# Final report

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*The guidance text (in italic) should be deleted, so the application form **only** contains numbered headings as well as relevant text from the applicant.*

## 1. Project details

| | |
|---|---|
| **Project title** | SpeedUp |
| **File no.** | 64020-1021 |
| **Name of the funding scheme** | Energieffektivitet |
| **Project managing company / institution** | Weel & Sandvig |
| **CVR number** (central business register) | 27255817 |
| **Project partners** | Ecergy AB, DTU-MEKANIK |
| **Submission date** | 13 March 2023 |

## 2. Summary

### 2.1 In English

The overall goal of the project is to develop an economically attractive heat pump for efficient electrification of the industry's energy consumption with a view to reducing the emission of greenhouse gases. The primary market segment is heat pumping in the temperature range 80 to 200˚C and in the heat output range ½-5 MW with unit sizes of heat pumps in the range ½-1 MW heat.

The project partner Ecergy has developed a prototype unit (full scale) of a high speed motor directly coupled to a turbo compressor. The unit was first tested in air, where challenges with vibrations and rotor dynamics caused delays in the project. Different solutions were tested and through experience gained here, this challenge was finally handled in a satisfactory manner.

The unit was then thoroughly tested with water vapor as the working medium in a test rig built for the purpose. The compressor performances (flow at varying pressure conditions), efficiencies and various losses in auxiliary equipment are either measured or calculated. The experiments have shown stable operation with high efficiency, which is very promising for the future perspective of the technology and the prototype device.

The successful development and testing means that we are now preparing the next phase towards market maturation of the technology through an industrial demonstration, also on a full scale. In fact we have already received a commitment from an industrial host willing to participate in a full scale industrial long term demonstration project.

## 2.2 In Danish

Projektets overordnede mål er at udvikle en økonomisk attraktiv varmepumpe til effektiv elektrificering af industriens energiforbrug med henblik på at nedbringe udledningen af drivhusgasser. Markedssegmentet er varmepumpning i temperaturområdet 80 til 200˚C og i varmeeffektområdet ½-5 MW med enhedsstørrelser på varmepumper i området ½-1 MW varme.

I projektet er udviklet en prototype-enhed (i fuld skala) af en højhastighedsmotor direkte sammenkoblet med en turbokompressor. Enheden er først testet i luft, hvor udfordringer med vibrationer og rotordynamik gav anledning til forsinkelser i projektet. Forskellige løsninger blev afprøvet og med erfaringer opnået herigennem er denne udfordring hånteret på tilfredstillende måde.

Enheden er derefter grundigt testet med vanddamp som arbejdsmedium i en testrig opbygget til formålet. I riggen er målt kompressorydelser (flow ved varierende trykforhold), virkningsgrader og beregning af diverse tab i hjælpeudstyr. Forsøgene har vist stabil drift med høj effektivitet, som er lovende for det fremtidige perspektiv for teknologien.

Den successfulde udvikling og afprøvning betyder er vi nu er i gang med at forberede næste fase frem mod markedsmodning af prototypen gennem en industriel demonstration. Vi har således fået tilsagn fra en industriel partner, som har givet tilsagn til at deltage i et projekt (forudsat at der opnås finansiel støtte) hvor planen at teknologien skal igennem industriel langtidsdemonstration i fuldskala.

# 3. Project objectives

The objective is to develop a cost effective and efficient high temperature heat pump suited for implementation in industrial processes. The purpose of the heat pump is to upgrade excess heat available in certain processes for substituting existing steam generation based on combustion of fuels in traditional boilers with related CO2 emission. The heat pump is powered by a high speed electrical motor, where related emission of green house gases in the electricity consumption is already very low and expected still decreasing.

The technology is based on combining a very high speed electrical drive (motor and frequency converter) in a direct coupling with a small turbo compressor in order to achieve a suitable and cheap steam compressor unit for compressing steam (clean water vapour) in a capacity range that fits with the demand and temperature requirements in many industrial sites.

A full scale steam compressor unit of this most advantageous technology has been developed and demonstrated successfullly in the project in a specially developed test rig installed at DTU lab. facility.

In order to achieve a suitable and efficient turbo compressor for the targeted capacity and temperature levels the rotations speed needs to be higher than 50000 rpm. The electric motor has a power capacity of 110 kW at 70000 rpm. This is close to the technical limits (see Figure 1).

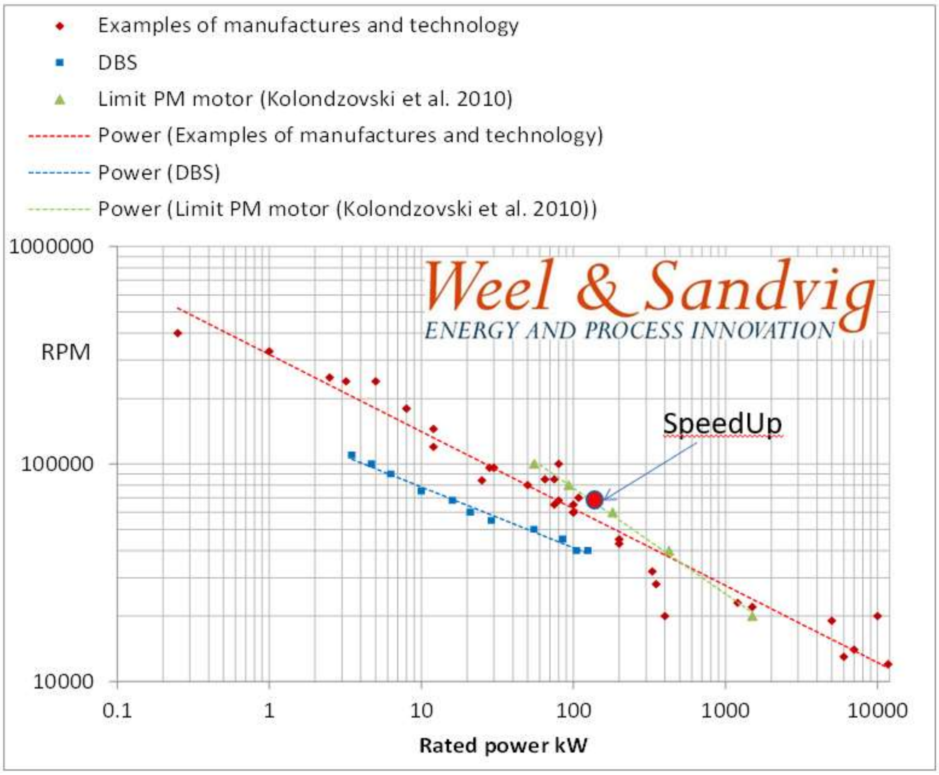



Figure 1. Relation between shaft power and maximum speed for electric motors.

