PERFORMANCE AND PREDICTIVE ANALYSIS OF A VERY HIGH-TEMPERATURE INDUSTRIAL HEAT PUMP

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ABSTRACT

Industrial high-temperature heat pumps are an emerging technology that have the potential to significantly contribute to industrial decarbonization by generating process heat up to 200 °C and replacing fossil fuel-fired boilers in various industries. This paper presents some of the work being done on analyzing the performance and the environmental impact of a novel reverse Stirling cycle high-temperature heat pump. A number of industrial integration cases are presented, with the heat pump utilizing waste heat sources between 30 °C and 84 °C while producing steam at temperatures between 152 °C and 184 °C.

A demonstration of how life cycle assessment tools can be included in the decision-making process regarding the choice of heat generation technology, be it a high-temperature heat pump or a fuel-fired boiler, is presented. Instead of considering only CO_2 emissions, as is often the case, life cycle assessment tools can be used to construct more complete pictures of the overall environmental impact by considering factors such as carcinogenic emissions, land occupation, non-renewable energy usage, and ecotoxicity, which may show up during various stages during the product life cycles. If renewable sources of electricity are used to operate the high-temperature heat pumps, significant improvements can often be seen in most environmental endpoint impact categories compared to natural gas or fuel oil boilers. In the case of Sweden, where electricity is mostly generated using wind-, hydro-, and nuclear power, it s estimated that up to a 97% reduction in CO_2 equivalent emission and a 52% reduction in resource related energy usage is possible by utilizing high-temperature heat pumps in place of natural gas boilers for producing high-pressure process steam.

An early attempt to develop a predictive maintenance model for a known pressure imbalance phenomenon is presented. A degradation model using various sensor measurements as condition indicators to predict the condition of a set of piston rings is constructed, and a combined condition indicator is obtained. The model is prevented from being properly verified, due to the lack of cases with clearly identifiable initial and end conditions, lack of measurements to use as condition indicators, and an overall incomplete understanding of the pressure imbalance phenomenon itself.

1 INTRODUCTION

Heat production accounts for 66% of the European Union's industrial energy use and is estimated to emit 552 Mt CO_2 annually, and the method of heat production is currently dominated by fossil fuel combustion, accounting for approximately 77% of the demand (Boer *et al*., 2020). As such, moving towards more affordable and less polluting modes of heat production is critical if the European Union is to achieve its current goal of a 55% reduction in greenhouse gas emissions by 2030, and net climate neutrality by 2050 (European Commission, 2019).

Approximately 26% of the European industrial heat demand exists in the 100 °C to 200 °C temperature range (Boer *et al*., 2020), which is typically out of reach for traditional heat pumps. Technological advancements during the last decade or so have resulted in the development of so-called high-temperature heat pumps (HTHP), many of which are capable of generating sink temperatures over

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150 °C, and some even up to 200 °C (IEA HPT, 2023). Electrifying industrial heat production with HTHPs and replacing traditional fuel-fired boilers has the potential to significantly reduce overall CO_2 emissions as well as optimize energy usage due to the significantly higher efficiency of heat pumps compared to traditional boilers. It is estimated that up to 37% of European industrial process heating can be covered by heat pumps, potentially reducing CO_2 emissions by 146 Mt and energy usage by 487 TWh annually (Boer *et al*., 2020).

This article presents a number of case studies pertaining to a novel reverse Stirling cycle HTHP decarbonizing industrial heat production by generating process temperatures up to 184 °C. Along with reducing CO_2 emissions, it is demonstrated how life cycle assessment tools are used to quantify the overall environmental impact of individual projects by assessing the impact on human health, ecosystems, and resource usage. Finally, an early attempt to develop a predictive maintenance model based on process signals is constructed in order to better understand the occurrence of a pressure imbalance phenomenon known to affect double acting Stirling machines.

2 INDUSTRIAL INTEGRATION AND PERFORMANCE METRICS

The system studied in this article is the HighLift heat pump, an industrial HTHP based on the reverse Stirling cycle manufactured by Olvondo Technology AS (Olvondo Technology AS, n.a). The heat pumps used in this case are installed in the pharmaceutical company AstraZeneca's R&D center in Gothenburg, Sweden. Similar installations are at Lerum fabrikker AS, a juice, beverage, and jam factory in Norway, TINE Ålesund a dairy plant in Norway, and soon in Friesland Campina's Maasdam dairy plant.

