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HighLift – a very high temperature heat pump for industrial use – key results from a Horizon2020 Fast Track to Innovation Project

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Keywords:
Very high temperature heat pump, steam generation, helium (R704), waste-heat recovery

Abstract

The HighLift project was a cooperation between AstraZeneca, Olvondo Technology, and Åbo Akademi University, and partly financed through the European Commission's Horizon2020 Fast Track to Innovation. The project developed the next-generation very high temperature heat pump, suitable for combined heating and cooling, waste-heat recovery, and steam generation up to 10 bar_g. Here we present some of the key results of the project. The project aimed to increase the system efficiency, improve the reliability, cut production costs, refined quality control, and improved ICT platform for the very high temperature heat pump. Supporting theoretical and desktop studies address energy efficiency, life cycle assessment (LCA) and market potential for the HighLift technology. In this extended abstract some key development results from the project are presented. The focus will be on the high operating temperatures of the heat pump.

Introduction

The project developed a next-generation prototype heat pump (750 kW heat output) that was installed at the AstraZeneca R&D centre in Gothenburg, Sweden. Three very high temperature heat pumps (500 kW heat output each) were already installed at the site, using the waste-heat recovery circuit at the site as the cold side heat source and the 10 bar_g steam system as the hot side heat sink. The prototype was integrated into the existing 10 bar_g steam system and connected to the heat recovery circuit at the site. Details about the installation can be found in the previous work by the authors [1]. Besides the design, construction and implementation of the prototype, theoretical studies addressed energy efficiency and life cycle analysis (LCA). For more details regarding the technical development in the project, refer to the other work by the authors [2,3].

Methods

The high temperatures (>150°C) make it challenging to find sealing material that can withstand the temperature in addition to thermal cycling. Prior to the start of the project various tests were made with various FKM and FFKM seals. The results of the tests showed that the seals either did not work properly for the required temperatures or were prohibitively expensive for standard applications. The task of the new design changes was to try to eliminate as many of the polymer seals as possible, either by changing the type of seal or by removing the separation between the surfaces.

The mechanical design of the kinematical parts of the heat pump is close to a large-scale piston compressor or a medium speed ship diesel engine. In contrast to a piston compressor or a diesel engine, the acceptable leak-rate from the piston rod seal is very low. The working medium in the heat pump is helium, which increases the challenge to design a seal with low enough leak rate. Additional challenges are presented by not being able to cool the working medium and that no oil should leak into the cylinders. The temperature of the piston rod is lower than the gas temperature, but still presents a challenge for the lifetime of the seal. Oil in the cylinders would start clogging the regenerator and the performance of the heat pump would decline. The new design of the seal was an iteration of the seal used in the existing heat pumps, primarily improving the durability of the seal and withstand the higher pressure difference needed for the increase in output.

Exergy analysis is used to quantify the efficiency of energy used in thermal systems such as heat pumps, "normalising" all energy streams by their capacity to do work [4]. For power P, heat Q and fuel lower heating value LHV the exergies can be calculated and losses defined as irreversibilities, i.e. entropy generation. A further quantification of any inefficient use of resources and impact on the environment was made using life cycle assessment, LCA.

Results and Discussion

Figure 1. Heat pump installed on site.

Error! Not a valid bookmark self-reference. shows the heat pump installed on site. The heat pump is installed in the same room as the three previous heat pumps and is connected to the sink/source system through the common connections.

The cold side of the heat pump is facing towards the main motor, while the hot side of the heat pump is towards the wall. Cold heat is transferred from the site's heat recovery system through a plate-heat exchanger. The closed loop water circuit circulates water through the plate-heat exchanger and the internal heat exchangers on the heat pump. Steam is produced in a plate-and-shell steam generator, where a closed super-heated water loop circulates over the steam generator and the hot side internal heat exchangers on the heat pump. Oil for the bearings is cooled by the cold closed loop water circuit. This means that the friction heat in the bearings and other mechanical components is recycled internally in the heat pump, reducing the thermal losses, and improving the efficiency. An estimate of the heat from the oil transferred to the cold circuit is between 10 and 15 kW. The estimates are based on the temperatures of the oil and shaft speed of the oil pump.