# 4. Project implementation

The development of the prototype unit began with extensive investigation of the design and performance evaluation of a high speed turbo compressor unit combined with a high speed rotor design and sealing system.

Performance of the compressor operating in steam is investigated by Weel & Sandvig and MEK, DTU (Brice, post doc) by use of CFD-modeling and simulation. Brice used The “Frozen rotor” method combined with exploiting axial symmetries (impeller is with splitter meaning two channels are included) was used for reducing the size of the model. ANSYS CFX was chosen for the study due to its high performances in turbomachinery applications.

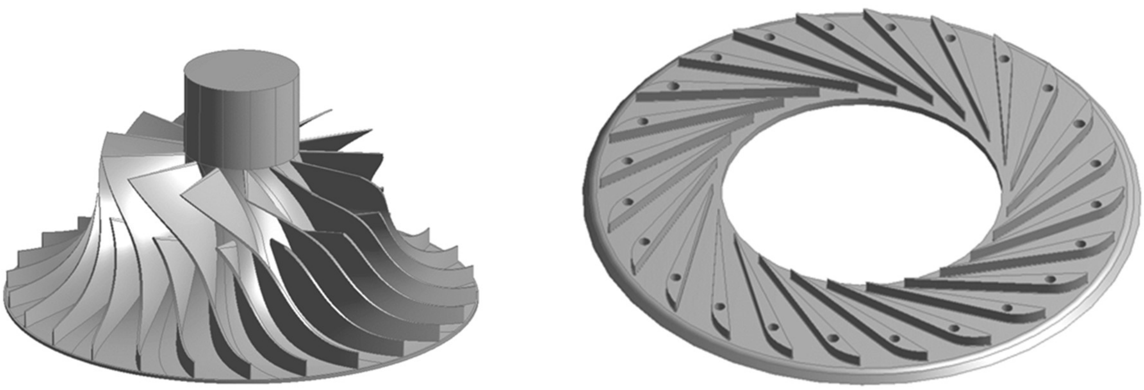
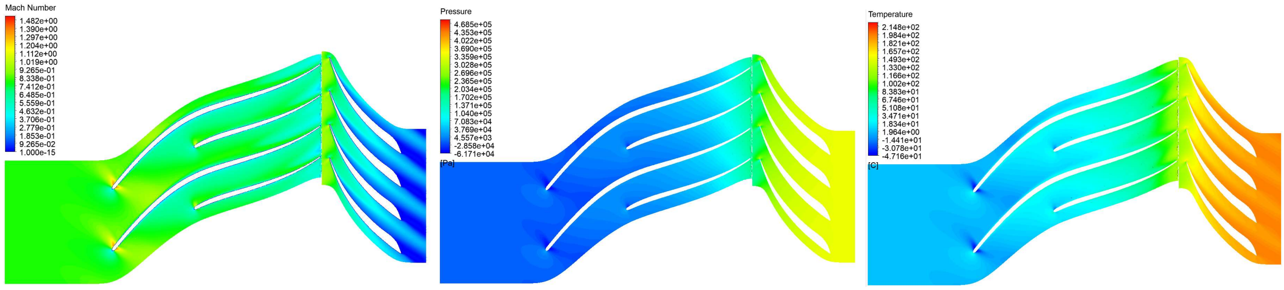
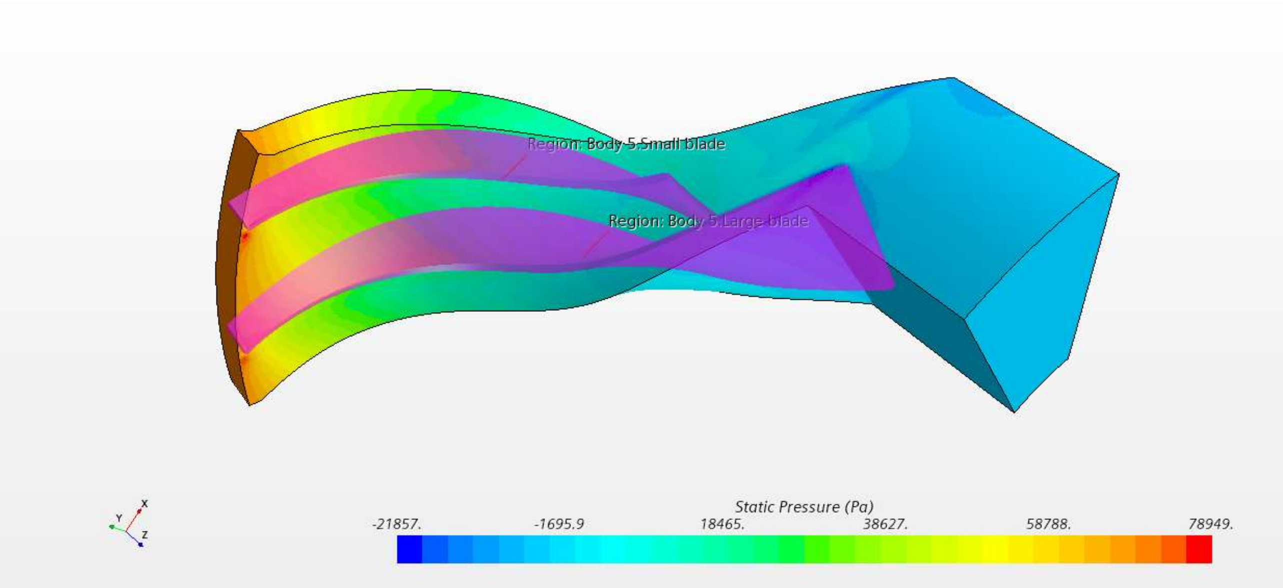


Figure 2. 3-D model of the impeller (left) and the diffuser (right).