2.1 Heat pump description

The heat pump unit consists of four cylinders with double-acting pistons operating on four individual helium gas circuits undergoing periodic expansion and compression. The system is set up in an α-configuration with two gas circuits on either side of the pistons in two cylinders, with the designated cold side piston being phase-shifted ahead of the hot side piston. Two cylinder banks consisting of two circuits each are arranged to balance the mechanical stress during operation. The working fluid remains in the gas phase during the entire operating cycle and is as such not restricted by any evaporation or condensation limits. High single-stage temperature lifts are therefore possible, and the cycle will automatically adjust to rapid changes in sink or source temperatures. Figure 1 depicts four HighLift heat pumps stationed at the AstraZeneca R&D center in Gothenburg, Sweden. A more detailed description of the heat pump design can be found in previous publications by one of the co-authors (Høeg *et al*., 2016).

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Figure 1: Four HighLift high-temperature heat pumps at AstraZeneca's R&D center, Gothenburg, Sweden.

The refrigeration cycle is described by the reverse Stirling cycle which can be characterized into four distinct idealized stages. Heat flows into the working fluid from the cold source during isothermal expansion and isochoric heat addition, and heat is rejected to the heat sink during isothermal compression and isochoric heat removal. Figure 2 illustrates both the idealized cycle as well as the real cycle taking place in the heat pump gas circuits due to the sinusoidal piston motion. The operating characteristics of the heat pump can be modified by varying the phase angle between the hot and the cold pistons. Larger phase angles will in general result in more efficient operation, albeit with smaller thermal outputs.

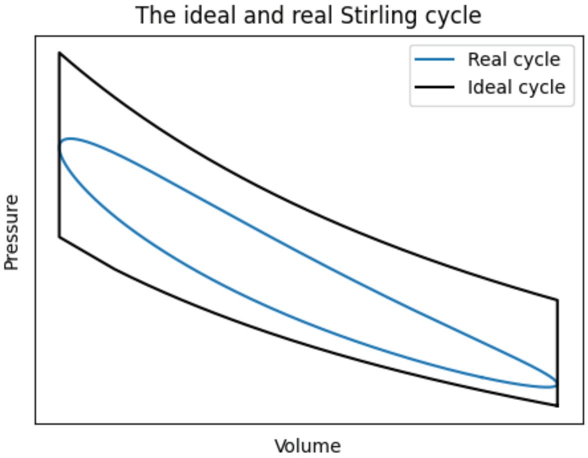

Figure 2: Illustration of the idealized Stirling cycle with four distinct stages (black cycle), and the approximated real cycle with sinusoidal piston motion (blue cycle).

2.2 Industrial case integrations

The pharmaceutical company AstraZeneca produces steam between 175 °C (8 barg) and 184 °C (10 barg) at a research facility in Gothenburg, Sweden, with the help of four heat pump units. Waste

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heat at a variable temperature of roughly 35 °C is used as a heat source, resulting in a temperature lift up to 150 degrees. The waste heat is part of the plant's heat recovery system, and it is also used for other low temperature heating demands. During summer periods, most of the steam demand is covered by the heat pumps, while the winter periods also see steam production using bio-gas and electric boilers. During summer periods, the heat load on the heat recovery system is also low, making steam generation using the heat pumps more attractive.

Two heat pumps are operating in a juice, beverage, and jam production facility in Kaupanger, Norway. The two heat pumps deliver steam to the same steam header at around 168 °C (6.5 barg) utilizing different cold sources. One heat pump is used to pre-cool ice water at temperatures between 7 °C and 12 °C, reducing or eliminating the use of a cooling compressor, and the second heat pump uses hot water between 30 °C and 40 °C as the heat source. The hot water is generated from waste heat sources in the plant, primarily cooling compressors. The hot water is also used to pre-heat process water and for room heating. The alternative method of steam production is electric boilers.

Two industrial heat pumps are installed in a dairy plant located in Ålesund, Norway, where process steam at 184 °C (10 barg) is being produced using a district heating network at 85-100 °C as a heat source. Up to 9.6 GWh of heat is supplied to the steam network annually with an effective total Coefficient of performance (COP) of ~1.85. The steam is used for UHT production and other heating and cleaning needs in the plant. The main alternative steam generation method at the plant is natural gas boilers.

