current operating conditions.

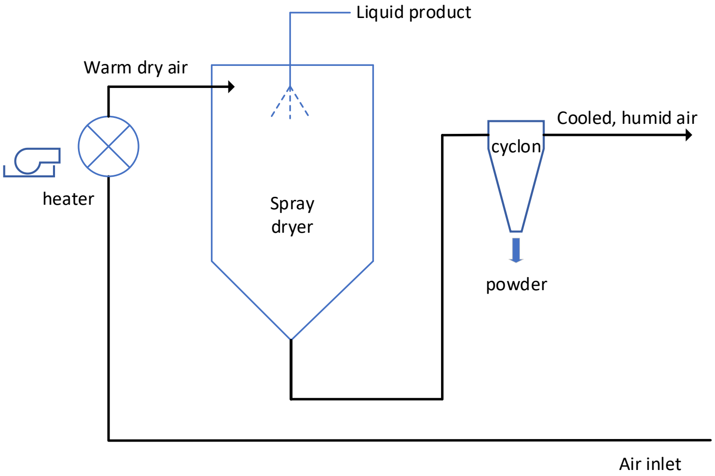

Figure 6: Sketch of existing gas fired spray dryer unit. A heat pump can be integrated directly between inlet air (condenser) and exhaust air (evaporator).

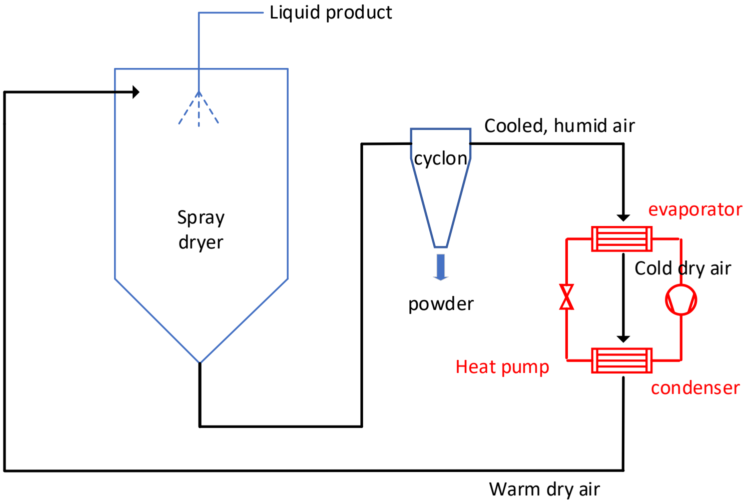

Figure 7: Potential integration of the heat pump in the spray dryer in case of recirculation.

The operational conditions can somewhat vary, depending on the product in question. Typically, the conditions include supply temperatures in the range of 150°C to 250°C and outlet temperatures in the order of 80°C to 120°C with relative low humidity and, thus, typically lower dew points for condensation. Cooling of the product could also serve as heat source for the heat pump.

5. Water as refrigerant

Water has many advantages as a working fluid for heat pump and energy distribution systems. It is harmless and environmentally friendly, and steam is well-known by the industry in the very widespread central steam systems with gas-fired boilers, which serve as energy infrastructure.

The disadvantage of water as a refrigerant is that sufficiently cheap and efficient compressors have not yet been developed, and that is the key component in the heat pump system. The other components such as heat exchangers, valves, etc. are available for the existing steam systems, and certain types of steam traps or drain valves can be used as expansion valves.

Water has some special physical properties, which makes it necessary to develop technology that differs from the traditional technology used for HFC, CO_2, and NH_3. Figure 8 shows the saturation pressure as a function of the temperature and as seen in the figure, when the temperatures are below 100°C, the pressure is below 1 bar, i.e., vacuum conditions. This is relevant for both applications as the heat source can be at a level as low as about 50°C if it is the dehumidification that acts as a heat source (condensation at dew point). The critical temperature for steam is 374°C. Thus, water can in principle be a fine refrigerant for heat pumps with supply temperatures up to 330°C to 340°C, where the corresponding pressure will be above 100 bar. A heat pump operating in the range from 50°C to 250°C must therefore be able to handle pressure levels in the range from 0,1 bar to 40 bar, as shown in Figure 8.

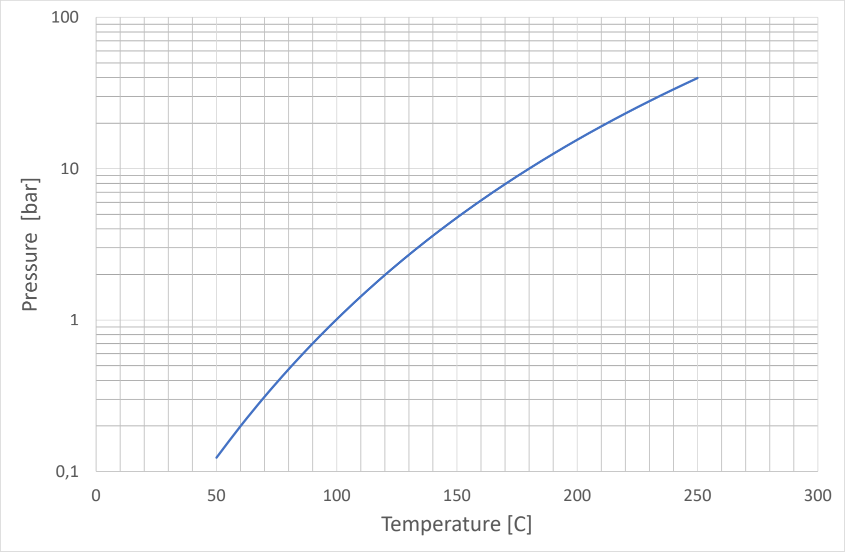

Figure 8: Saturation pressure vs temperature for steam.

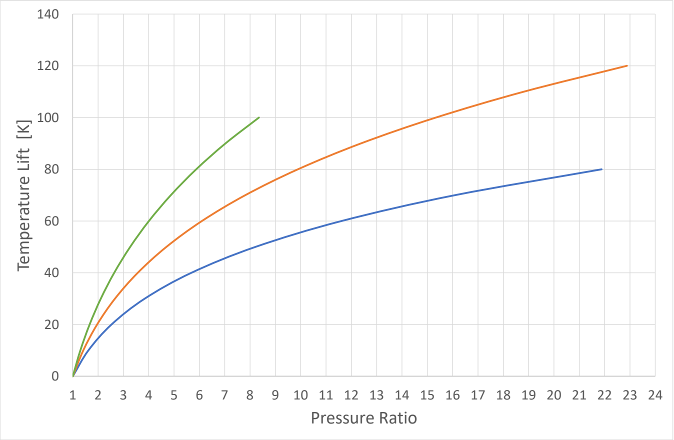

Figure 9: Temperature lift vs pressure ratio at inlet conditions 50°C (blue), 100°C (orange) and 150°C (green).

A consequence of the relatively low atomic mass of water is the high pressure ratio which is required to achieve the temperature lifts in demand for the high temperature heat pumps. The relation depends on the inlet conditions, for example a pressure ratio of 20, the built-in pressure ratio for the spindle compressor would give a temperature lift of approx. 75K, if the evaporator temperature is 50°C, thus, condensing at 125°C. If the inlet temperature is 100°C, the similar numbers would be 100°C to 210°C (110K lift) and finally 150°C to 310°C as seen in Figure 9.

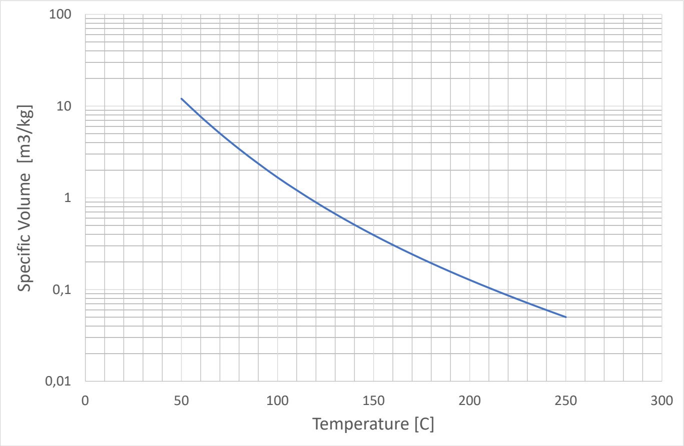

Figure 10: Specific volume vs saturation temperature.

The specific volume varies quite strongly with the suction temperature as shown in Figure 10. This figure shows that the variation is more than a factor 700 between the 40°C inlet and the 250°C inlet. For a fixed geometry, there will be a similar capacity variation.

6. Specifications and economic feasibility study

The main requirement from the buyers or customers for the heat pump when developed is a high supply temperature in the range of 180°C to 250°C. The evaporator temperature depends on how the heat pump is integrated in the process as mentioned in the previous sections, and consequently, the expected COP will depend on the details of the operating conditions.

For the project partner Senius, a tunnel oven with supply temperatures in the range of 185°C to 225°C are of particular interest, and if the heat source temperature is obtained by condensing humid air, it is estimated to be in the range of 60°C to 80°C. Thus, operating conditions for the tunnel oven could for example be the temperature combinations shown in Table 1.

Also, for the spray dryer application, it is assumed that the heat source will be condensation of the humid air. In this case, the performance has been calculated for three concrete measurements, also shown in Table 1. In these cases, it is likely that COP will be in the range 1.5 to 1.9.

The spindle compressor is designed for an inlet pressure corresponding to the saturation temperature of approx. 105°C and a supply saturation temperature of 230°C. So, in both the tunnel oven and the spray dryer applications, a cascade system is required where e.g., a one- or two-stage water vapor turbo compressor or a traditional heat pump system (or a second stage of spindle compressor) provides the necessary temperature lift from the source temperature up to about 105°C, the inlet conditions for the spindle compressor.

Table 1: Example of operation conditions for the heat pump and the expected Carnot COP.

Application	T supply [°C]	T source [°C]	COP estimated
Tunnel oven	225	60	1.81
	205	70	2.13
	185	80	2.62
Spray dryer	182	35	1.86
	202	36	1.72
	241	39	1.53

The heat pump is intended as a contribution to the phasing out of fossil fuels and the electrification of the process industry. Therefore, an economic comparison is based on the alternatives, direct electric heating and biogas as fuel. For both these alternatives to the heat pump, the installation costs are less than those of the heat pump, but the operating costs are higher. That is, it is possible to set up a calculation for a payback period for the investment in the installation of a heat pump.

The cost of the heat pump once developed is not yet known, but as a reference, Figure 11 shows the information gathered by [11] that can be used as a starting point for the expected heat pump cost, and based on the preliminary estimates, it seems to be a realistic cost level.