(a) Mach number (b) Static pressure (c) Static temperature

Figure 3. Compressor performance (Ansys CFX in air) for ω=66500 RPM, PR=4.35, $\dot{m}$=0.856 and η=0.850, Span=0.5.




Figur 1 3-D view of static gauge pressure though impeller segment with steam at. 70000 RPM. Impeller static outlet pressure =0.7 barg and total pressure = 1.48 barg (inlet total pressure 0 barg and 388 K).

Extensive and numerous investigations and modifications of rotor design was applied before suitable rotor dynamics, vibrations levels and restricted speed range due to critical speed was achieved. This part of the project was more tedious and time consuming than expected. Though, due to our experiences achieved, we expect that possible limitations on other future rotor designs for specific applications (capacity, temperature levels and temperature lifts) will not be a major problem or imply serious limitations concerning operational range and restrictions related to critical speed ranges.

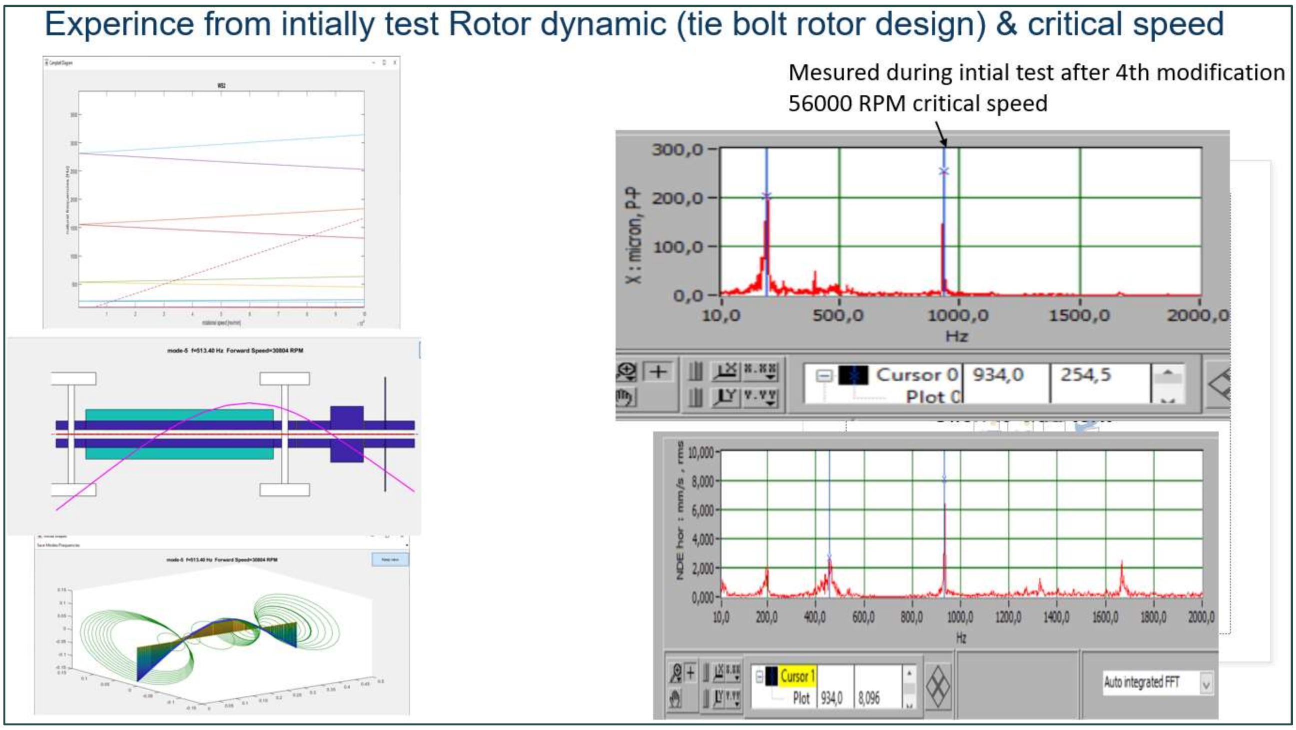



Figure 4. Left: Analysis of rotor dynamics. Right: Vibration analysis applied by Colding A/S.

In parallel to the development of the steam compressor a test rig suitable of testing and measuring performance of the compressor operating in steam was designed and erected in a lab facillity at DTU.

The compressor unit has been tested in numerous operating points in steam and the performance has been measured.

