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Dynamic performance evaluation of an R718 high-temperature heat pump within the GEOSYN project

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Abstract

High-temperature heat pumps (HTHPs) offer a viable solution for reducing greenhouse gas (GHG) emissions in hard-to-abate industrial sectors by replacing fossil fuel-based boilers to supply heating for various thermal processes. This paper presents the modelling and simulation results of an HTHP that uses geothermal energy as the heat source. The study is part of the ongoing GEOSYN project, which aims to develop and demonstrate an R718 heat pump integrated with a heat-powered chiller to enhance the utilization of geothermal energy sources. The HTHP is designed to operate at an evaporator temperature of approximately120 °C, delivering a temperature lift of up to 80 K. The system employs a newly designed four-stage reciprocating compressor with intercooling between each stage. The overall performance and environmental benefits of the R718 HTHP in the context of its application to the textile industry were investigated based on a system dynamic model along with the proposed control strategy. Field measurements from a geothermal plant in Tuscany (Italy) were used for the dynamic analysis of the proposed system, in addition to the varying steam load profile of the selected case study requiring steam at 185 °C. The results show that the proposed HTHP system can achieve an average coefficient of performance (COP) of 3.48, along with a reduction in operating costs and GHG emissions of up to 64% and 96%, respectively, compared to a natural gas-fired boiler. Furthermore, the proposed control strategy effectively maintained the discharge temperature within the compressor's safe operating limits. The findings contribute to the advancement of HTHP technology by providing insights into control strategies and integration with geothermal energy sources.

Keywords: Control strategy; Dynamic modelling; High-Temperature Heat Pump; Industrial Process Heating; Water

1. Introduction

Industrial process heating is a major energy-intensive area with significant GHG emissions, as it is predominantly powered by natural gas and other fossil fuels. In Europe, approximately 37% of the process heating demand is for temperatures below 200 °C [1]. Electrifying these industrial processes is essential to decarbonize the sector, reduce GHG emissions, and potentially lower energy costs. To support this transition, the deployment of high-temperature heat pumps (HTHPs) is crucial for meeting process heating demands sustainably and cost-effectively, as they deliver multiple units of thermal energy per unit of electricity consumed, resulting in significantly lower energy consumption for the same heat output. HTHP technologies are primarily based on closed vapor compression cycles, steam compression, and heat transformers. Currently these systems can achieve supply temperatures ranging from 115 °C to 240 °C; however, commercial models

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are limited to a maximum outlet sink temperature of 160 °C [2]. These HTHPs use both synthetic and natural refrigerants as the working fluid(s). Among these, water (R718) has emerged as one of the most promising candidates for applications exceeding 160 °C, thanks to its superior coefficient of performance (COP) compared to other alternatives, no environmental impact or safety risks [3,4]. Therefore, R718 HTHPs have drawn significant attention, and important recent studies are summarised here. Hegner et al. [5] theoretically investigated (steady-state) cascade HTHP systems using water and R1336mzz(Z)e as refrigerants, optimizing multi-stage compression and intercooling for improved COP. Simulations identified optimal designs achieving COPs between 1.5 and 2.2, while maintaining evaporation pressures near atmospheric levels, thus avoiding the need for vacuum equipment. Similarly, Hosseinnia et al. [6] also assessed R718 as a suitable refrigerant for the high stage of a high-temperature cascade heat pump, targeting water condensation at 190 °C while recovering low-temperature waste heat at 50 °C. Wu and Hu [7] compared six water-based (steady-state) HTHP configurations highlighting the benefits of water injection and intercooling in reducing discharge temperatures. It was found that two-stage cycles surpass single-stage systems at high temperature lifts, with the flash tank configuration yielding a COP of 4.14 at the evaporation temperature of 80 °C and condensation temperature of 140 °C, respectively. Hockenkamp et al. [8] conducted a computational fluid dynamics (CFD) simulation study to evaluate the use of R718 twin-screw compressors for supplying industrial heat and process steam at temperatures up to 200 °C. The study contributed to the understanding of advanced compression technologies in the field of high-temperature heat pumps, offering a detailed examination of a water-injected steam compressor's applicability and efficiency in a practical system setting. In another study, Zhang et al.[9] investigated multi-stage water-based high-temperature heat pumps with self-circulating water spraying to address high discharge temperatures in large temperature-lift systems. It was concluded that three-stage compression-throttle systems can significantly reduce discharge temperatures and enhance overall performance, with even small increases in water spraying ratio noticeably improving COP. Further, Zühlsdorf et al.[10] developed guidelines for constructing two-stage R-718 heat pumps for high temperature applications. The study proposed a compact and cost-effective design featuring a vertical vessel with separation packings for desuperheating, showing both superior performance and economic viability for heat sources above 100 °C. The results of another theoretical (steady-state) study suggested that the HTHP configuration with intercooling arrangement can achieve a COP of 5.86 at a sink outlet temperature of 200 °C along with a 92% reduction in GHG emission compared to existing industrial fossil boilers [11]. Furthermore, the steady-state comparative study conducted by [12] on various R718-based industrial heat pumps showed that the two-stage wet compression cycle outperforms dry compression configurations by effectively controlling discharge temperatures, reducing compressor power by 5–8 %, and achieving the highest heating COP. However, although dry cycles were found to offer slightly higher volumetric heating capacity, they face reliability issues due to high discharge temperatures. A recent comprehensive literature review carried out by Wang et al. [3] summarized that existing closed-cycle water vapor HTHPs are effective for industrial waste heat recovery and non-steam applications, delivering heat up to 150 °C with COPs of 2.5–6.0, while open-cycle steam compression systems efficiently supply direct steam above 120 °C. However, the authors highlighted high initial costs, efficiency losses due to overheating, and limited large-scale compressor options. They concluded that future development should focus on reducing costs, improving equipment efficiency through advanced cooling and multi-stage compression, expanding system capacities, and validating performance via simulations and real-world field measurements as current key challenges.