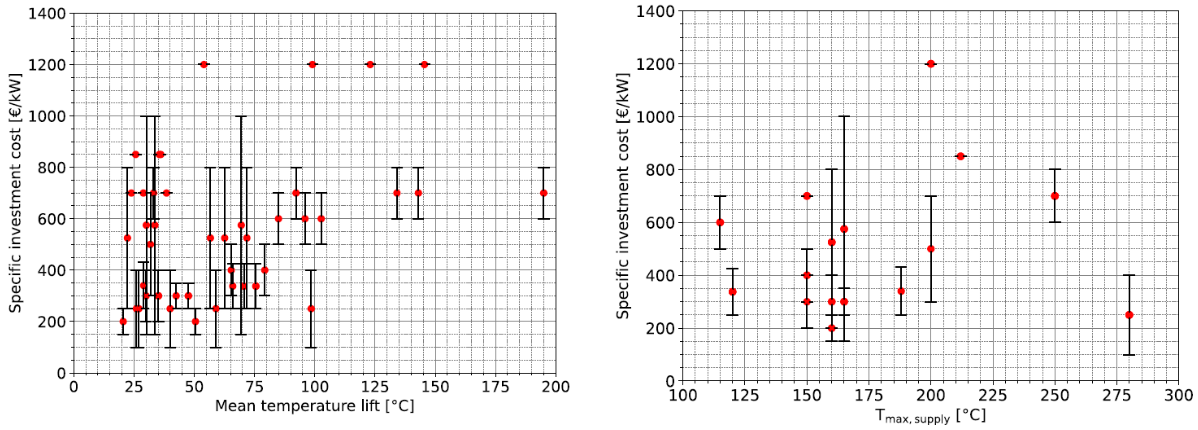

Figure 11: Specific investment cost of high-temperature heat pumps as a function of temperature lift (left) and supply temperature (right).

The spindle compressor is intended for the supply temperature of 230°C and a temperature lift of 125°C. According to the diagrams, the existing heat pumps have specific costs in the range 400 €/kW to 700 €/kW corresponding to approximately 3000 DKK/kW to 5000 DKK/kW. For a 150kW unit, this corresponds to € 60k to € 105k (DKK 450k to DKK 750k) per unit of compressor cascade heat pump.

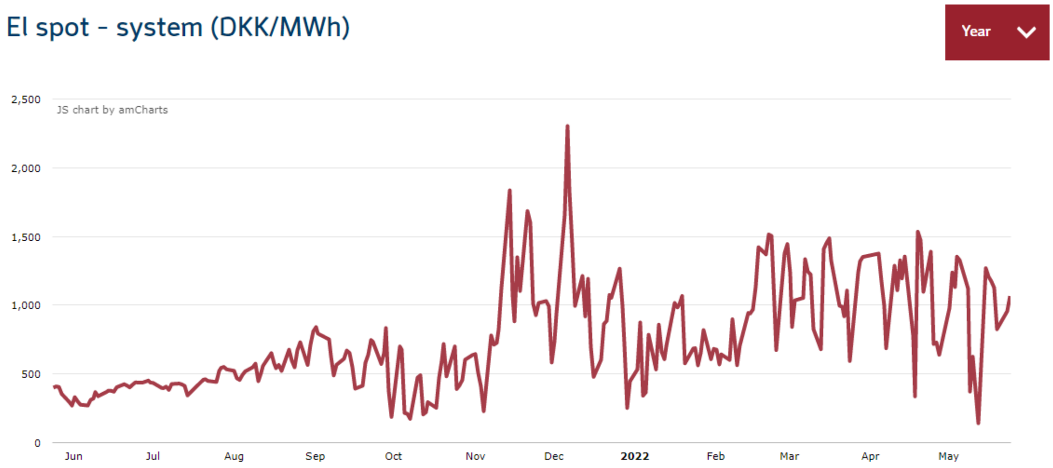

Figure 12: Cost of electricity from June 2021 to June 2022 at the spot market.

The specific cost of electricity (Figure 12) depends on the hourly market price (spot price) as traded in special markets for electricity, primarily NordPol. The spot price used to be relatively stable at the level 0.4 to 0.5 DKK/kWh in the past, but since early in 2022, the price has increased to about 1.0 DKK/kWh in average. The final cost of the electricity for the industry is somewhat higher as cost of distribution, trading company margin, and energy tax must be added, typically in the order of an additional 0.1 DKK/kWh.

Table 2: Example of calculation of simple payback time for heat pump vs. direct electrical heating

T supply	205	°C
T source	70	°C
Eta ideal Carnot	60	%
Estimated COP	2.13	
Annual operating hours	8200	h/year
Heat Capacity	150	kW
Annual power consumption	579	MWh
Specific electricity cost	0.5	DKK/kWh
Annual energy cost	0.289	Million DKK/year
Direct electricity heating	1230	MWh
Annual cost, direct electrical heating	0.615	Million DKK/year
Annual energy cost saving	0.326	Million DKK/year
Specific heat pump cost	5000	DKK/kW
	≈700	Euro/kW
Heat pump cost	0.75	Million DKK
Simple payback period	2.30	Years

Based on the input on heat pump cost and electricity cost, Table 2 shows an example of a calculation of simple payback time for a heat pump vs direct electrical heating. The example is complex in that it includes a temperature lift from 70°C to 205°C, high heat pump cost, and low electricity cost, and still the payback time is as short as 2.3 years. The lifetime of this equipment is expected to be in the order of 15 years for the heat pump, and even longer for the tunnel oven and spray dryer unit.

Finally, Figure 13 shows a more general calculation of payback time vs COP of the heat pump. The four curves show the combination of high and low cost of investment as well as high and low electricity cost to illustrate 'worst case' and 'best case' scenarios. The examples of specifications from Table 1 are shown as a reference in the diagram. All the calculations show very attractive payback periods ranging from less than a year up to three and a half year.

The comparison with biogas is highly dependent on the level of subsidies for the coming years. The production cost for biogas is in the order of 6 to 7 DKK per m^3 which corresponds to approx. 11 kWh of energy [12]. In addition to the production cost, there are expenses to storage, distribution, etc. In total, this adds up to at least the same cost as electricity per kWh and, thus, the same range of payback periods for heat pumps vs. biogas.

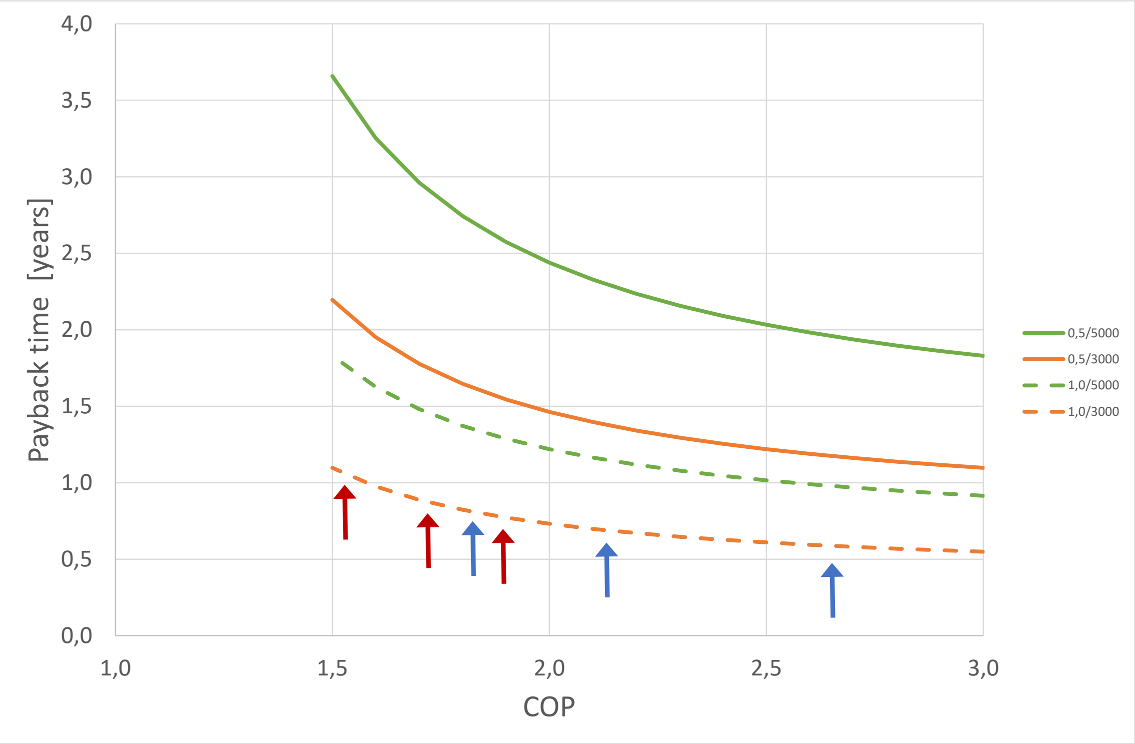

Figure 13: Calculated simple payback period for specific heat pump cost of 3000 DKK/kW and 5000 DKK/kW (approx. 400 and 700 EUR/kW) and electricity cost of 0.5 DKK/kWh and 1.0 DKK/kWh. The blue arrows indicate the tunnel oven examples, and the red arrows indicate the spray dryer cases.

7. Spindle vacuum pump and spindle water pump technology

The spindle compressor developed for the high-temperature heat pump is inspired by two other applications of a similar geometry. These are the vacuum pump from SIHI (SIHI^{dry} M and H series) and a water pump from KRAL (Z-series).

The project partner Hamburg Vacuum develops the heat pump. The founder of Hamburg Vacuum participated in the development of the SIHI^{dry} dry running vacuum pump illustrated in Figure 14, and the basic idea of this new spindle compressor is based on this vacuum pump. The vacuum pump consists of two spindles with a special geometry that allow for suction air and other gasses down to a very low pressure. The two spindles are operated with separate electrical motors that are electronically synchronized and, thus, eliminating the need of oil lubricated gear wheels and seals as seen in standard screw compressor designs.

The vacuum pump [13], [14], see Figure 14, was developed by SIHI in the 1990s, and it is intended to evacuate to the level of around 0.001 mbar absolute pressure with exhaust to atmospheric pressure. The vacuum pump is an alternative to e.g., a rotary vane vacuum pump, and it has the advantage that it is dry running as opposed to the oil lubricated rotary vane vacuum pump type.

The manufacture of the spindle vacuum pump requires very small tolerances to achieve the high pressure ratio and minimize back-flow. The spindles are manufactured by turning on a lathe, where it has been found that the cylindrical shape with a constant outer diameter of the spindles is a great advantage for this method (cf. section 9).

The two spindles in the SIHI^{dry} vacuum pump rotate in opposite directions, and they are controlled individually by separate motors. The electronic speed control enables the two spindles to rotate without contact and without the use of oil lubricated gear wheels which are otherwise common for this type of compressors, e.g., traditional screw compressors.

Figure 14: SIHI^{dry} ® dry running spindle vacuum pump.

The rotational speed is between 500 and 12000 rpm, and the volume flow varies from 100 to 1500 m^3/h. For reference, this corresponds to a heat capacity in the order of almost 50 to 750 kW at 100°C inlet.

As a partner of Hamburg Vacuum for manufacturing and assembly, the Austrian water pump manufacturer KRAL is involved in the project as they produce spindle water pumps among other types of water pumps. The KRAL water pump and the SIHI^{dry} have some common roots back in the 1990s.

The spindle water pump from KRAL was developed as a pump for high-demanding liquid medias which could have large variations in viscosity, lubricity, contamination, and aggressiveness. The pump could operate with two-phase flow, and it is a very robust pump when it comes to the pumping fluid or media. The maximum pressure difference is in the order of 25 bar, and the program covers volume flow in the range from 20 to 1060 m^3/h. The allowed operational temperature is in the range of -40°C to 300°C.