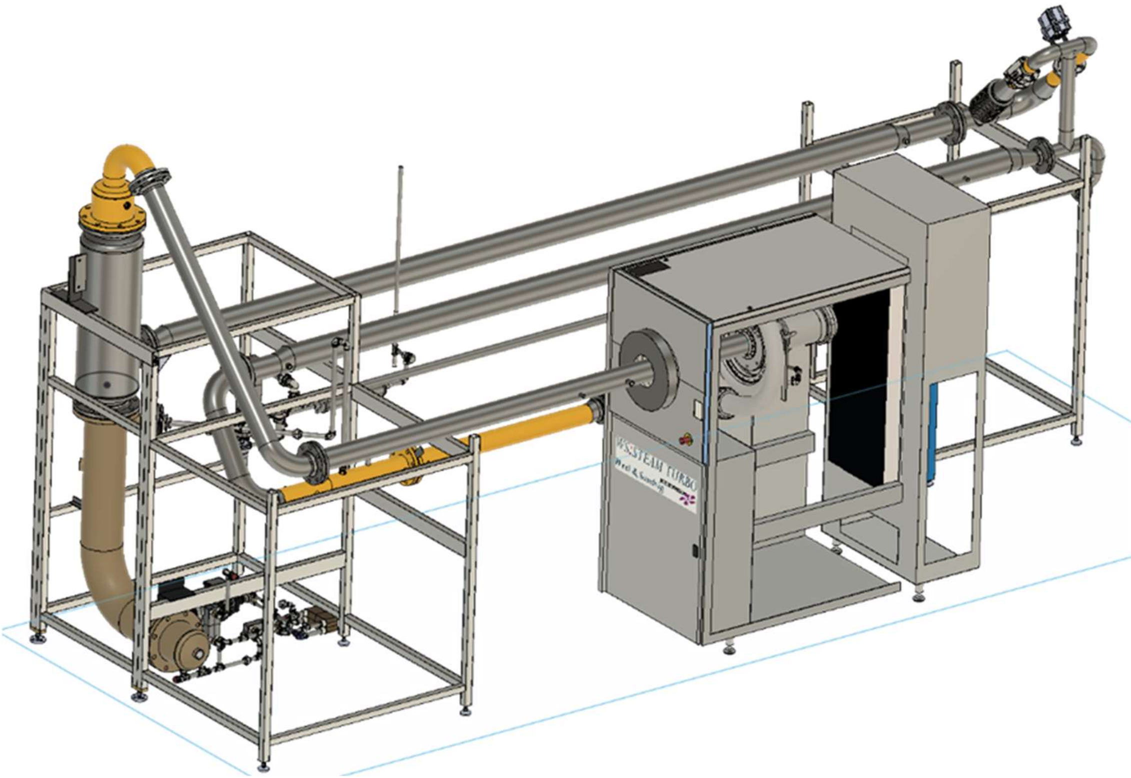


Figure 5. Design of test rig (Weel & Sandvig).


Figure 6. Left: Test rig and compressor unit as built and installed at DTU lab. Lower right: turbo compressor impeller (outer diameter 142 mm) capable of delivering 1 MW condensing heat at 133 C with a temperature lift of 25 C at a rotational speed of 70000 rpm. Upper right: For comparison of impeller size: the size of a normal beverage can.

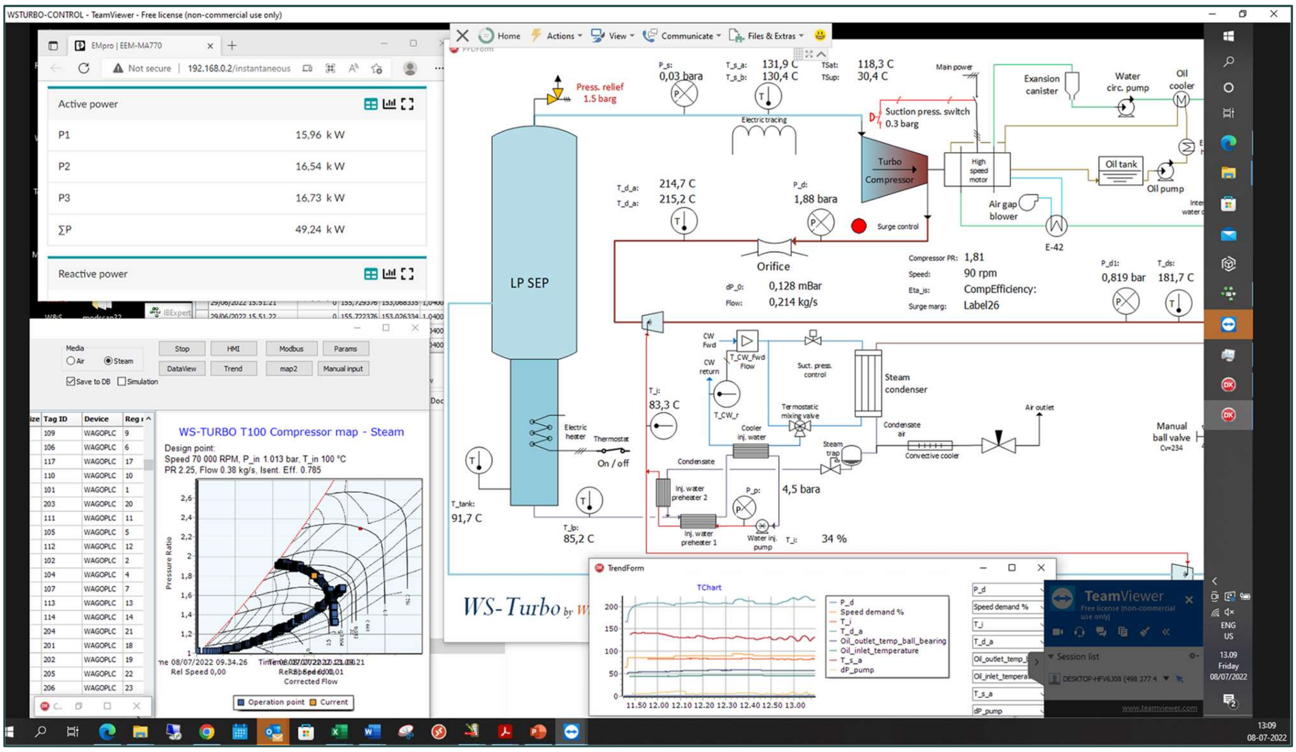



Figure 7. Screen from performance and data aquisition system (WS-Turbo).