One heat pump is being installed in a Friesland Campina dairy production facility in Maasdam, the Netherlands. The heat pump will produce process steam at 152 °C (4 barg) using either hot water at 84 °C or 30 °C as the heat source. The primary heat source is the water at 84 °C, as illustrated in Figure 3. This heat is in turn produced with a separate hot water heat pump using waste heat from an ice water condenser as a source of heat. This condenser waste heat at 35 °C would pass through a cooling tower unless otherwise utilized before being distributed to various cold water users. The installation of a HTHP allows for more efficient utilization of existing waste heat and provides a baseline hot water demand. The hot water heat pump and the HTHP operate at COPs of 4 and 2.4 respectively, for an overall COP of 1.75 over the entire temperature lift.

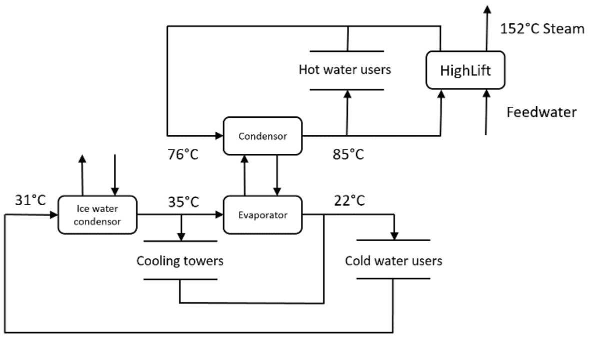

Figure 3: Simplified process diagram of the HTHP integration in a FrieslandCampina dairy production facility.

3 ENVIRONMENTAL IMPACT ASSESSMENTS

Producing industrial heat by utilizing high-temperature heat pumps instead of traditional boilers can significantly alter the environmental impact of the overall process. The construction of the initial equipment differs in that industrial heat pumps are not only technologically more complex, but also tend to be materially more intensive to build compared to equivalently sized natural gas- or fuel oil boilers. During operation, fossil fuel boilers emit carbon dioxide, and depending on the fuel used, nitric oxides, sulfur oxides, and soot among other things directly onsite. Meanwhile, heat pumps use electricity and low-temperature heat sources, and as such have no direct emissions onsite. To get a complete picture of the environmental impact of the process, it is important to account for the source of the electricity used as well as any upstream emissions related to the material procurement for building the heat pump and the electricity generation equipment. This can be done systematically using life cycle assessment (LCA) tools.

3.1 Impact categorization

Depending on the methodology used, the environmental impact can be classified into a number of different categories. The impact 2002+ methodology (Humbert *et al*., 2012) was used to perform the LCA in this case, and has the following four endpoint categories: Climate change, Human health impact, Ecosystem impact, and Resource usage. These endpoint categories are the sum of a number of midpoint categories such as carcinogenic emissions and emissions associated with respiratory illnesses for Human health, and land occupation and ecotoxicity for the category Ecosystem impacts. These impacts are usually expressed as kg substance $s_{\text{-eq}}$, where s is an appropriate reference substance for the category in question, such as kg sulfur dioxide emissions for terrestrial acidification/nutrification. Other reference units such as m^2 arable land for land occupation, or Becquerel C-14 equivalent for the category ionizing radiation are used when a mass equivalent reference substance is not suitable.

3.2 Environmental impact assessments in decision making

LCA has been used to quantify the environmental impact of operating the industrial HTHP in question under various conditions. A system model of the heat pump unit itself has previously been constructed and compared to alternative heating systems (Khan *et al*., 2021). Previous work by the authors has addressed the overall effect of steam generation using industrial HTHPs in place of natural gas boilers (Högnabba *et al*., 2023), and a model was developed to estimate the impact of operation for a given set of circumstances. This model provides utility in the form of additional information input in a decision-making process on whether or not it is beneficial to operate HTHPs or traditional fuel-fired boilers in a given industrial environment.

The environmental impact estimates consist of the number of heat pump units and the associated impacts of construction which have been previously documented (Khan *et al*., 2021) as well as the impact of the electricity generation used during operation. If grid electricity is used without any guarantees of origin, a country-specific model is used which accounts for the local electricity generation mix. A model for each country has been built in the LCA software SimaPro using the ecoinvent 3.8 database (Wernet *et al*., 2016) and electricity production data from the ENTSO-E transparency platform (ENTSO-E, n.a).