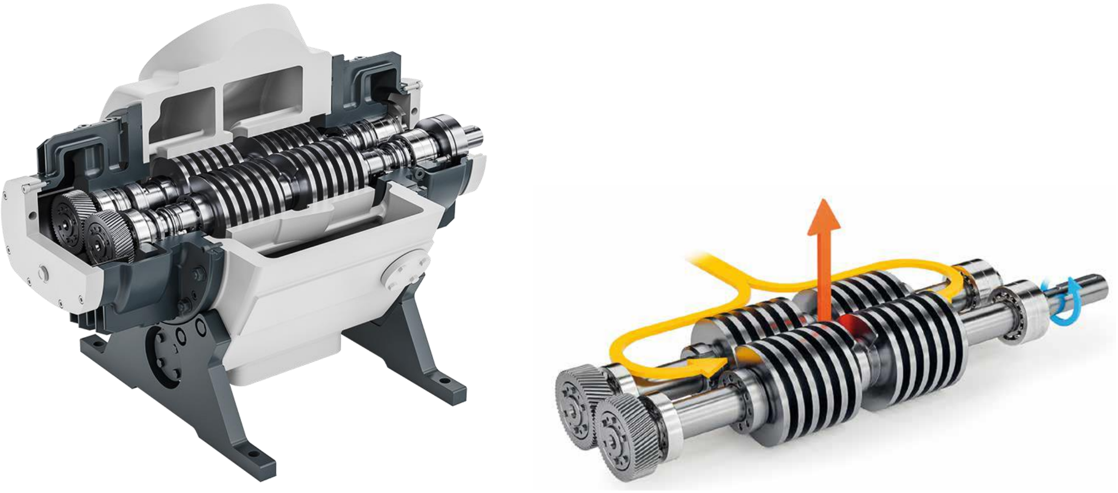

Figure 15: KRAL water pump, Z series, with symmetric, double intake to eliminate axial forces.

The configuration with two symmetrical inlets and one central outlet in the middle ensures that the axial forces are balanced, which means less challenging bearing specifications and longer service life. This pump is driven by just one motor, and the synchronous rotation is ensured by oil lubricated gears. The two high-precision, oil lubricated gears ensure that there will not be contact between the two spindles, and the water lubricated mechanical seal ensures the separation of the oil from the pumping media.

8. Hamburg Vacuum spindle compressor for water vapor (steam) uHeater

The spindle compressor for this project was designed based on the input from the project partners that would be the end-users of the heat pump. The general request was a heat pump that could deliver as high temperature as possible, at least more than 200°C, and with a capacity in the order of 150 kW.

The final design from Hamburg Vacuum had the following specifications:

Thermodynamic design data:

- Estimated COP = 3,1
- $\vartheta\_evap = 105°C$
- $\vartheta\_cond = 228°C$
- $\eta\_comp = 0,7$
- $\dot{Q}\_cond = 130$ kW
- $\dot{Q}\_evap = 88$ kW
- P_comp = 42 kW
- $\dot{V}\_trans = 206$ m^3/h

Physical properties:

- Rotational speed 8000 rpm (133 Hz)
- Volume flowrate 210 m^3/h
- $V_{in}/V_{out} = 12$, inner compression ratio
- L = 125 mm per spindle
- 6 windings per spindle
- 21 chambers
- min tooth gap = 4 mm
- 1 bar to 25 bar absolute

The premise of the design is that the same pressure ratio is present from turn to turn, and that the inner compression ratio is at the same level as the compression ratio inlet to outlet which is needed to fit the temperature lift with the lowest possible energy consumption. There is a total of six turns on the spindles, and the requirements to the inner compression ratio causes the height of the spindles to decrease sharply. It is necessary to modify the cylindrical design and modify the outer diameter as well as use variable pitch like the SIHI^{dry}. The contour means that the minimum height of the spindle on the last turn is about 4 mm. The ideal design of the spindles is shown in Figure 16.

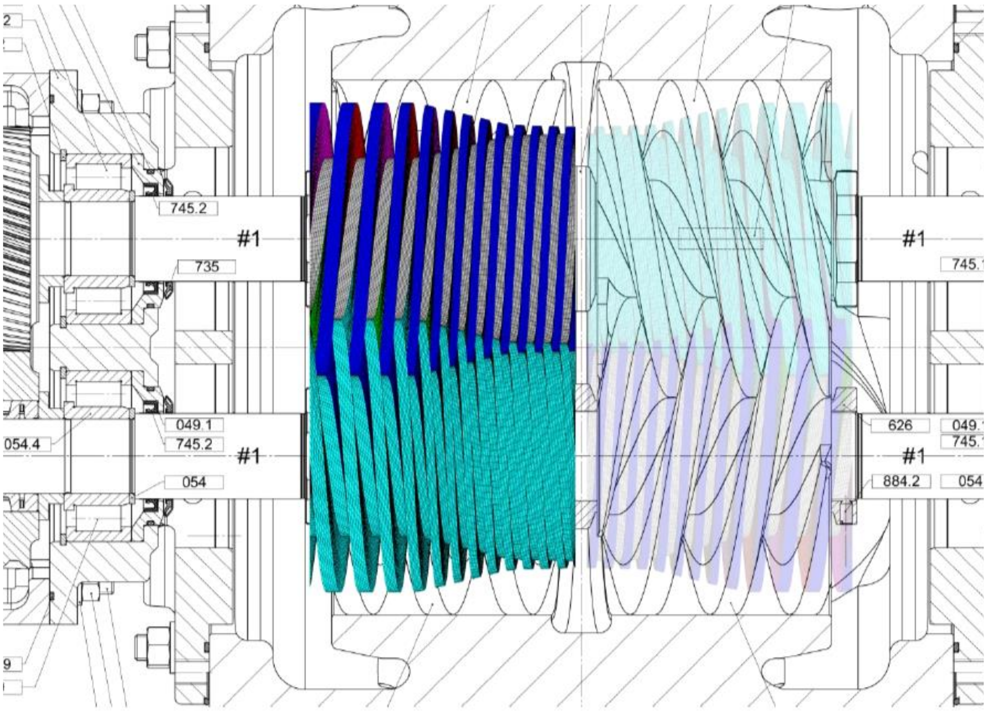

Figure 16: The optimal design of the spindles as designed by Hamburg Vacuum (left) compared to one of the original water pump spindle geometries (right).

This is a relatively complicated, new geometry as the spindles must be designed so that they seal at the center where they meet and at the same time also be able to rotate between each other, which is further complicated by the contour of the outer diameter. Unlike screw compressors, the two spindles are similar, only mirrored, and respectively right-handed and left-handed.

The basic geometry is not dependent on the inlet temperature conditions and can, therefore, be used for other temperature conditions. In addition, the geometry is scalable, so a range of capacities will also be relatively easy to design based on the basic spindle shape.

The built-in volume ratio can be changed by changing the number of spindle windings, e.g., only five windings instead of six and, thus, reducing the built-in volume ratio and/or a different variation of the pitch of the spindles and/or a different variation of the outer and inner diameter. In addition, the compressor housing can be modified so that it is possible to continuously adjust the compression ratio to the given conditions, for example adjust to varying condensing temperatures. That will improve the overall efficiency and energy economy so that the compressor can operate more like a piston compressor than a traditional screw compressor.

In this ELFORSK project, the drive operates with just one motor and the well-known gear synchronization and sealing concept of KRAL.

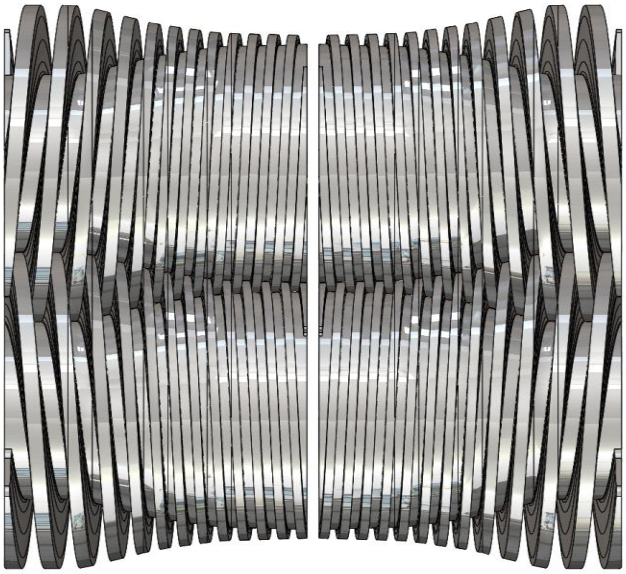

Figure 17: The optimal design of the two double-stage spindles.

9. Manufacturing

The manufacturing of the spindles turned out to be a major challenge for the project. The spindles for the SIHI^{dry} vacuum pump were made by turning on a lathe. Hamburg Vacuum and the manufacturing partner KRAL decided also to use a lathe to cut the spindle with variable pitch and a noncylindrical diameter. A tool specialist, which also supports the SIHI manufacturing process on a lathe, was involved to support Hamburg Vacuum. However, neither this sub-vendor, Hamburg Vacuum, KRAL nor the project partner CSTechcom could make this method work for the new spindle design with variable pitch and noncylindrical diameter.

The problems were due to the inclination of the bottom of the groove and the complicated geometry of the sides of the groove. The inclination of the bottom is due to the contour of the outer diameter and would in any case require shifts between specially made machining tools along the length of the spindle.

During this investigation, a simplified conical spindle design was introduced as shown in Figure 18, where the idea was to keep the slope of the bottom of the grooves constant and, thus, simplify the cutting and the cutting tools for that part of the spindles. Yet, it took too much processor time for the lathe rotational speed to become high enough for the spindles to be manufactured.

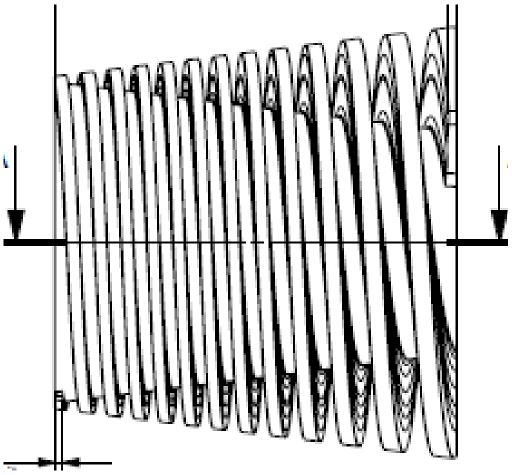

Figure 18: The simplified conical shaped spindle design, still with variable pitch.