During the test period of approximately 2500 hours the heat pump was generating steam at an average pressure of 9.0 bar, corresponding to a temperature of 180.5 °C. The average temperatures of the water in/out from the heat pump were 181.3 and 183.2 °C respectively, giving a ΔT of 1.9 K.

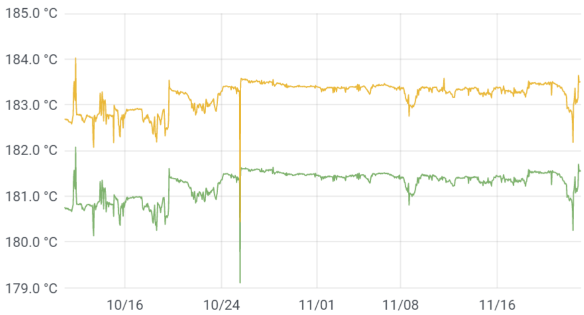

Figure 2. Hot circuit temperatures for the period between 10th of October to the 11th of November 2021.

Figure 2 shows the hot side temperature during a month's operation in October/November 2021. The variations in the temperatures are due to the changes in the steam pressure in the site's steam system. The pressure will vary slightly with the load of the system and is controlled by a gas boiler that forms the primary source of steam.

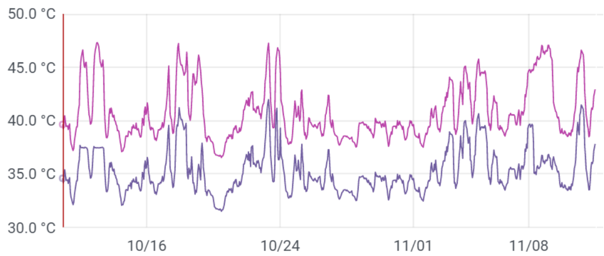

Figure 3. Cold circuit temperatures for the period between 10th of October to the 11th of November 2021.

When the control of the heat pump output is properly designed and calibrated, the heat pump should generate all the steam needed by the system with the heat pumps in the periods where the load is below the maximum steam capacity of the heat pumps. The temperatures on the cold source vary more than the hot sink temperatures. This can be seen in Figure 3, which shows the cold heat exchanger's inlet and outlet temperatures of the heat recovery circuit.

The temperature difference, ΔT, between the outlet and the inlet is controlled by the heat pump. The setpoint of the ΔT is given by the site's control system and can vary freely between 5 and 10 K. The ΔT for the period was 5 K most of the time, but there were also shorter periods with a ΔT of 6 K and 10 K.

The average temperature lift for the heat pump, that is, from the average cold temperature to the average hot temperature was approximately 144 K.

The target leak rate for the dynamic piston rod seals for the project was set to less than 24 litre$_{STD}$/day. The heat pump's data acquisition system does not measure the leak rate directly, but the leak rate can be estimated from the working medium pressure and temperature over time. This gives a leak rate for all the components and not only the piston rod seal. Figure 4 shows the calculated working medium mass in the heat pump for a period of 24 hours. The two almost vertical lines in the graph are when the control system is refilling the heat pump. The total estimated leak rate for the heat pump is about 44 litre$_{STD}$/day. This means that the leak rate for each piston rod seal is less than 11 litres$_{STD}$/day. This is still approximately twice the acceptable leak rate. However, a considerable share of the leaking gas was leaking through a faulty brazing joint. A better estimate of the leak rate will be available when the leak in the joint is fixed. Nevertheless, based on the observations of the leak in the joint it is very likely that the leak rate for the seals is within the acceptable limits, and the current estimate of the leak rate for the whole heat pump (without the faulty brazing joint) is between 22 and 24 litre$_{STD}$/day.