Table 1 illustrates an overarching estimate for both the heating and cooling performance as well as the environmental impact of a hypothetical project involving two HTHPs producing steam at 8 barg using a cold source at 35 °C. The estimated heating and cooling capacities as well as the COP are estimated with the temperature fraction T_H/T_C and internal performance models fitted to heat pump units in operation. In this case, the installation is assumed to be located in Sweden, and the HTHPs are assumed to utilize grid electricity during operation. It is estimated that the total CO_2 emissions could be reduced by up to 97% compared to an equivalently sized natural gas boiler. Non-renewable energy usage could be reduced by 52%, and the impact on human health could be reduced by 17%. The impact on ecosystems would increase by 352%, mostly as a result of increased terrestrial ecotoxicity mostly linked to the mining and refinement of copper used in renewable electricity generation equipment and the HTHP motor itself.

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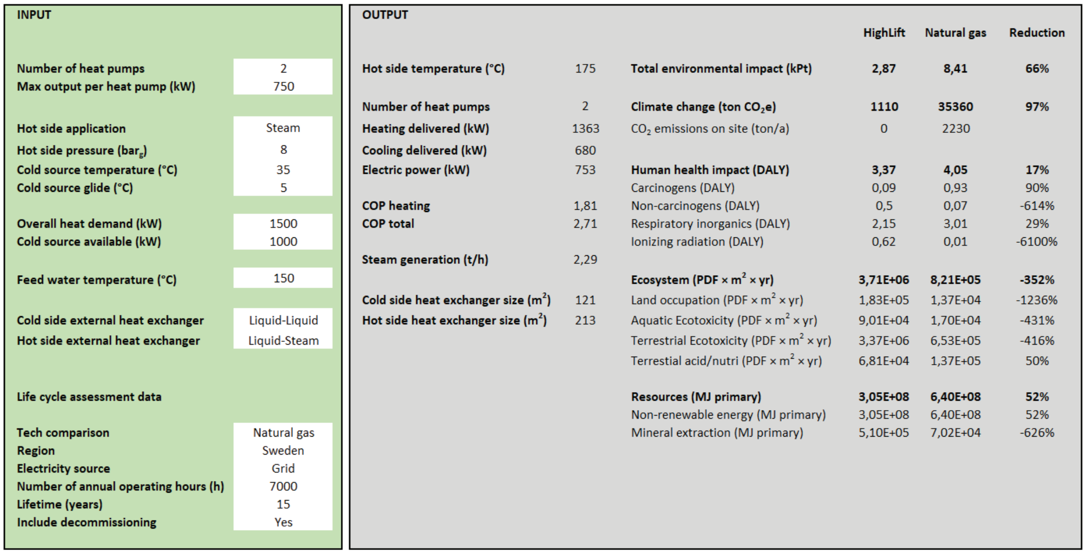
Table 1: User interface for estimating the performance and environmental impact of a HTHP installation.



INPUT	
Number of heat pumps	2
Max output per heat pump (kW)	750
Hot side application	Steam
Hot side pressure (bar$_g$)	8
Cold source temperature (°C)	35
Cold source glide (°C)	5
Overall heat demand (kW)	1500
Cold source available (kW)	1000
Feed water temperature (°C)	150
Cold side external heat exchanger	Liquid-Liquid
Hot side external heat exchanger	Liquid-Steam
Life cycle assessment data	
Tech comparison	Natural gas
Region	Sweden
Electricity source	Grid
Number of annual operating hours (h)	7000
Lifetime (years)	15
Include decommissioning	Yes

OUTPUT	
Hot side temperature (°C)	175
Number of heat pumps	2
Heating delivered (kW)	1363
Cooling delivered (kW)	680
Electric power (kW)	753
COP heating	1,81
COP total	2,71
Steam generation (t/h)	2,29
Cold side heat exchanger size (m^2)	121
Hot side heat exchanger size (m^2)	213

	HighLift	**Natural gas**	**Reduction**
Total environmental impact (kPt)	**2,87**	**8,41**	**66%**
Climate change (ton CO$_2$e)	**1110**	**35360**	**97%**
CO$_2$ emissions on site (ton/a)	0	2230	
Human health impact (DALY)	**3,37**	**4,05**	**17%**
Carcinogens (DALY)	0,09	0,93	90%
Non-carcinogens (DALY)	0,5	0,07	-614%
Respiratory inorganics (DALY)	2,15	3,01	29%
Ionizing radiation (DALY)	0,62	0,01	-6100%
Ecosystem (PDF × m^2 × yr)	**3,71E+06**	**8,21E+05**	**-352%**
Land occupation (PDF × m^2 × yr)	1,83E+05	1,37E+04	-1236%
Aquatic Ecotoxicity (PDF × m^2 × yr)	9,01E+04	1,70E+04	-431%
Terrestrial Ecotoxicity (PDF × m^2 × yr)	3,37E+06	6,53E+05	-416%
Terrestial acid/nutri (PDF × m^2 × yr)	6,81E+04	1,37E+05	50%
Resources (MJ primary)	**3,05E+08**	**6,40E+08**	**52%**
Non-renewable energy (MJ primary)	3,05E+08	6,40E+08	52%
Mineral extraction (MJ primary)	5,10E+05	7,02E+04	-626%