As summarized above, R718 HTHPs are promising eco-friendly technologies to satisfy various high-temperature industrial process heating demands. However, their application is still hindered by several technological constraints, e.g., elevated discharge temperatures and low volumetric heating capacity. Most recent studies on R718 high-temperature heat pumps use steady-state models, which only describe how the system behaves under a fixed operating condition. While this is useful for estimating nominal performance and thermodynamic potential, it does not show how the system behaves when conditions change over time. In real industrial applications, heat demand and heat source temperatures can vary continuously, and the heat pump must adapt to these changes. For R718 systems, this is especially important because limits, such as compressor discharge temperatures, can easily be exceeded during transient operation. Dynamic modeling and control are essential to verify whether an R718 HTHP can operate safely and reliably under real industrial conditions, not just under ideal steady-state assumptions. Therefore, this work contributes to the current status by:

1. developing a preliminary dedicated control strategy that guarantees compliance with all technological constraints of a real R718 HTHP, such as maintaining acceptable discharge temperatures during normal heat pump operation under continuously varying steam demand and geothermal source temperature. The reliability of this strategy was assessed through the selected real-world case study (i.e., textile industry);

2. assessing the economic and environmental advantages of the proposed R718 HTHP in comparison with conventional natural gas-fired boilers, based on the same industrial case study;
3. incorporating field measurements from an actual geothermal well into the analysis, addressing the current lack of use of actual field measurements (including the heat source side).

In particular, this paper presents the modelling and simulation study of an HTHP that uses geothermal energy as the heat source. The simulation model was based on the GEOSYN HTHP prototype and the performance was evaluated for a dynamically varying actual heat load and geothermal source temperature. The economic and environmental impact (GHG emission) of the replacement of a natural gas-fired boiler with the proposed HTHP was analyzed in the context of an actual textile industry needing saturated steam at approximately 11 bar and 185 °C in three countries, namely Italy, Austria and Denmark.

2. Materials and Methods

2.1. GEOSYN High-Temperature Heat Pump

Within the framework of the GEOSYN project, an HTHP utilizing R718 as the refrigerant is currently under development to improve the utilization of geothermal energy and provide eco-friendly industrial process heating. The vapor compression heat pump is designed to operate with an evaporator temperature of approximately 120 °C and is capable of achieving a temperature lift of up to 80 K. The evaporator is intended to be coupled with a geothermal heat source providing temperatures in the range of 130 °C to 140 °C and located in Monterotondo Marittimo (Italy) where the GEOSYN HTHP will be installed. The geothermal heat source enables the evaporator to function above atmospheric pressure, which simplifies system design and eliminate operational safety concerns. A simplified schematic representation of the HTHP is shown in Fig. 1.