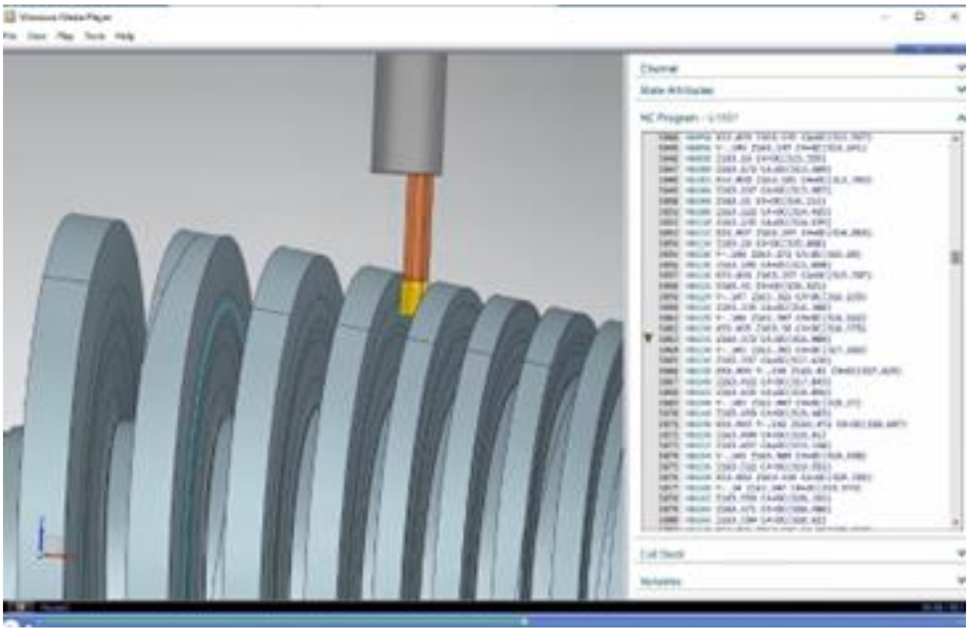

Figure 19: The video snapshot shows the processing of the data points
for the manufacturing on the lathe.

Finally, the project partner CSTechcom managed to manufacture the spindles on a 5-axis machining center, see Figure 21. The 5-axis method is more involving and resource intensive, but the additional cost is only a minor addition to the total cost of the compressor. The advantage of the 5-axia method is its flexibility. It can manufacture the more complicated, ideal shape of the spindles just as well as the simplified, conical method.

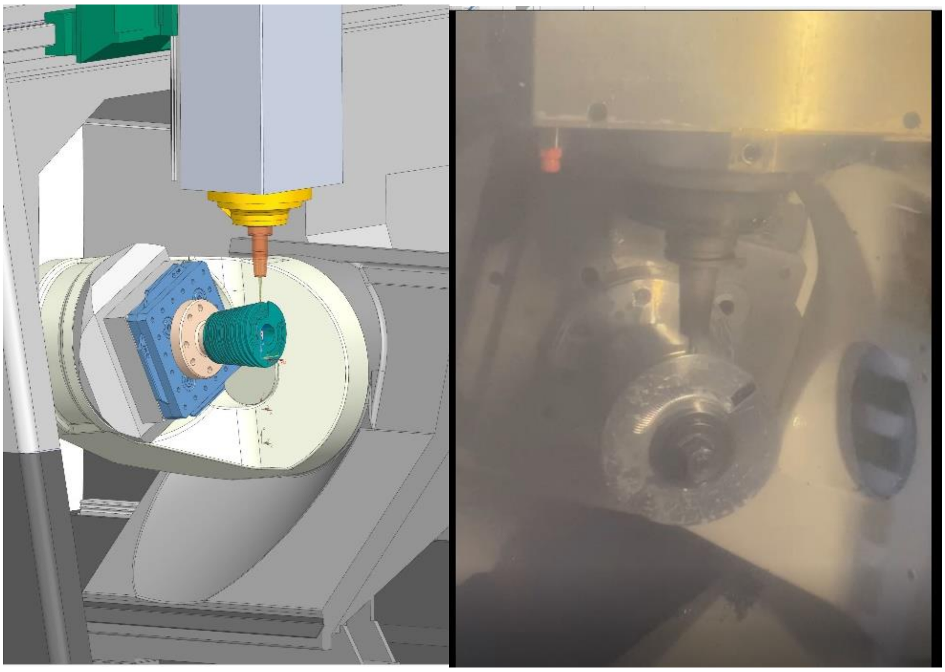

Figure 20: Programming and manufacturing the spindles by 5-axis machining.

Figure 21: The conical spindles manufactured by 5-axis machining at CS Techcom.

It was necessary to design and manufacture an insert to the KRAL housing that corresponded to the shape of the new spindles. Such a horizontal separated insert has the same conical bore as the outer diameter of the spindles and the right shaft distance - and the precise axial position of the conical bores as well. The insert was produced by CSTechcom by 5-axis machining.

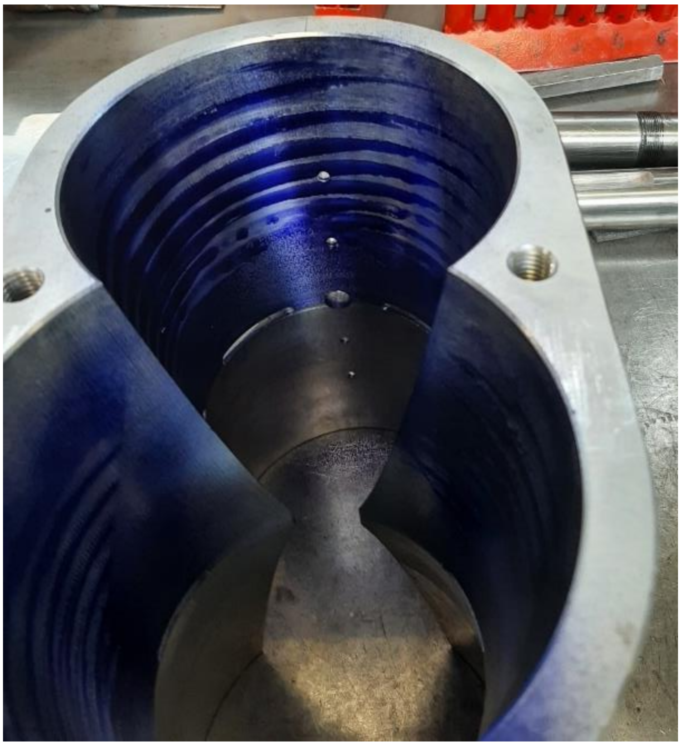

Figure 22: The conical bore inside the housing insert, painted to check the gap to the spindles

10. Water injection

The purpose of the planned water injection is twofold; to limit the discharge temperature and to seal the spindles and housing to reduce the backflow and improve the compression efficiency.

Compression of steam with high-temperature lift and, thus, a high pressure ratio results in a very high discharge temperature. For example, the compression from 105°C to 230°C with an efficiency of 70% will theoretically lead to a discharge temperature of as much as 660°C. This temperature level will be difficult to handle, both in terms of material selection and in terms of design for thermal expansion.

The water injection will help bring the discharge temperature much closer to the saturation temperature of the condensing pressure by evaporating parts of the injected water and, thereby, cooling the steam during the compression. It is expected that the cooling of the gas is so efficient that the difference between the superheated steam and the saturation temperature is in the order of magnitude of 10°C, and this will be one of the important measurements of the test.

It should also be mentioned that the amount of injected water used to cool the gas is expected to correspond to about 25% to 30% of the evaporator mass flow depending on the efficiency of the compressor and the compressor speed.

The water injection on the prototype compressor takes place at two locations during compression through holes in the compressor housing. The compression process with water injection is illustrated in Figure 23, and it shows that the compression generally takes place in the two-phase area. The model calculations also illustrate that the control of the water injection will be an especially important part of the control of the compressor performance and operation.

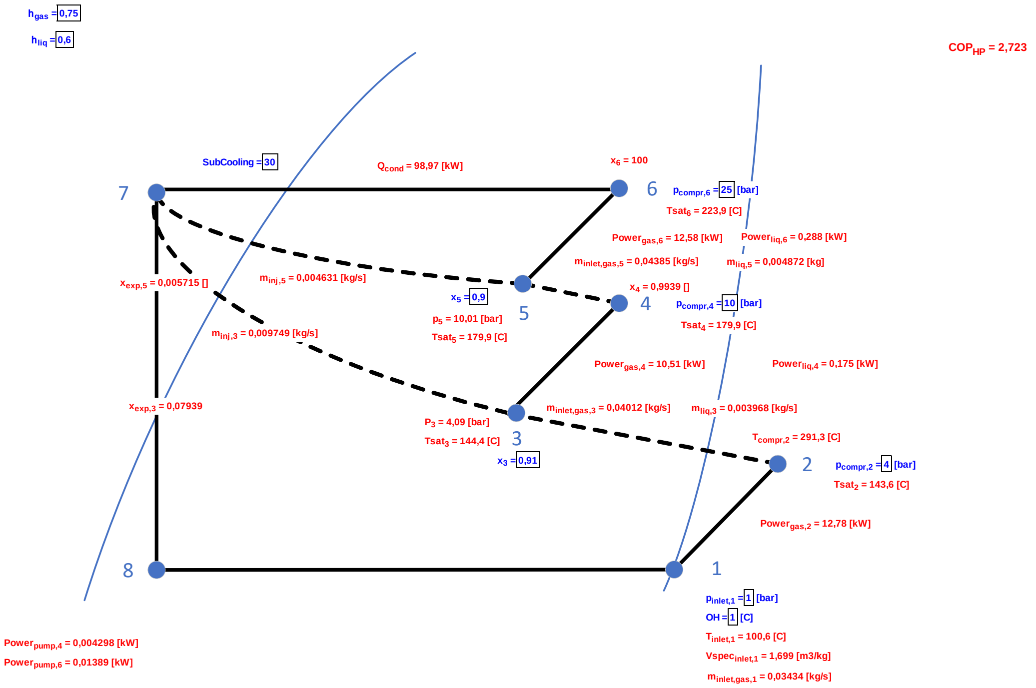

Figure 23: Simplified model of compression with water injection at two locations.

The two spindles are designed to run without contact with a small tolerance between the spindles and the housing and between the various spindle surfaces and spindle foot to outer diameter of the spindle as illustrated in Figure 24. The tolerances can allow for a quite significant backflow of steam, a rough estimate with 0.1 mm tolerance and sonic flow results in about 20% of the total flow. This has consequences for both the capacity of the compressor and the efficiency, both will be reduced by this factor.

The water injection will mitigate this backflow and, thus, improve the compressor performance. The presence of water will introduce some friction loss between the rotating spindles and the stationary housing. The surface speed of the spindles is in the order of 40 m/s at design speed 8000 rpm, and a rough estimate shows 2 to 3 kW loss if the clearance is filled with water, i.e., in the order of 5 % of the total power consumption.

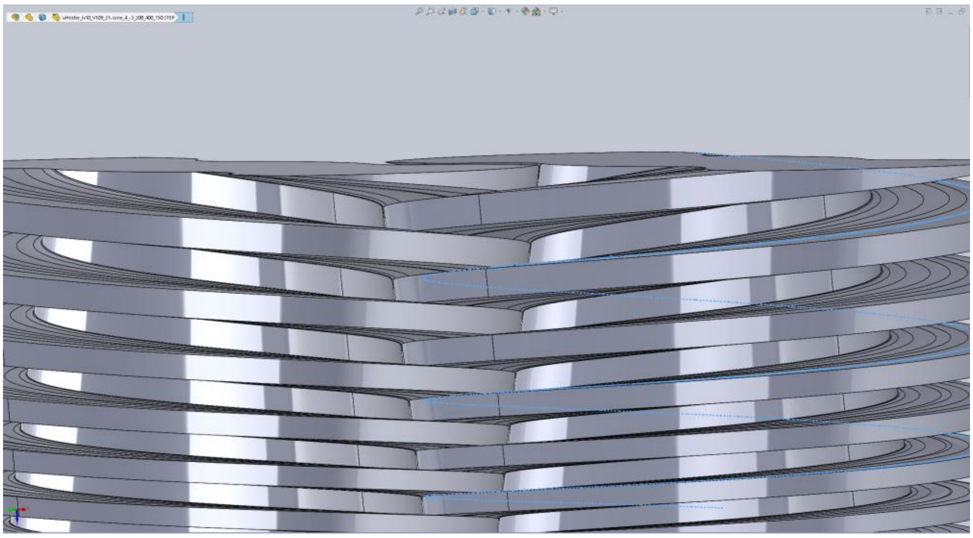

Figure 24: The figure shows the surfaces between the two spindles that must be sealed by water to mitigate backflow.