4 PREDICTIVE MAINTENANCE MODELS

To achieve the environmental impact reduction, the heat pumps must be able to operate over a long period of time, with preferably not more than one stop per year, for maintenance rather than repairs. Industrial equipment naturally accumulates wear over time which is remedied with periodic maintenance. This maintenance can be structured according to several different models depending on factors such as the expected cost of maintenance or how critical the system is.

Corrective maintenance involves work done once a failure event has occurred and is often utilized in cases where either failure is difficult to predict, parts are cheap and easy to replace, or failure is unlikely to cause cascading damage to other components or equipment.

Preventive maintenance (PM) aims to identify and rectify potential failures before they occur, usually by implementing scheduled maintenance sessions at fixed interval time periods. Equipment operating hours are often the criteria around which maintenance is planned, often irrespective of the equipment's actual condition. PM can minimize overall downtime, prevent expensive equipment failure and cascading damage events, and reduce overall maintenance costs compared to corrective maintenance by identifying and fixing small issues before they develop and result in complete failure.

Predictive maintenance (PdM) work is performed based on data signals which are used to estimate the condition of the equipment. Condition-based monitoring systems incorporate signals such as vibrational data, sound levels, temperature measurements, and oil analysis to estimate the condition and remaining useful life of a piece of equipment or an individual component. Ideally, PdM minimizes operational downtime and service costs by only performing equipment maintenance when necessary. On the other hand, PdM models are often non-trivial to implement and highly individualized for every piece of equipment. Sensor data needs to be gathered and logged before being combined and transformed into useful condition indicators by correlating signal data with known equipment conditions.

The reverse Stirling cycle heat pump analyzed in this article suffers from a certain pressure imbalance phenomenon that has been previously documented and studied (Haikarainen *et al*., 2020). The condition manifests in the form of a pressure imbalance between the two gas circuits located on either side of the double-acting pistons. This pressure difference results in uneven torque distribution over the full operational cycle, leading to component stress, and if left unchecked, the triggering of a shutdown mechanism to prevent equipment failure. It is therefore of interest to develop a model to predict the occurrence of this phenomenon, which could enable actions to be taken to prevent this imbalance, such as configuring the operating conditions or scheduling maintenance.

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4.1 Predictive maintenance

Predictive maintenance centers on the development of effective algorithms to predict the current and future condition of equipment with the help of various data signals and measurements. Once a specific system or piece of equipment has been defined for condition monitoring, potential data signals that could contain information regarding the system condition are gathered. Ideally, data spanning the entire lifetime of the system is available, including operation at ideal conditions and near failure. Data processing techniques are used to identify which measurement signals can be correlated to the actual equipment condition and therefore be included in a condition indicator. The combined condition indicator is constructed from the chosen measurement signals with individual weighting factors depending on how well they fit a degradation model of the system, which is often built as either a linear or an exponential degradation model. Finally, the model is verified with comparisons to new datasets. The process of constructing a condition indicator for the studied system is described in Chapter 4.3.

4.2 System description and data acquisition

Figure 4 depicts a simplified schematic of one cylinder bank in the heat pump, consisting of two cylinders, two pistons, two gas circuits, and four heat exchanger units (two visible) consisting of a cold side and a hot side heat exchanger as well as a regenerator. The pressure imbalance phenomenon is theorized to occur due to gaps between the pistons and the cylinder walls, allowing the working medium to seep from one circuit to the other. A small bypass valve connects the two circuits allowing for pressure to equalize over time, but the imbalance phenomenon persists.