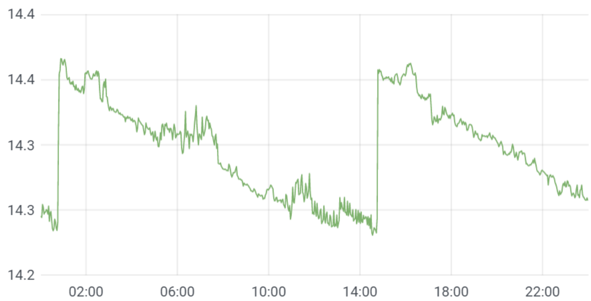

Figure 4. Helium mass in the heat pump during 24 hours of operation. The unit of mass is a normalised volume parameter used by the PLC to control the pressure.

For a 500 kW heat output system using either waste heat and electricity, or a fossil fuel the exergy analysis shows an efficiency of 71% for the heat pump versus 34% or 33% for a natural gas or fuel oil-fired heater, respectively, as shown in Figure 5.

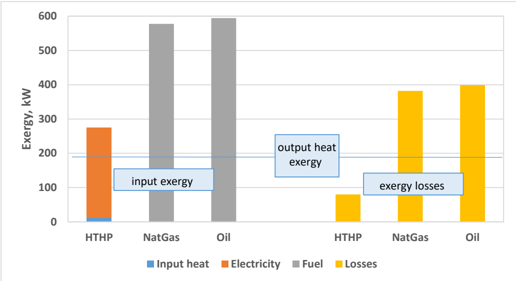

Figure 5. Exergy efficiency analysis of Highlift HTHP versus gas or oil boilers for 500 kW heat output at 200°C

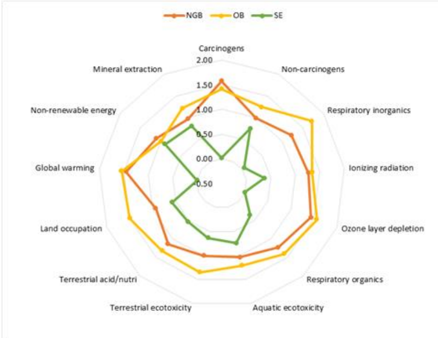

Figure 6. Radar chart of the relative environmental impacts of 15 years 500 kW heating using a natural gas boiler (NGB), oil boiler (OB) or Stirling engine heat pump (SE) incl. construction and decommissioning

LCA quantifies the life cycle impact resulting from use of resources or emissions to the environment, for the same system operated 15 years, including construction and end-of-life commissioning, for thirteen so-called midpoint categories. Figure 6 shows the outcomes as a radar chart [3].

Conclusion

The conclusion of the project was that the new generation heat pump had a stable operation at the required temperatures, and that the performance and wear of the parts was very good. There are still improvements that could be achieved with minor modifications. Energy efficiency analysis and LCA show the advantages of the system compared to fuel-fired heaters.

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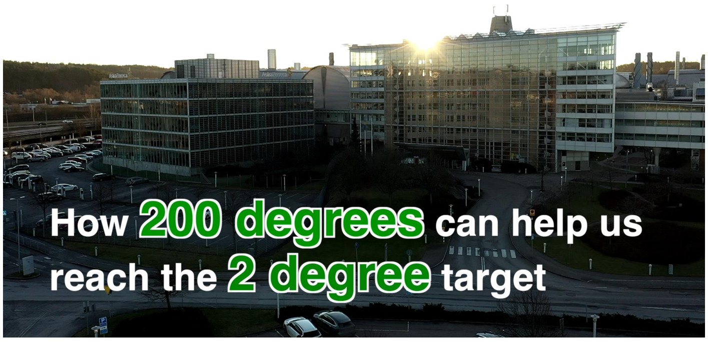
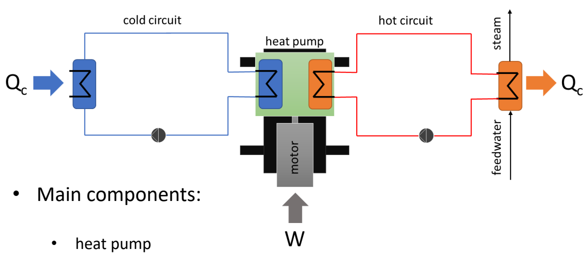
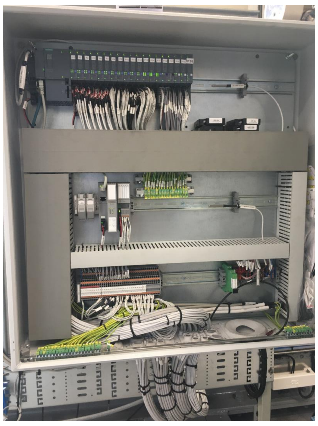