11. Assembling

The assembly of the compressor is complicated and challenging due to the geometry and the mutual requirements for exact arrangement of spindles, bearings, gears, inserts, etc. It is especially these three things that set the requirements:

- Variable pitch for each of the four spindles
- Double flooding, i.e., suction at both ends
- Double conical design which makes tolerance measurements difficult.

First, the axial position of the two spindles on each shaft must be set as this defines how they engage with each other while meeting the spacing requirements for the mechanical seals, bearings, and gears. Next, the distance to the spindle belonging to the second, symmetrical inlet at the same shaft is set with the help of a spacer, after which the last two spindles can be assembled.

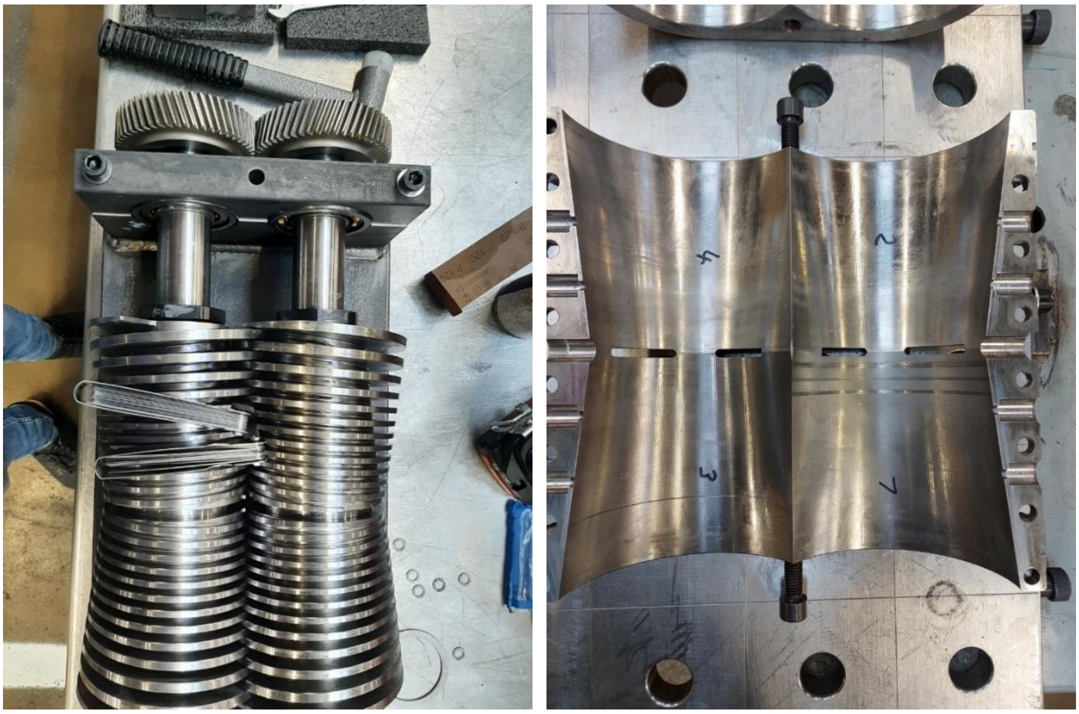

Figure 25: Setting the gap between the spindles to adjust the gears for synchronous rotation (left), one half of the housing insert with water injection ports for left and right spindle assembly (right).

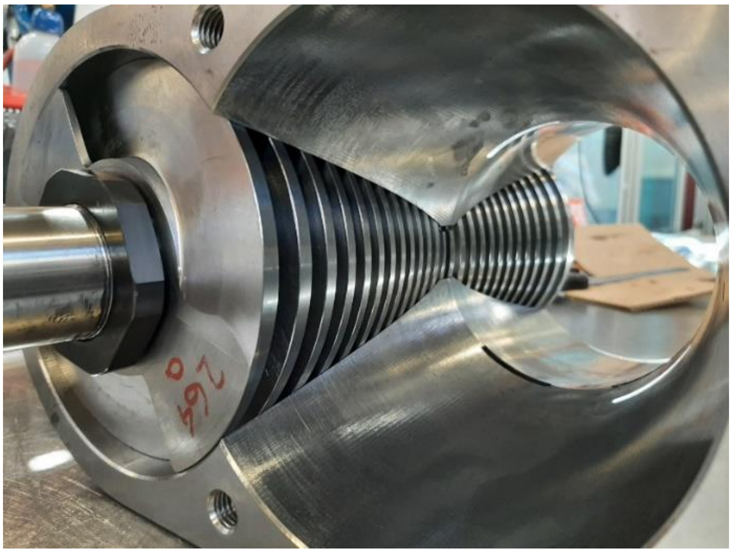

Figure 26: Testing position of one shaft spindle inside the housing insert.

The two shafts have very high requirements for parallelism. At the same time, the radial distance must be set exactly so that the spindles seal against each other, see Figure 25 left. All these measurements and distances must be reflected in the design of the inserts in the housing, both the axial and the radial distances, as this influences the clearance between the spindles and the compressor housing (insert), see Figure 25 right.

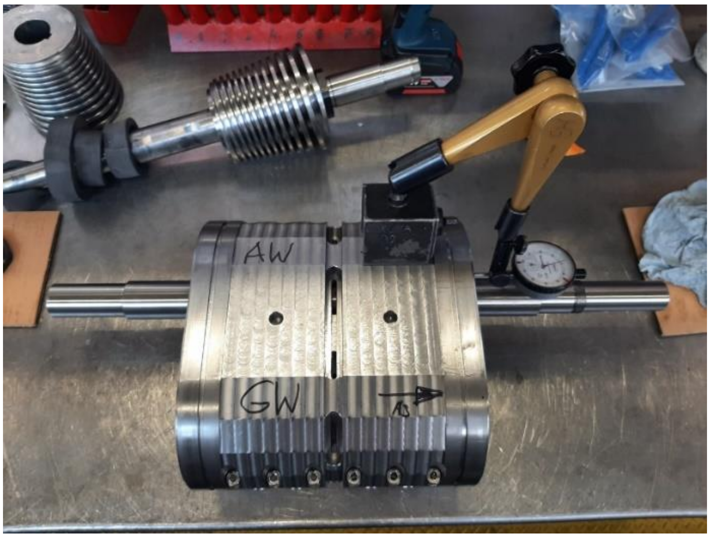

Figure 27: Finding the axial position of the shaft inside the housing insert
to set the gaps housing insert to the outer diameter of the spindles.

Figure 26 and igure 27 show how the axial position of the spindles are set in relation to the housing insert to place it symmetrically and to determine the clearance between the spindles and the housing.

Figure 28: One shaft on the balancing test bench.

Due to the design speed of 8000 rpm, there are high requirements to the balancing of the rotating parts, Figure 28 shows how one of the rotors is balanced after assembling the two spindles on the shaft.

Using the basic KRAL pump design means that there is no way to check the gaps in the assembled compressor by a feeler gauge. So, all positions must be measured first, and spacers/adapters for the right position were designed, manufactured, and build into the compressor.

The gaps between the spindles are designed to around 0.2 mm, but they had to be re-cut twice during the assembling process. This means disassembling all parts and re-cutting the spindles at CSTechcom in Denmark, each time with a 0.1 mm expansion of the gaps in order to get some space in-between to find a possible assembling all over.

12. Test at high-temperature test rig

Senius (formerly Flexmatic) has a test section of the tunnel oven energy section at its disposal where continuous development measures can be made. This applies to both test baking of new products for customers as well as improvements and changes to the construction of the tunnel ovens energy section itself.

Thus, experiments can be carried out with the air distribution on the product belt as well as the air circulation for the entire section, including the heating of the air. Traditionally, this is done by gas firing where a heat exchanger heats the air.

It was the idea that this test tunnel oven could be converted to heat pump operation and could serve as a test rig for the newly developed spindle compressor.

In heat pump operation, the heat exchanger at the top of the section should be replaced with a condenser for the heat pump, i.e., the energy is transferred to the heating of the air by condensation of steam in the heat exchanger. For practical reasons, it was better to design the top of the section with three separate condensers to maintain the overall geometry of the upper part of the section.

Figure 29 shows the PI diagram for the test rig that was planned in connection with the existing test tunnel oven. The tunnel oven is shown to the right in the diagram and the three heat exchangers (condensers) in the upper part of the diagram.

The condensate is collected from the three condensers and led to a steam trap where the pressure is reduced to the evaporation pressure (about 100°C in this case) and subsequently led back to the separator tank shown to the left in the diagram along with the flash gas generated by the expansion.

From the top of this separator tank, the compressor (shown in the middle of the diagram) sucks the steam and compresses it to the condenser pressure in the line to the condensers.

To reduce the complexity of the test and the number of unknowns, an electric heater was planned as the heat source. This solution is for test purposes only; it will be relatively simple to connect a flooded evaporator to the separator tank as the next development step in the process integration. The test rig is planned with thorough instrumentation to retrieve information about the operating conditions and the compressor performance.

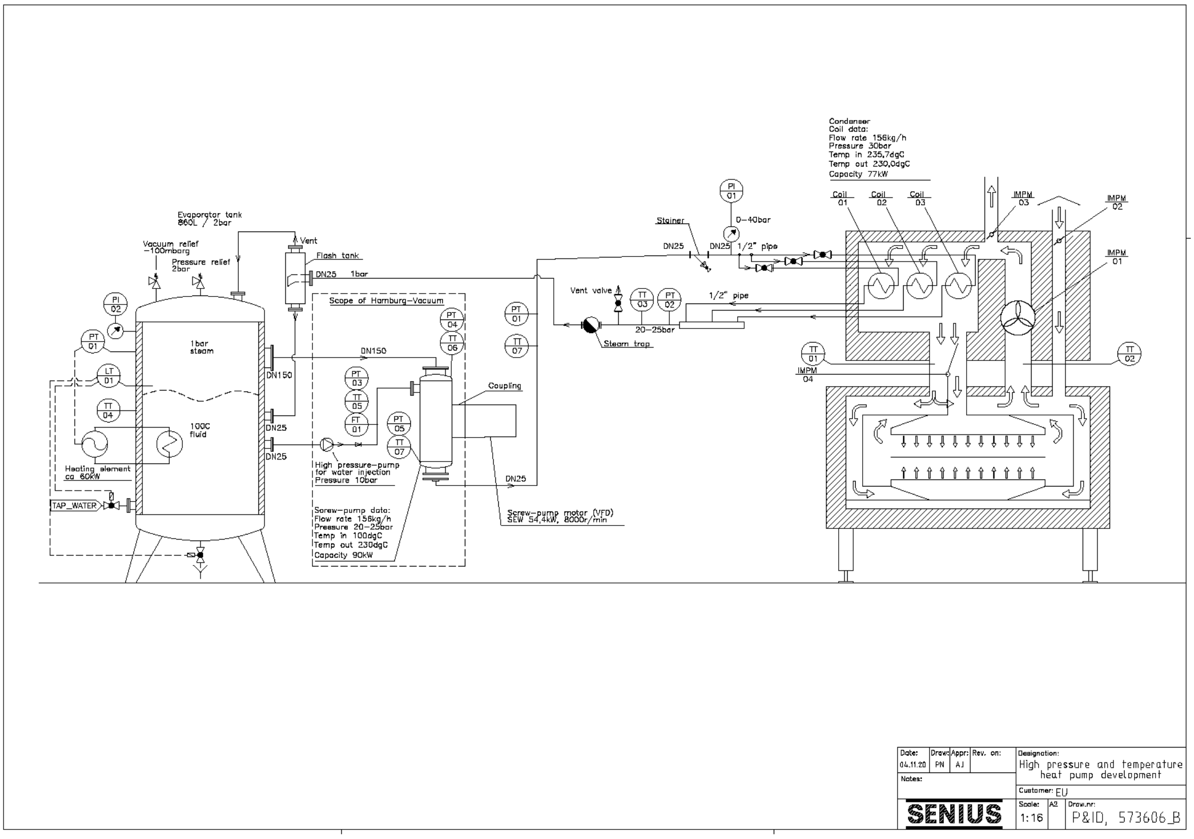

Figure 29: Original test rig PI Diagram from Flexmatic/Senius.