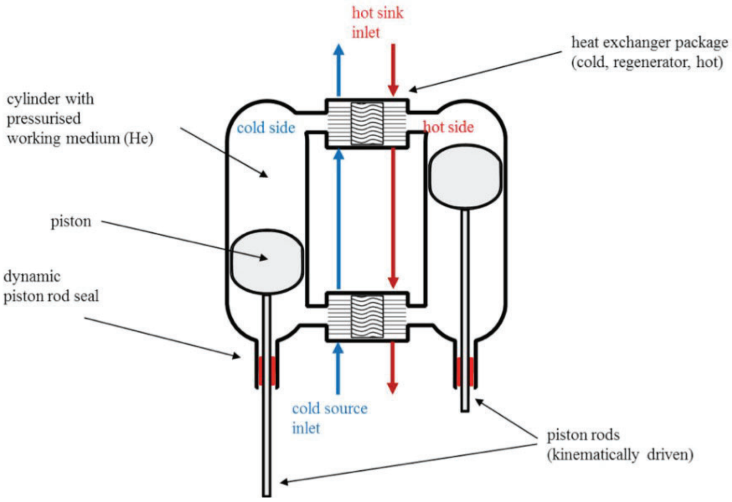

Figure 4: Simplified schematic illustration of the major components in one cylinder bank in the heat pump unit.

Figure 5 depicts the development of one pressure imbalance case over the course of ten days. The difference in pressure between gas circuits 1 and 3 (blue line), calculated as the pressure in the top circuit minus the pressure in the bottom circuit, varies around zero bars before suddenly dropping to over negative 4 bars. This imbalance is associated with in the torque amplitude (orange line), calculated as the maximum torque minus the minimum torque measured during a full revolution. The pressure imbalance between the circuits and the associated increase in the torque amplitude eventually triggered a shutdown mechanism to prevent damage to the heat pump unit.

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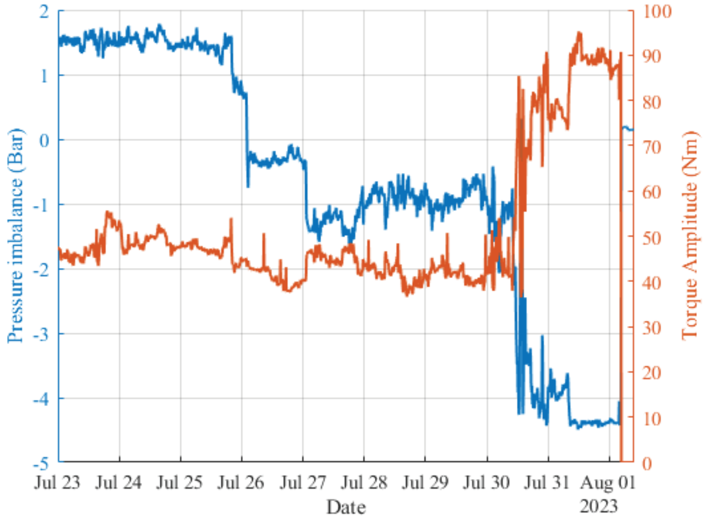

Figure 5: Pressure imbalance measurements in bank 1-3 (blue line) and torque amplitude measurements (orange line) over the course of 10 days.

Over longer time periods, gradual increases in the calculated torque amplitude can be observed between periods of maintenance. In some cases, this gradual increase can be associated with an increased number of pressure imbalance occurrences as seen in Figure 6. This figure also illustrates how a positive pressure imbalance in one cylinder bank and a negative pressure imbalance in the other bank will reduce the maximum torque amplitude, evidenced by the correlation between the absolute value of the combined pressure imbalances in the middle figure, and the torque amplitude measurements in the bottom figure.

Haikarainen *et al*. (2020) constructed a model of the pressure imbalance in the software Simulink, where different possible causes were considered. Working medium leakage through the cylinder piston-ring gaps was identified as a likely cause, and the phenomenon was simulated as a small temporary valve opening at specific points in time when the pressure difference across the seals is reversed. The pressure fluctuations in the simulations matched the measured pressure signals well, and it was concluded that improper sealing between the gas circuits on both sides of the pistons is the likely cause of the pressure imbalance phenomenon.