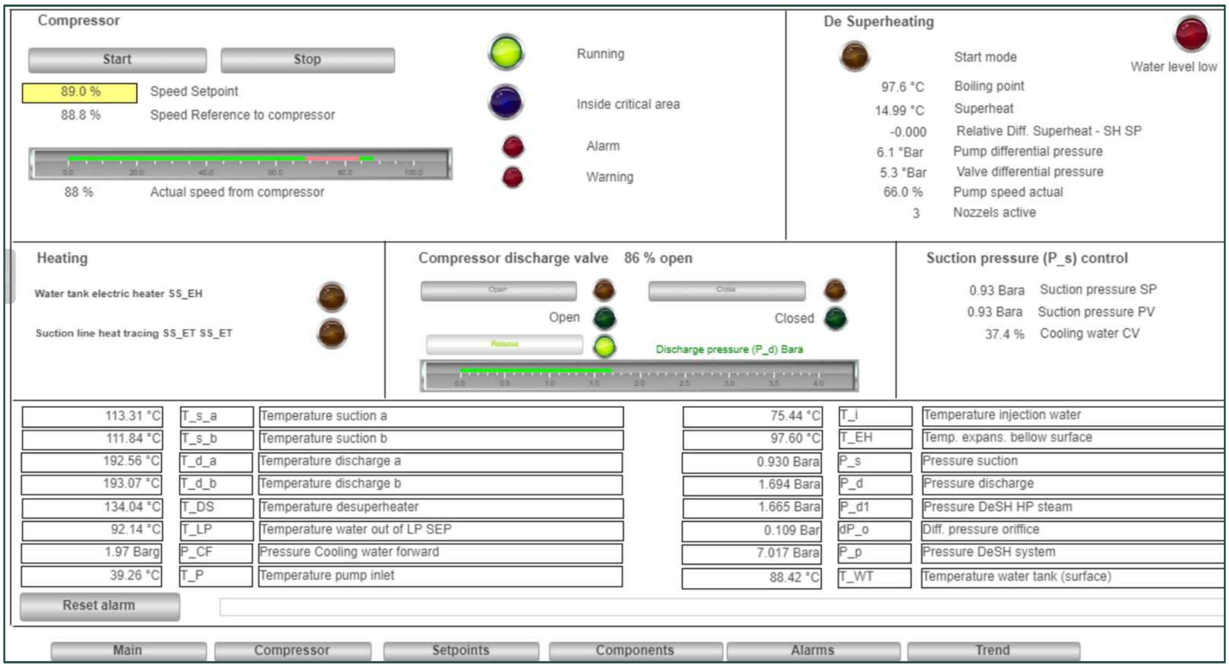



Figure 8. “Main” screen of the test rig control system.

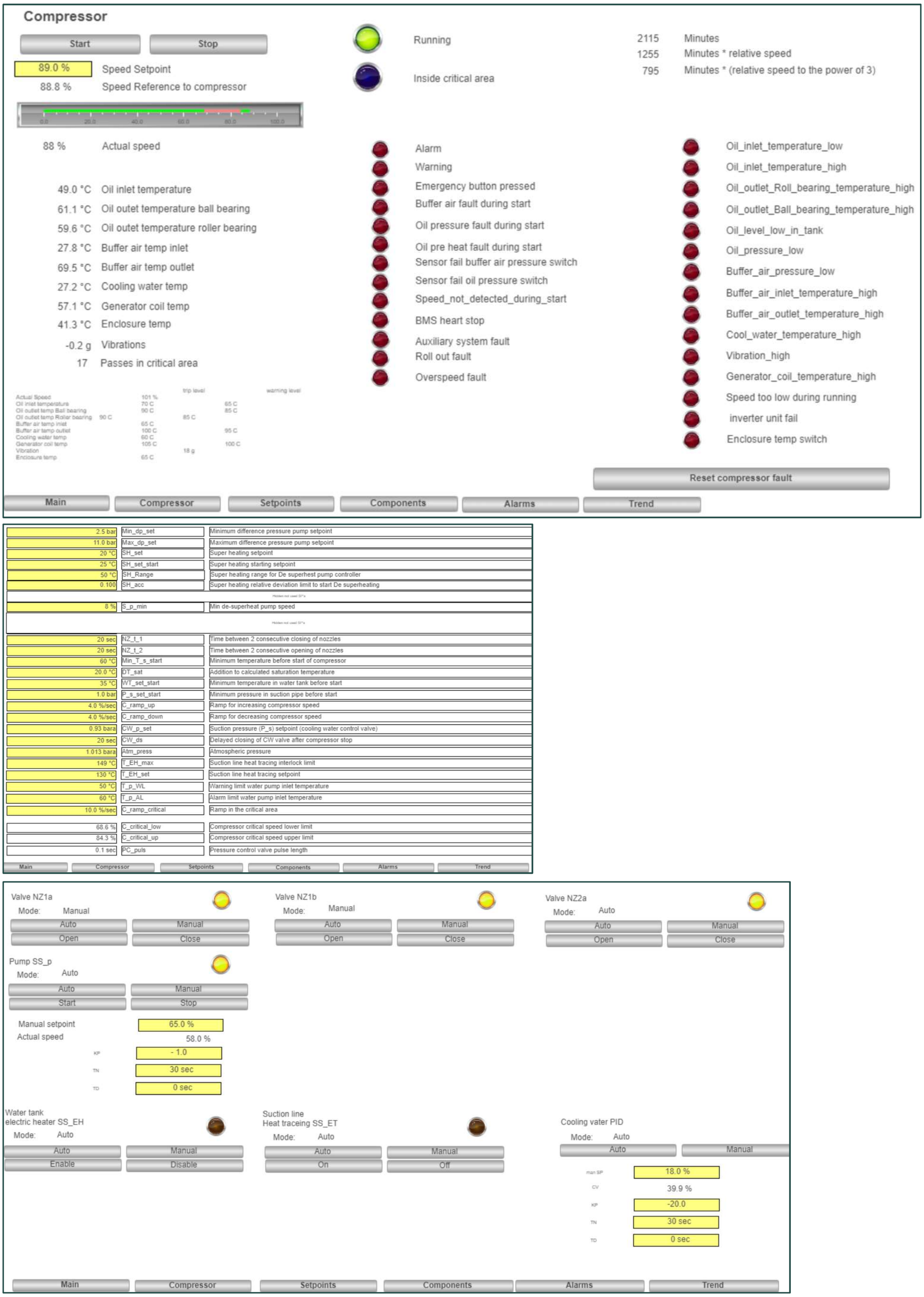



Figure 9. Other screens from the test rig control system.