Methods and test setup



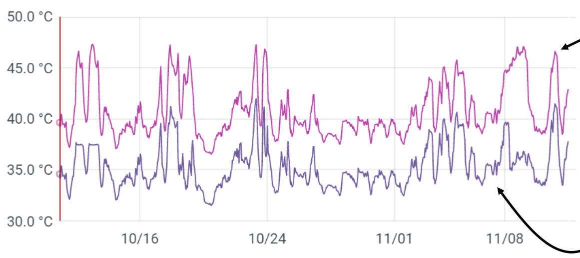
- Main components:
  - heat pump
  - steam generator
  - plate heat exchanger
  - auxiliary circuits
  - working-medium system

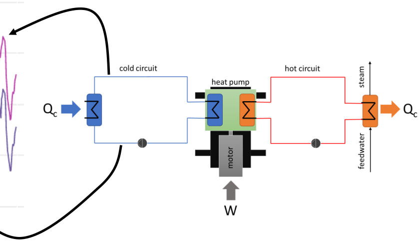
Control, data acquisition, data processing



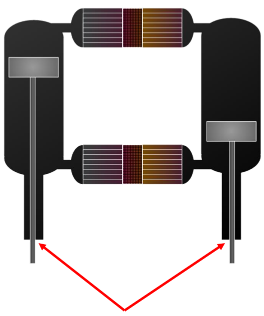
Hot side temperatures

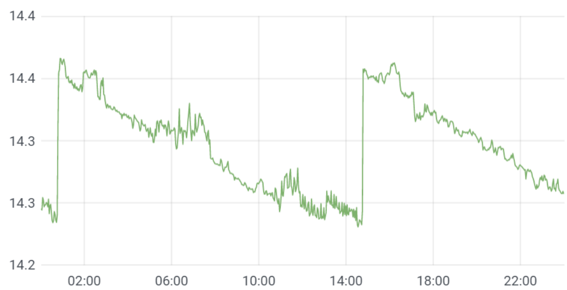
Cold side temperatures





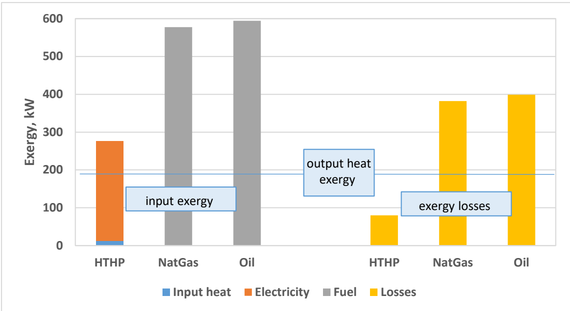
Helium leak rate

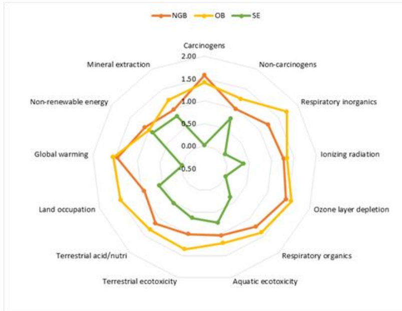




The total estimated leak rate for the heat pump is about 44 $litre_{STD}$/day.

Exergy analysis and LCA





Concluding remarks

The conclusion of the project was that the new generation heat pump had a stable operation at the required temperatures, and that the performance and wear of the parts was very good. There are still improvements that could be achieved with minor modifications. Energy efficiency analysis and LCA show the advantages of the system compared to fuel-fired heaters.

Links on the HighLift-webpage:

http://highlift.olvondotech.no