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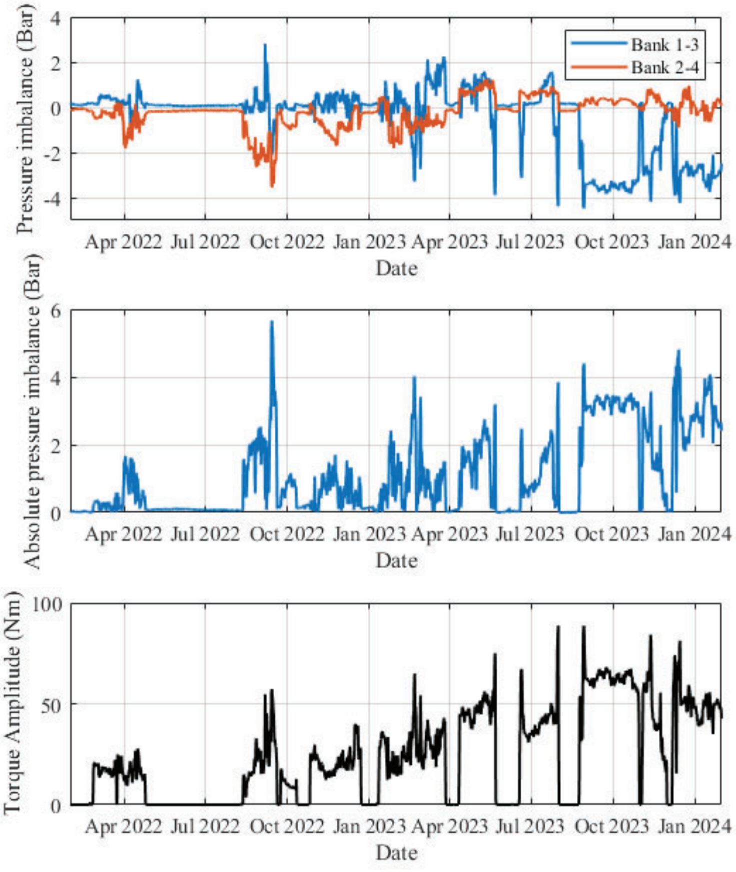

Figure 6: Individual bank pressure imbalances (top), overall absolute pressure imbalance (middle), and torque amplitude measurements (bottom) for HP1 at AstraZeneca, Gothenburg, over the course of 2 years.

4.3 Condition indicators and system modeling

It is of interest to construct a condition indicator to estimate the condition of the sealings in the heat pump cylinder. Potential signals considered for inclusion in a combined condition indicator were absolute circuit pressure measurements, circuit pressure imbalances, torque measurements, and torque amplitudes. Vibration measurements could also potentially be of interest, but were not available at the time of writing. The construction of the degradation model was done in MATLAB using the predictive maintenance toolbox (The MathWorks Inc, 2023).

As part of the data preparation, distinct time periods of operation were selected to fit a condition indicator to. The time ranges were chosen based on maintenance performed related to piston sealings documented in a maintenance report, and potentially relevant sensor data for each case was collected in data ensembles. These ensembles consist of an identifier for each case, the number of hours the machine has been in operation since maintenance, and every previously mentioned sensor measurement. Each case includes data measurements from the start of operation after maintenance has been performed until the next maintenance period. A total of six unique cases are identified, consisting of distinct operation periods for the four HighLift heat pumps located in AstraZeneca's R&D facility in Gothenburg, Sweden, pictured in Figure 1.

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Various sensor measurements can vary significantly over a short timeframe without necessarily indicating anything regarding the condition of the equipment monitored. Therefore, a moving mean value over a longer timeframe can potentially better capture any underlying changes in the equipment condition, and may also be more trendable as a result. Additionally, while individual occurrences of significant pressure imbalance measurements may not be indicative of the overall condition, the frequency of these events might be. An attempt to capture the volatility of the pressure imbalance was made by including a moving standard deviation window over the pressure imbalance measurements as a condition indicator. Figure 7 depicts the three most trendable indicators that were chosen which include the moving mean pressure imbalance (MM_PI) in both cylinder banks, the moving mean torque amplitude (MM_TA), and the moving standard deviation of the pressure imbalance (MSD_PI). All sensor measurements have been normalized.