Unfortunately, the test rig was not fully realized due to the delay and uncertainty regarding the timing of the assembling of the compressor. As the test tunnel oven was used for other tests, it was necessary to keep the traditional gas-fired heat source until the compressor was ready. It was estimated that the rebuilding of the test oven required 4-6 weeks were , and finally this timing became critical in relation to the time limit of the project. However, much useful knowledge and design work have been obtained so that the heat pump can be integrated when it is developed with a better performance. Among other things, extensive component studies and specifications have been made as well as calculations and studies of how the heat pump can be installed and how heat sources can be identified in different operating conditions for various products.

An alternative to building the test rig at Senius emerged during the spring of 2022 as a steam test rig was established at Danish Technological Institute in connection with another high temperature heat pump project. Due to the very tight schedule that the project ended up with, it was decided to try to carry out the test on this test rig as it was faster to rebuild and connect the compressor here, even if it gave certain other limitations to the operating conditions.

The test rig at Danish Technological Institute differs from the Senius test rig in that the condensation energy is fed back to the evaporator and, thus, serves as the heat source. Therefore, there is no need for an external heat source. It is a pure compressor test stand. The PI diagram for the test rig is shown in Figure 30 where the spindle compressor is shown at the top left of the diagram in parallel with another compressor, a turbo compressor, which was also tested on the test rig. The steam pipes are shown in yellow and the liquid pipes in green. The cooling of the evaporator water is shown in blue while the water injection nozzle for the spindle compressor is shown in red. The evaporator serves as a separator tank and holds approximately 1 m^3 of water (liquid) which is circulated by the pump GP1.

On the pressure side of the compressor, the steam can either be led to the condenser or directly back to the evaporator via a bypass. In both cases, the condensing energy is returned to the evaporator.

The temperature in the evaporator is controlled by a regulation loop that is connected to either the district heating or the cooling towers (as shown in figure 30). The district heating can be used to heat the water in the evaporator to a desired starting temperature of up to approx. 80°C.

When connected to cooling towers, the water temperature in the evaporator can be maintained at a desired level of up to approx. 120°C. Since the input engine power is transferred to the steam, it is necessary to cool this capacity to maintain a constant temperature of the liquid in the evaporator.

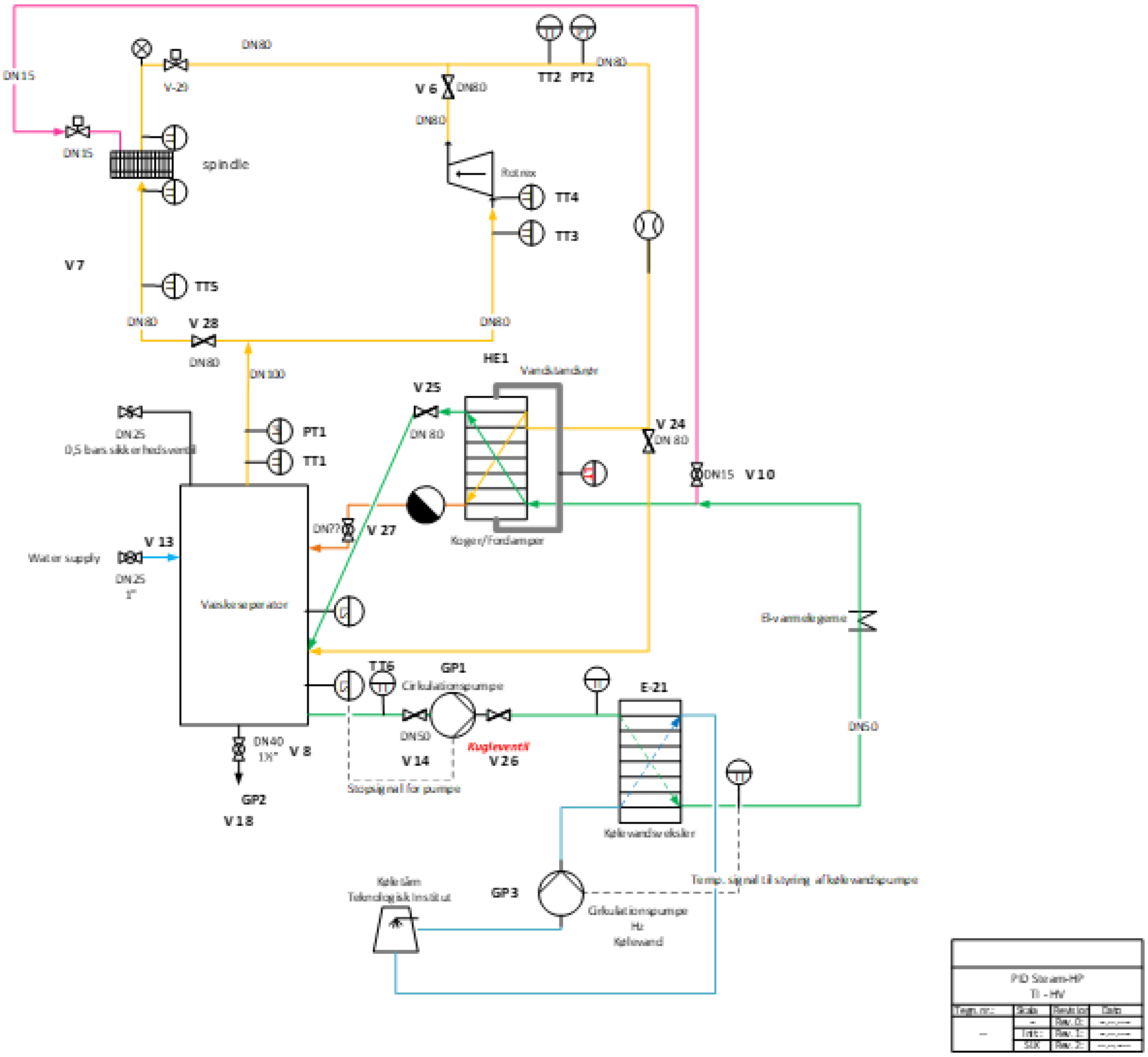

Figure 30: The steam test rig at Danish Technological Institute with the uHeater spindle compressor installed.

13. Initial test results

Upon arrival at Danish Technological Institute, the water injection system and the oil lubrication system were installed by Hamburg Vacuum, see figure 31. When ready, the compressor was electrically connected to the power net via the frequency converter, and the very first testing of the compressor running in open air took place.

These tests revealed the need to improve the oil return system or the oil level indicator. The tests in open air were performed at speeds up to 40 Hz (2400 rpm), where the uHeater was running neither with significant vibrations nor sound. The overall finish is already on a serial level like a liquid pump.

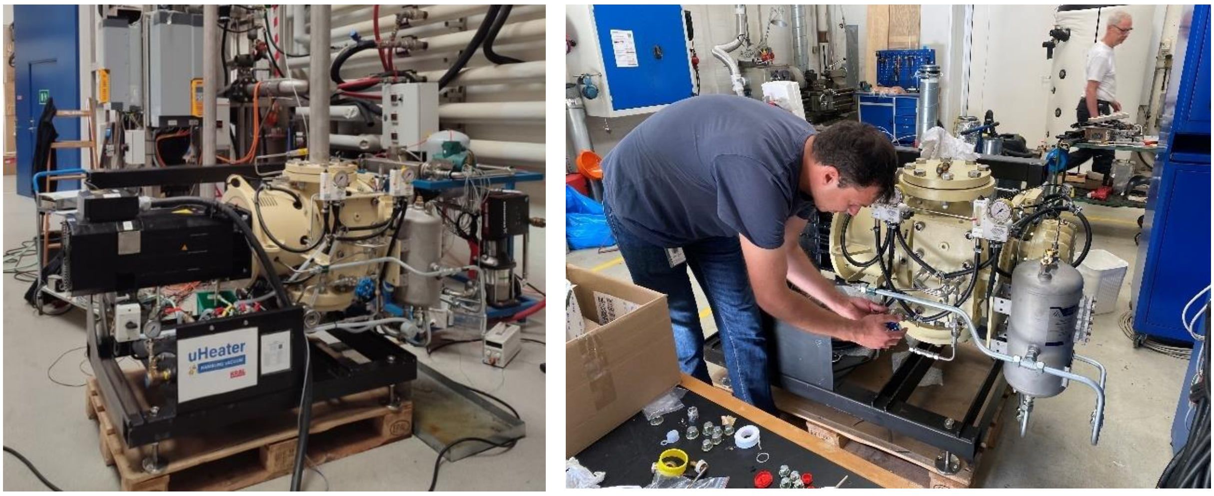

Figure 31: uHeater installation of water injection system and electrically connected to the steam test rig at Danish Technological Institute.

14. Performance test results

The performance tests took place over a period of one and a half week after the installation of the compressor at the test rig, and the first initial shake down, including the improved oil system. The evaporator was heated by the district heating system to approximately 70°C, and the intention was to remove the remaining air in the system to the environment via an open valve V25 by means of the compressor as it has been the case with the previous test with the turbo compressor. In all the runs, the by-pass valve V24 was closed.

Figure 32: Installation of the uHeater at the test rig at Danish Technological Institute.

Unfortunately, the compressor did not provide sufficient pressure ratio or volume flow to evacuate the test rig system, so all the tests of the compressor were performed with a mixture of air and steam at the partial pressure corresponding to the water temperature in the evaporator. At 70°C, the saturation pressure is roughly 0.3 bar. Thus, the gas is a mixture of approximately 30% steam and 70% air. In order to evacuate the air, the compressor has to lower the inlet pressure to 0.3 bar with a pressure ratio of slightly more than 3.

Figure 33 shows the pressure level at the inlet and exit of the compressor as the speed was gradually increased from 1500 rpm to 6600 rpm, and the water injection was on with a tap water pressure of 2–3 bar. The inlet pressure is far from the required 0.3 bar and, thus, the capability to evacuate the test rig for air.