# 5. Project results

The original objective of the project is obtained. We have applied numerous test of the compressor unit compressing steam in a test rig constructed in the project. Performance measurements of the compressor unit and quantification of power and heat losses related to the utility system in terms of oil, water and buffer air systems have been conducted.

The results show a bit lower efficiency than expected, which among others may be related to larger clearances between impeller and compressor shroud than designed for and strictly necessary. During the testing phase in critical speed range possibly there has been more situations with rubs. Also, the impeller has been balanced several times, including removing smaller parts of some impeller blades at the inlet.

| | | | | | | | | | IF97 | | Gas constant R | 461.5 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Time | Speed | T_s_avg | T_d_avg | P_s_avg | P_d_avg | PR_avg | dp_o | T_s_sat | T_d_sat | h_s | S_s | h_is_d | h_d_sat | h_d |
| | | % | ˚C | ˚C | bara | bara | | bar | ˚C | ˚C | kJ/kg | kJ/kgC | kJ/kg | kJ/kg | kJ/kg |
| 1 | 06/10/2022 10.02.30 | 0.598 | 113.1 | 154.7 | 0.932 | 1.282 | 1.376 | 0.055 | 97.65 | 106.70 | 2703.4 | 7.466 | 2761.7 | 447.4 | 2784.0 |
| 2 | 06/10/2022 10.40.30 | 0.878 | 112.0 | 190.6 | 0.910 | 1.640 | 1.802 | 0.103 | 96.99 | 114.05 | 2701.4 | 7.472 | 2812.6 | 478.5 | 2853.7 |
| 3 | 06/10/2022 11.06.30 | 0.940 | 112.0 | 203.3 | 0.910 | 1.792 | 1.969 | 0.119 | 96.99 | 116.77 | 2701.4 | 7.472 | 2830.7 | 490.1 | 2878.3 |
| 4 | 06/10/2022 11.28.30 | 0.940 | 111.9 | 205.7 | 0.910 | 1.832 | 2.014 | 0.102 | 96.99 | 117.46 | 2701.1 | 7.471 | 2835.0 | 493.0 | 2883.1 |
| 5 | 06/10/2022 11.52.30 | 0.940 | 112.1 | 211.2 | 0.910 | 1.877 | 2.063 | 0.071 | 97.00 | 118.22 | 2701.6 | 7.472 | 2840.5 | 496.2 | 2893.7 |
| 6 | 06/10/2022 12.09.30 | 0.940 | 112.1 | 216.1 | 0.911 | 1.886 | 2.071 | 0.050 | 97.02 | 118.37 | 2701.6 | 7.472 | 2841.3 | 496.9 | 2903.6 |
| 7 | 06/10/2022 12.37.30 | 0.940 | 111.0 | 202.9 | 0.880 | 1.729 | 1.965 | 0.119 | 96.07 | 115.67 | 2699.7 | 7.483 | 2828.2 | 485.4 | 2877.9 |
| 8 | 06/10/2022 12.58.30 | 0.940 | 115.7 | 207.3 | 0.930 | 1.832 | 1.970 | 0.127 | 97.59 | 117.46 | 2708.7 | 7.480 | 2839.2 | 493.0 | 2886.1 |
| 9 | 06/10/2022 13.12.30 | 0.940 | 114.4 | 204.5 | 0.930 | 1.793 | 1.929 | 0.141 | 97.58 | 116.80 | 2706.1 | 7.474 | 2831.9 | 490.2 | 2880.9 |
| 10 | 06/10/2022 13.18.30 | 0.940 | 115.4 | 204.1 | 0.931 | 1.744 | 1.873 | 0.156 | 97.62 | 115.93 | 2708.0 | 7.478 | 2828.1 | 486.5 | 2880.3 |
| 11 | 06/10/2022 13.29.30 | 0.940 | 116.0 | 203.0 | 0.930 | 1.647 | 1.771 | 0.178 | 97.59 | 114.17 | 2709.3 | 7.482 | 2818.0 | 479.0 | 2878.5 |
| 12 | 06/10/2022 13.42.30 | 0.940 | 115.0 | 201.7 | 0.932 | 1.649 | 1.770 | 0.180 | 97.64 | 114.21 | 2707.1 | 7.476 | 2815.5 | 479.2 | 2875.9 |
| 13 | 06/10/2022 14.17.30 | 0.940 | 112.0 | 205.6 | 0.910 | 1.820 | 1.999 | 0.109 | 96.99 | 117.25 | 2701.4 | 7.471 | 2833.8 | 492.1 | 2882.9 |
| 14 | 06/10/2022 09.48.00 | 0.598 | 116.9 | 156.5 | 0.947 | 1.212 | 1.279 | 0.087 | 98.10 | 105.06 | 2710.8 | 7.477 | 2755.9 | 440.5 | 2788.1 |
| 15 | 06/10/2022 10.16.30 | 0.598 | 115.2 | 152.4 | 0.969 | 1.298 | 1.340 | 0.050 | 98.73 | 107.07 | 2707.3 | 7.458 | 2760.9 | 448.9 | 2779.1 |
| 16 | 06/10/2022 11.34.30 | 0.940 | 112.1 | 206.6 | 0.910 | 1.843 | 2.025 | 0.098 | 96.99 | 117.65 | 2701.5 | 7.472 | 2836.7 | 493.8 | 2884.9 |
| 17 | 06/10/2022 11.43.30 | 0.940 | 112.0 | 209.0 | 0.910 | 1.867 | 2.051 | 0.081 | 97.00 | 118.05 | 2701.5 | 7.472 | 2839.2 | 495.5 | 2889.4 |
| 18 | 06/10/2022 13.22.45 | 0.940 | 115.9 | 203.7 | 0.930 | 1.700 | 1.827 | 0.167 | 97.60 | 115.15 | 2709.1 | 7.481 | 2824.2 | 483.2 | 2879.7 |