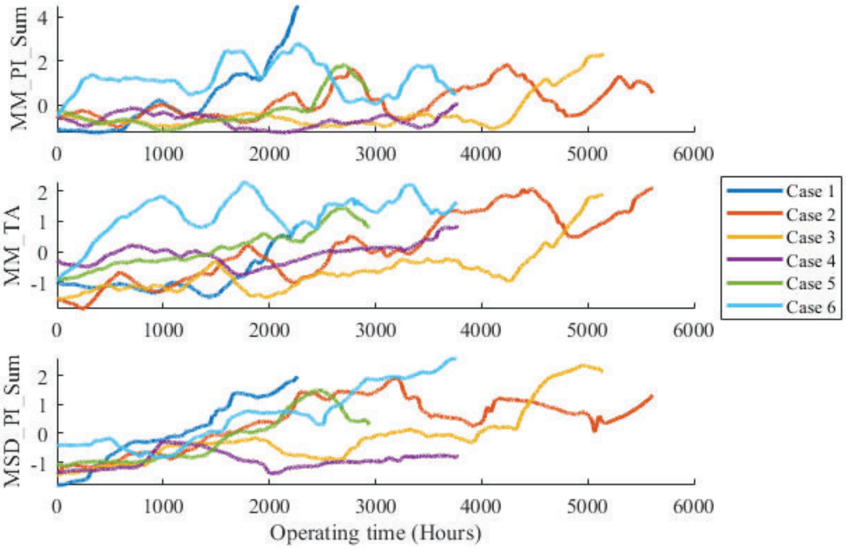

Figure 7: Normalized moving mean pressure imbalance (MM_PI), moving mean torque amplitude (MM_TA), and moving standard deviation pressure imbalance (MSD_PI) sensor measurements used to construct the condition indicator.

Once an appropriate set of trendable signals has been selected, a condition indicator can be constructed via sensor fusion. A linear degradation model is assumed where the initial condition at the start of the operational period is assumed to be 1, and 0 at the end of the period. Linear regression was used to fit the selected sensors to one single condition indicator with appropriate weight factors, and the final condition indicator was calculated by multiplying each sensor with this associated weight.

Figure 8 depicts the estimated condition for six separate cases which all consist of periods of operation between maintenance intervals. No case consists of data ranging all the way to actual failure, and is instead concluded when maintenance to a set of piston rings is performed. Information about the condition of these rings at the time of replacement is not documented, and as such, the genuine condition of the equipment at the end of a set of data is difficult to assess.

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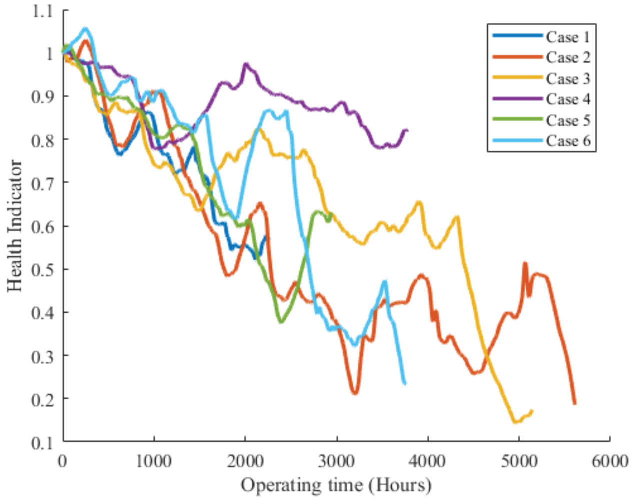

Figure 8: Estimated condition for six cases between maintenance intervals.

4.4 Limitations

A lack of identifiable cases where the initial and end conditions for the equipment can be clearly labeled is a major limitation of the model. As of now, signal variations not necessarily indicative of the equipment condition in a single case can result in large variations in the final degradation model. Proper verification of the model is also not feasible due to the lack of data.

The set of condition indicators is limited, and the inclusion of additional sensors may be needed to adequately model the degradation process. The selection of these additional measurement signals is difficult to predict, as the nature of the pressure imbalance phenomenon is not fully understood.

5 CONCLUSIONS

Performance data and case summaries regarding an industrial HTHP based on the reverse Stirling cycle in various operational settings were presented. The cases included four different factories utilizing one or multiple HTHPs for generating process steam between 152 °C and 184 °C, using various cold source temperatures between 30 °C and 100 °C. LCA tools were introduced as a way to construct more comprehensive views of the actual environmental impacts of electrifying the heating sector with HTHPs. Lastly, an initial attempt to construct a predictive model to assess the condition of a set of piston rings based on the occurrence of an unwanted pressure imbalance phenomenon. While initial results are promising, a lack of process data for verification and further development significantly limits the model in its current state.

NOMENCLATURE

CM	Corrective Maintenance
COP	Coefficient of Performance
HTHP	High-Temperature Heat Pump
LCA	Life Cycle Assessment
MM	Moving Mean
MSD	Moving Standard Deviation
PdM	Predictive Maintenance
PI	Pressure Imbalance
PM	Preventive Maintenance
TA	Torque Amplitude

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