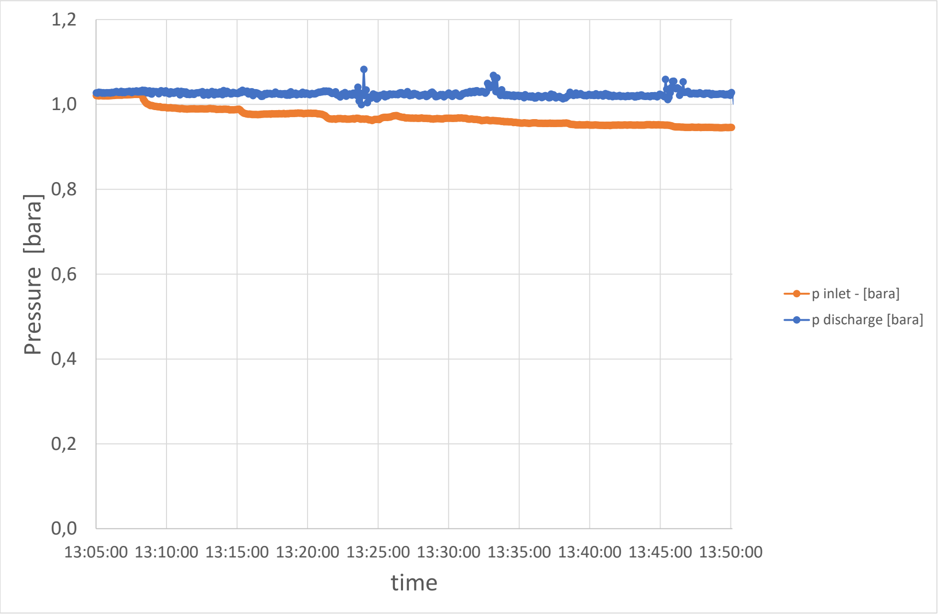

Figure 33: Inlet and exit compressor pressure at increasing speed (1500 to 6000 rpm).

The corresponding calculation of the achieved pressure ratio is shown in Error! Reference source not found.. This is far from the expected pressure ratio for the compressor.

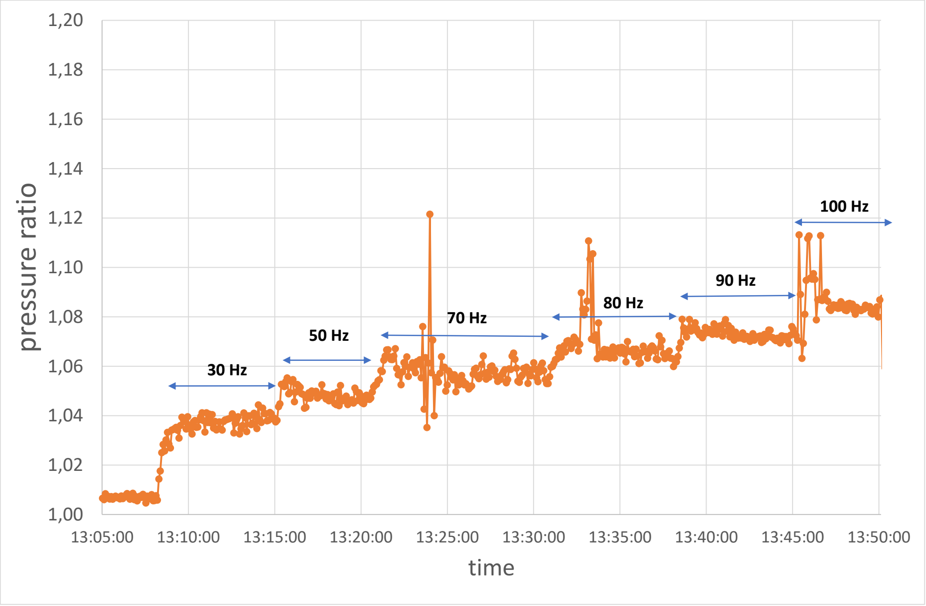

Figure 34: The corresponding pressure ratio.

All the tests were performed at the temperatures shown in Figure 35. The blue line is the water temperature in the evaporator as heated by the district heating system. The inlet temperature (yellow) is somewhat higher indicating some recirculation and heating of the air at the compressor inlet. The outlet temperature (grey) is dominated by the temperature of the inlet tap water for the water injection, approximately 15°C, but this gradually increases as the spindles warms up.

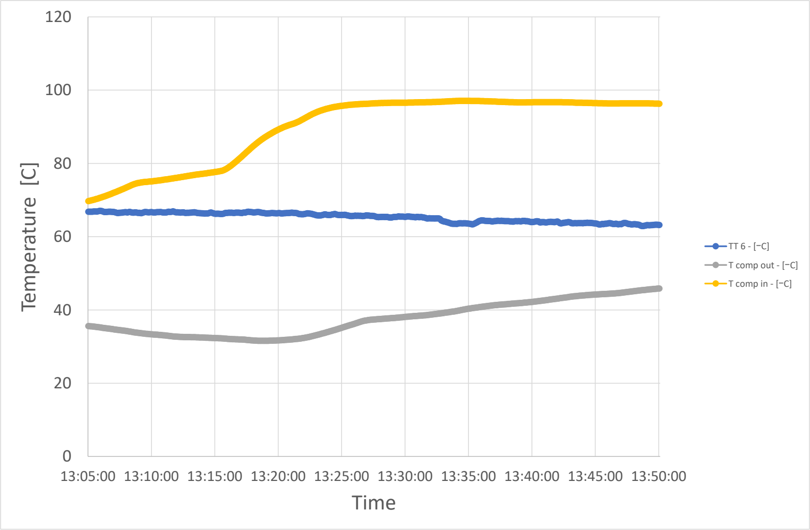

Figure 35: Temperature of evaporator (blue), compressor inlet (yellow), and discharge (grey).

The next test was to investigate the ultimate suction pressure if the compressor was operated as a vacuum pump, i.e., to run with the inlet valve V28 closed. The results of this test are shown in Error! Reference source not found. and Figure 37. In all cases, the rotational speed was 100 Hz (6000 rpm). The ultimate pressure in the dry running operation proved to be approximately 0.85 bar which is unexpected compared to the suction level of the SiHi vacuum pump that formed the inspiration for the compressor. However, as soon as the water injection was turned on, the pressure decreased rapidly to approximately 0.43 bar with tap water system pressure (2-3 bar estimated) and down to approximately 0.33 bar with the water pump tuned on which could deliver a pressure of 6 bar. The corresponding pressure ratios are 1.2 (dry running), 2.4 for tap water inlet water pressure and, finally, 3.0 for the water pump operation.

The compressor was also operated in reverse direction, and as it turned out with much better results. In the dry running mode, the results were the same as the results for forward rotation, essentially no volume flow and no pressure ratio.

However, a fast increase of pressure in the suction line was observed in connection with water injection – which in reverse rotation changes to the discharge port – already at 20 Hz and tap water supply pressure. An example of the operation at 25 Hz with closed valve V25 is shown in Figure 38.

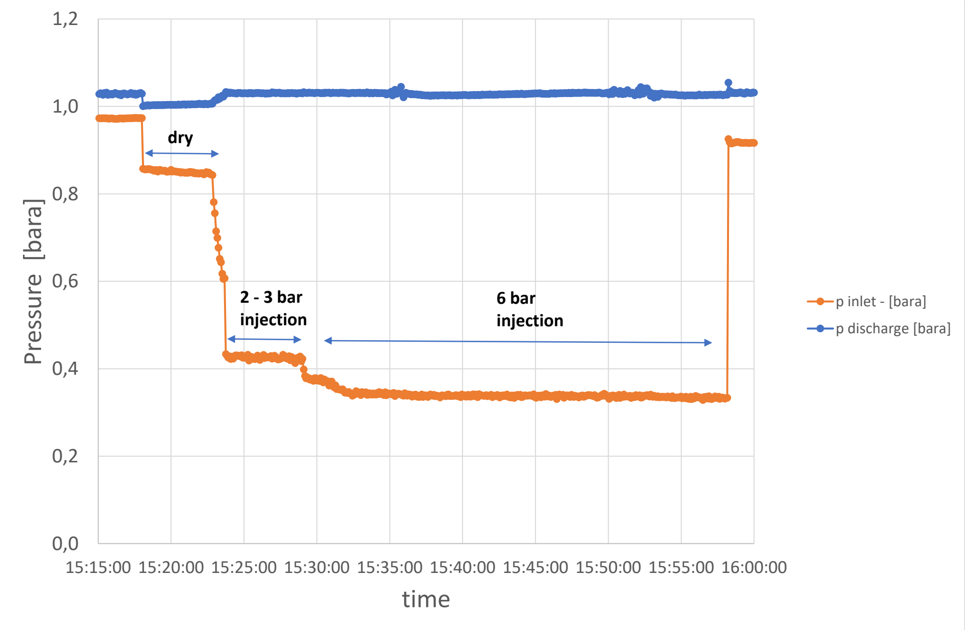

Figure 36: Pressure at inlet and exit of compressor for closed suction valve (zero volume flow).

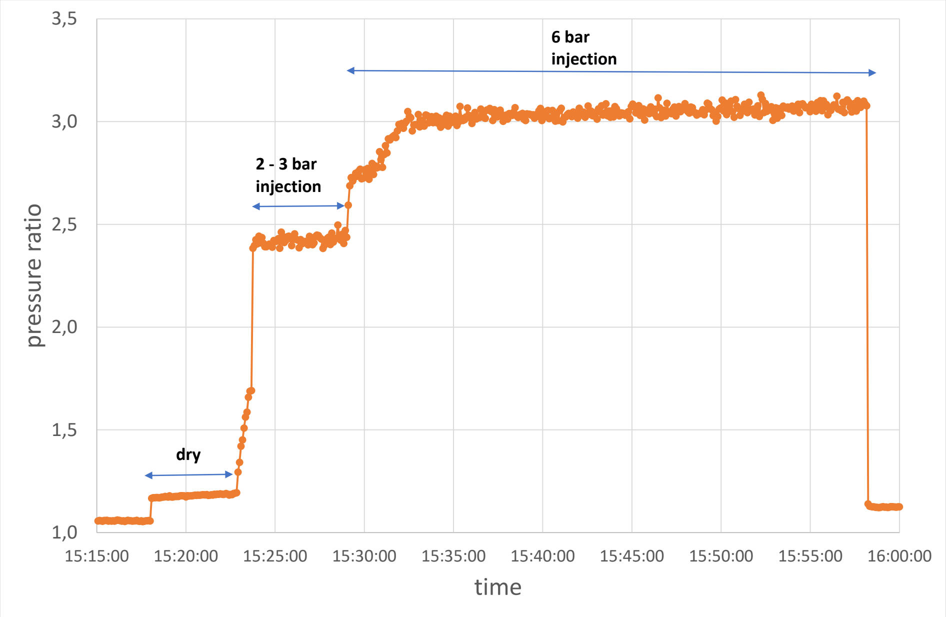

Figure 37: The corresponding pressure ratio for dry running and water injection with two different supply pressures.

The volume of the five meter long DN80 piping is approximately 0.088 m^3 and as the time difference between data points is five seconds, the compressor volume flow can be calculated to approx. 25 m^3/s. This is more than would be expected at 25 Hz for the inlet area at the end of the spindles (the small diameter). The interpretation of the data is that there is still a leakage flow at the lower diameters, and it is not until some of the middle windings that the water is able to seal sufficiently for a pressure to build up in the compressor.