| | | | | | | | | | Heat/Power | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Time | Eta_is | T_lift MVR | **Mass flow** | Gaspower | Q_cond. | COP | COP_gp*T-lift | Q_c/EmPro | COP | Eta |
| | | | ˚C | kg/s | kW | kW | gas power | "˚C" | COP | Carnot | Carnot |
| 1 | 06/10/2022 10.02.30 | 0.724 | 9.1 | 0.140 | 11.29 | 327.1 | 28.98 | 262.4 | | 42.0 | |
| 2 | 06/10/2022 10.40.30 | 0.730 | 17.1 | 0.207 | 31.56 | 492.3 | 15.60 | 266.1 | | 22.7 | |
| 3 | 06/10/2022 11.06.30 | 0.731 | 19.8 | 0.230 | 40.64 | 548.8 | 13.50 | 267.1 | 10.6 | 19.7 | 53.7% |
| 4 | 06/10/2022 11.28.30 | 0.735 | 20.5 | 0.215 | 39.16 | 514.3 | 13.14 | 268.9 | 10.2 | 19.1 | 53.4% |
| 5 | 06/10/2022 11.52.30 | 0.723 | 21.2 | 0.182 | 35.04 | 437.2 | 12.48 | 264.9 | 9.4 | 18.4 | 50.8% |
| 6 | 06/10/2022 12.09.30 | 0.692 | 21.4 | 0.154 | 31.07 | 370.0 | 11.91 | 254.3 | 8.6 | 18.3 | 46.7% |
| 7 | 06/10/2022 12.37.30 | 0.721 | 19.6 | 0.226 | 40.19 | 539.8 | 13.43 | 263.2 | 10.6 | 19.8 | 53.5% |
| 8 | 06/10/2022 12.58.30 | 0.736 | 19.9 | 0.238 | 42.30 | 570.4 | 13.49 | 267.9 | 10.8 | 19.7 | 54.7% |
| 9 | 06/10/2022 13.12.30 | 0.720 | 19.2 | 0.248 | 43.42 | 593.8 | 13.68 | 262.8 | 11.0 | 20.3 | 54.1% |
| 10 | 06/10/2022 13.18.30 | 0.697 | 18.3 | 0.257 | 44.20 | 614.4 | 13.90 | 254.5 | 11.3 | 21.2 | 53.1% |
| 11 | 06/10/2022 13.29.30 | 0.643 | 16.6 | 0.265 | 44.88 | 636.4 | 14.18 | 235.2 | 11.5 | 23.4 | 49.2% |
| 12 | 06/10/2022 13.42.30 | 0.642 | 16.6 | 0.267 | 45.12 | 640.9 | 14.21 | 235.4 | 11.5 | 23.4 | 49.2% |
| 13 | 06/10/2022 14.17.30 | 0.729 | 20.3 | 0.222 | 40.21 | 529.7 | 13.17 | 266.8 | 10.4 | 19.3 | 54.0% |
| 14 | 06/10/2022 09.48.00 | 0.583 | 7.0 | 0.169 | 13.10 | 397.9 | 30.37 | 211.4 | | | |
| 15 | 06/10/2022 10.16.30 | 0.747 | 8.3 | 0.136 | 9.74 | 315.8 | 32.44 | 270.5 | | | |
| 16 | 06/10/2022 11.34.30 | 0.737 | 20.7 | 0.212 | 38.80 | 506.0 | 13.04 | 269.4 | | | |
| 17 | 06/10/2022 11.43.30 | 0.733 | 21.0 | 0.194 | 36.47 | 464.6 | 12.74 | 268.1 | | | |
| 18 | 06/10/2022 13.22.45 | 0.675 | 17.5 | 0.262 | 44.63 | 627.1 | 14.05 | 246.5 | | | |

Figure 10. Performance data of compressor operation (6.th of October 2022).

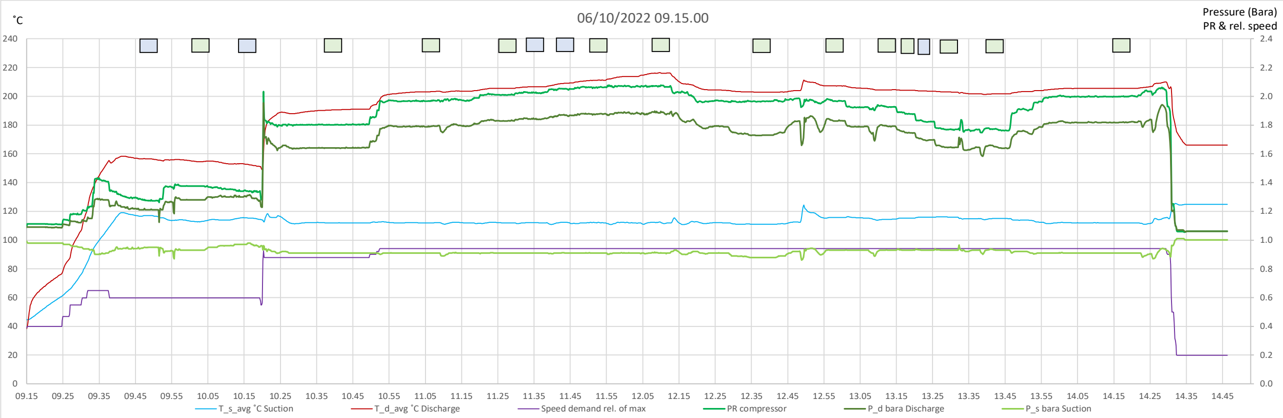



Figure 11. Example of compressor operation during a test (6.th of October 2022).