In any case, the test shows that it is possible to establish sealing, but due to the limitations on the test rig inlet line, it is not possible to measure the ultimate pressure ratio at these conditions.

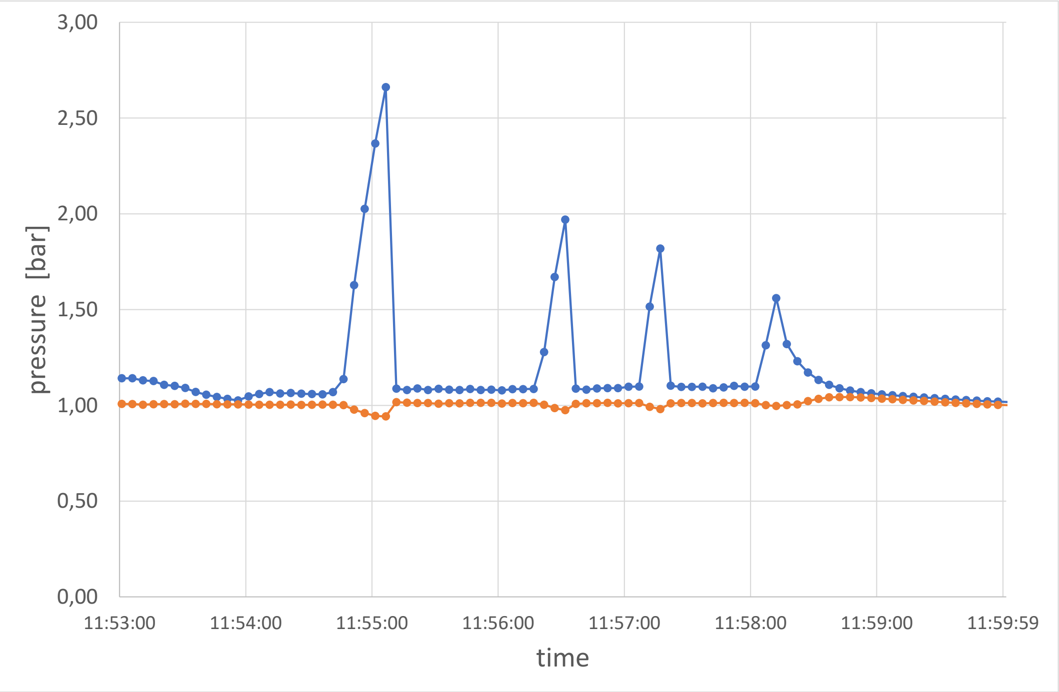

Figure 38: Pressure at reverse operation and built-up pressure by closing V28 in short periods (15 – 25 seconds). The last peak shows internal leak test with stopped compressor and closed inlet.

The internal leak rate for the compressor was evaluated, and it may include some contribution from the test rig valves etc. The test is shown in Figure 38 at the time 11:59. Here, it is seen that during testing at the maximum pressure (1.56 bar), the valve at the compressor discharge (V28) is closed and that the compressor operation has stopped. During the stand-still, the pressure is equalized to the conditions at the compressor suction side (V29 is open). The period is approximately 45 seconds corresponding to a leak rate at 4 m^3/s.

Another way of testing the performance of the compressor at reverse operation – and apparently better sealing – is to close the V29 valve in the discharge line. In reverse operation, this line serves at the inlet, and it is possible to test the ultimate pressure at vacuum conditions when the valve is closed.

The results for operating at 20 Hz with water supply from the tap water system are shown in Figure 39. The ultimate pressure is in the order of 0.05 bar and, thus, a pressure ratio of more than 1:20 as shown in Figure 40.

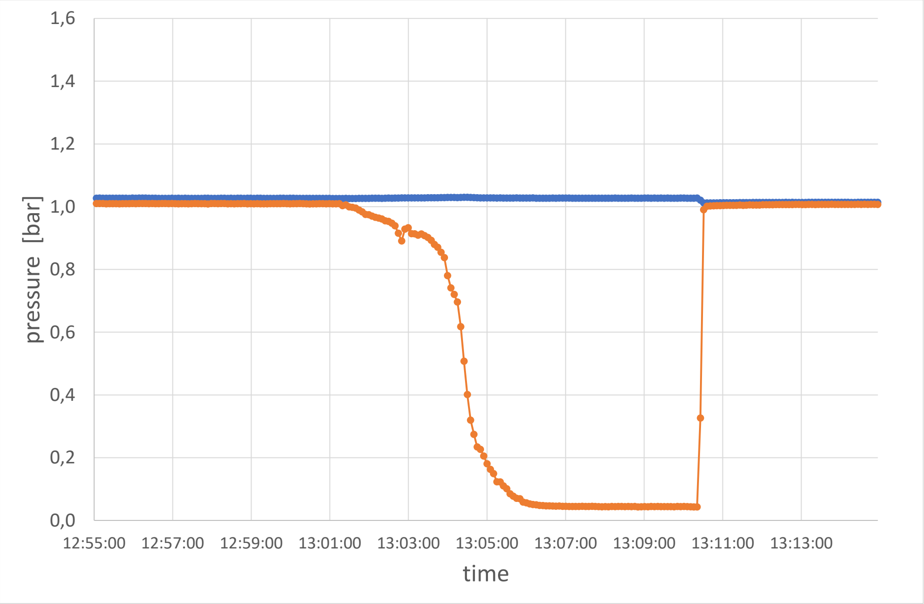

Figure 39: Pressure at inlet (orange) and exit (blue) at reverse operation at 20 Hz and water injection.

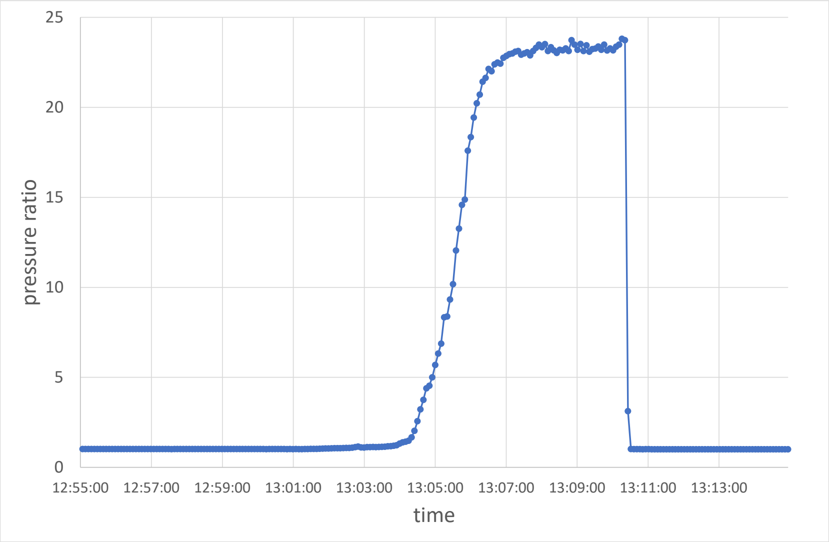

Figure 40: Pressure ratio at reverse operation and closed V29 (suction line).

The power consumption of the compressor, see Figure 41, was observed during the operation under various conditions, and it tends to depend on the square of the speed as expected for losses in the bearings and water lubricated mechanical seals. There is a difference of 1–2 kW in case of various forms of water injection, but the level is far from the expected level of 45-50 kW at full speed – which supports the impression of a very limited mass flow and compression of the gas.

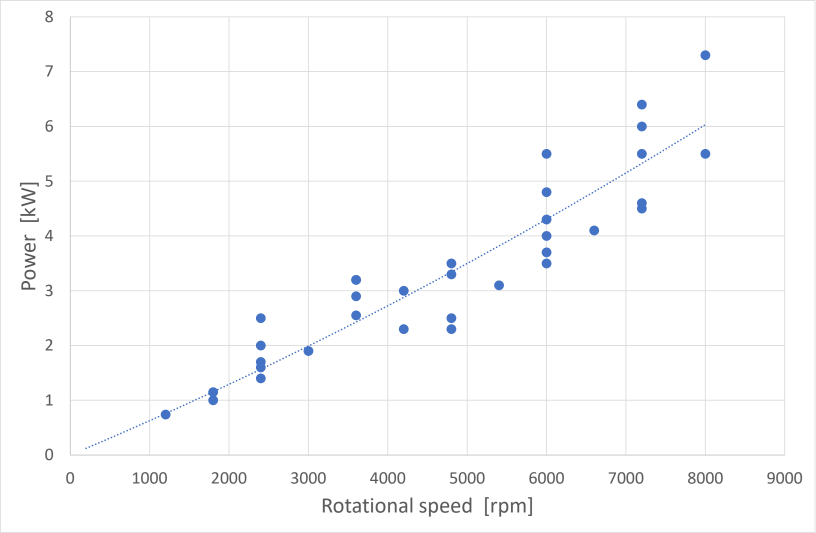

Figure 41: Power consumption vs rotational speed.

15. Conclusion

The test of the compressor can be summarized as follows:

- Mechanically, the compressor works fine. The vibration level and the noise level are both low. Everything is rotating in the right direction, and spindles, gears, and coupling are in correct positions and work properly. The seals work fine, the oil level is rather easy to control, and the oil cooling works fine. The water injection as a system works fine. There are no shortcuts, lack of flow, etc. A flow meter would be a good addition though. The mechanical loss is in the order of 6 kW at full speed.

- In the dry running mode, it was a surprise that there was no performance at all. No volume flow and no pressure ratio independent of either ‘forward’ rotation or ‘reverse’ operation. It is a surprise in that it differs from the SIHIdry vacuum pump with the same level of tolerances and distance between the spindles and the housing. This was also the case after heating the spindles to at least 75°C. It has not been possible to double check the spindle-housing clearance.

- With water injection, the performance in ‘reverse’ direction showed significant volume flow. The pressure in the suction line increased rapidly up to 2 bar even at 20 Hz operation (3 bar in a single case) and was confirmed several times. The water was able to seal the clearances after 1-2 minutes of operation. In the ‘forward’ direction, the performance was still the same as for the dry running case; no volume flow and no pressure except for closed valves operation.

The next step is to double check all clearances and to analyze why the water film sealed in reverse direction but not in forward direction – and to see if it is related to clearance, pressure differences, geometry, injection location and type, or something else.

It might simply be a question of clearance or tolerances, or it might be a more complicated adjustment with a new spindle design and/or a modified water injection design.

16. Perspectives and next steps

The need for a heat pump like this is even more pronounced at the time of writing this report than when the project was initiated, and the compressor might be very close to an operating prototype for the first customers.

Since the project started, there has been an increased acceptance internationally, that the heat pumps with supply temperatures in the range up to 200 – 250°C are desirable and competitive compared to the alternatives such as direct electrical heating and biofuels by proper process integration.

There is also an acceptance, that steam or water vapor is expected to be the preferred media at least for the supply temperature range 150 – 250°C.

There are customers for the uHeater compressor who would want it as soon as possible The special situation concerning natural gas as a consequence of the Russian invasion of Ukraine has further actualized the need for transformation from gas heating to heat pumps, so there is a large market for the heat pump when it is fully developed, in Denmark alone, market studies performed for an EUDP application have shown a need for more than two hundred heat pumps per year only for one application.

There is ongoing negotiations among the three manufacturers concerning cooperation and further development of the spindle concept compressors.

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