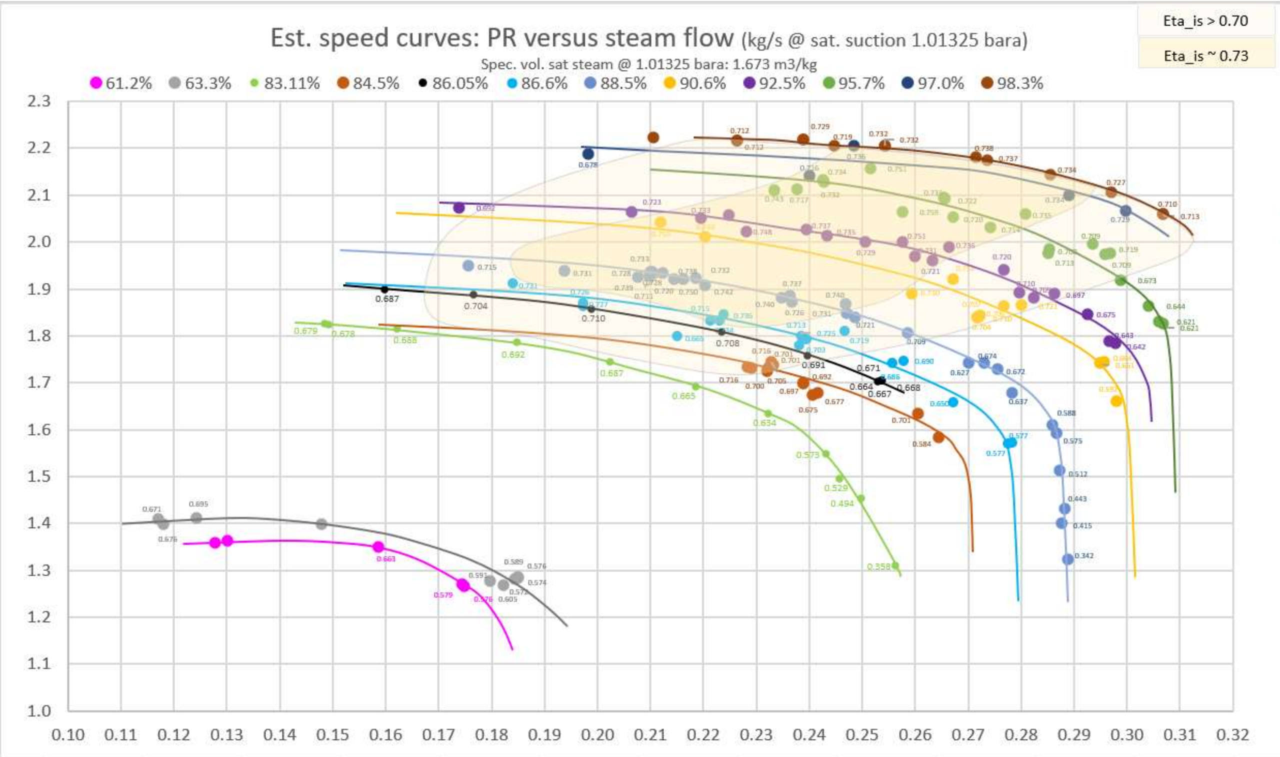



Figure 12. Compressor map based on measured performances in the Weel & Sandvig test rig.

In the project so far the compressor unit have demonstrated:

- About 120 hours of operation with steam.
- Inlet pressure from 0.6 bara to 1.3 bara.
- Steam suction capacity 0.2 – 0.6 m3/s (100 % speed).
- Inlet temperature from 90 C to 170 C.
- Pressure ratio 1.8 – 2.2 with actual test rig impeller design. New design up to 2.9 can be achieved.

- Discharge pressure demonstrated: 2.7 bara (130 C saturation temperature). Suction pressure was limited by power input and thereby also discharge pressure.
- Temperature lift 25 K in one stage providing a heat pumping COP of 8-10.
- Measured compressor isentropic efficiency 0.73 – 0.75.
- Loss in motor, inverter and aux system: Gas Power/Grid Power 0.82 at 80 % power.
- Very smooth and stable operation above 82 % speed (very low vibration level).
- Critical speed range (considered conservatively from 68 – 82 % speed) must be passed quickly.
- All safety systems for compressor startup and safe operation worked as expected.
- Slightly insufficient capacity of deSH and cooling for controlling the gas loop system at full load.
- Compressor system is on TRL 4-5 and is considered ready to test in real industrial environment.

# 6. Utilisation of project results

The project has demonstrated that the technology can work as efficent heat pumping in temperature and capacity ranges similar to many possible industrial applications, where existing heat pumping technology is either not suitable or applicable.

Industrial full scale demonstration on a long term is the next phase and the planning is started.

More competitors are developing heat pumps for high temperature heat supply (above 100 C). Large turbo compressors have for many years been available, but is not suitable for the smaller heat capacity range below 5 MW heat.

Traditional heat pump technologies is being redesigned for working at higher temperature levels. But we do not consider the traditional heat pumping technologies (based on mechanical displacement compressors) as a competitive technology for upgrading heat available at high temperatures.

# 7. Project conclusion and perspective

The project has successfully demonstrated a technology in full scale that delivers high temperature heat pumping with high efficiency suitable for upgrading excess heat to useful heat in industrail processes, and thereby reducing or eventually eliminating the demand for combustion of fuel related to steam generation in many industries.

The next step is to demonstrate operatbility and long term reliability in a real industrial site.

We certainly expect the technology will pass this real industrial demonstration phase successfully also, and thereby open the door for low-cost high-efficiency industrial heat pumping applications at high temperature levels. Thereby providing an important part of the industry a valuable, cost and ressource efficent solution in the transition from fuel based heat supply to low emission electrified heat solution.

# 8. Appendices