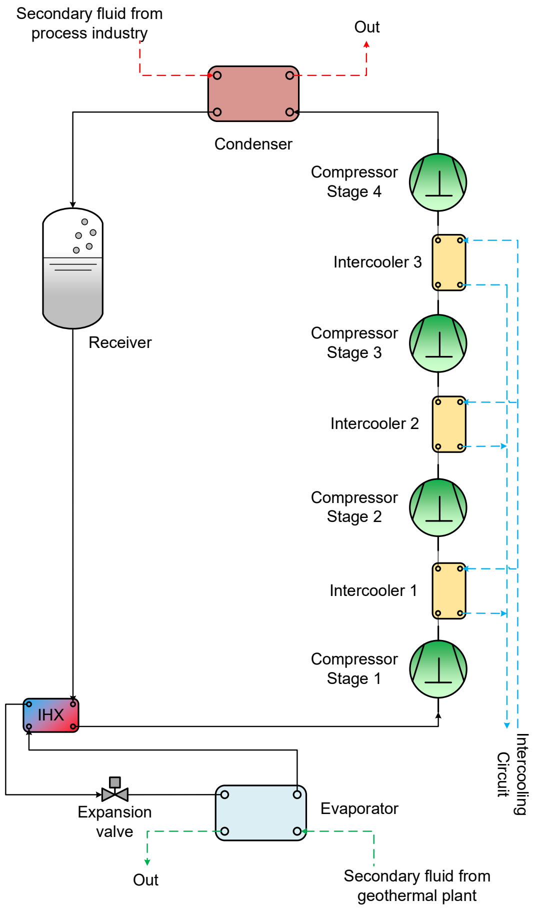

Figure 1. Schematic of the GEOSYN heat pump.

For the 50 kW prototype, a novel four-stage oil-free piston compressor is being developed, capable of operating at condensation temperatures up to 200 °C. Water vapor has a high specific heat ratio, which leads to a high discharge temperature during compression. Oil-free operation is essential at such elevated temperatures, as conventional lubricants are susceptible to thermal degradation, which can compromise compressor reliability and reduce its operational lifespan. Also, discharge temperature must be controlled to ensure compliance with the material limits of the compressor. The pressure ratio of each stage needs to be selected to ensure that the operating temperature will not exceed 270 °C. In addition, to ensure a reasonable discharge temperature of each compression stage, the refrigerant is intercooled after every stage, limiting the degree of superheating to approximately 20 K. Furthermore, an internal heat exchanger (IHX) is incorporated to ensure a superheating degree of approximately 20 K at the suction of the first compression stage. This design measure prevents liquid refrigerant from entering the compressor, thereby protecting it from potential mechanical damage and ensuring safe operation. Additionally, the IHX enhances system performance by increasing subcooling on the high-pressure side. The details of the control mechanism are provided in Section 2.3.

2.2. Selected Case Study

With its current design, the GEOSYN HTHP is well-suited for heating applications requiring temperatures between 180 °C and 200 °C. In the present study, a detailed analysis was conducted to evaluate the viability of the GEOSYN HTHP for meeting the thermal demands of a case study related to the textile industry. In the textile industry, various processes, such as drying, pressing, fixing, and printing, require process heating at temperatures of about 180 °C. Steam and water are commonly used as the heating media to meet these high temperature demands efficiently. The required technical information for the selected case study was obtained from a study carried out by Schenk et al. [13]. Currently the required saturated steam at approximately 11 bar and 185 °C is provided by a natural gas-fired boiler, whose specifications are given in Table 1. The daily average steam requirement of the selected industry for different months is shown in Fig. 2. The hourly steam demand varied between 0.085 t/h and 2 t/h across the year. The lowest steam demand was recorded in the month of March, while the highest was observed in July. On a typical day, peak steam demand occurs between 15:00 and 16:00, whereas the minimum demand was observed between 19:00 and 20:00.

Table 1. Relevant parameters of the process heating required by the selected case study [13].

Parameter	Value
Working Pressure	11 bar
Maximum steam flow rate	2 t/h
Nominal heating capacity	1380 kW
Nominal thermal efficiency	94.6 %
Overall thermal efficiency (with Economizer)	Up to 95.1 %
Nominal feed-water temperature	102 °C
Nominal saturation pressure and temperature	11 bar & 184.2 °C

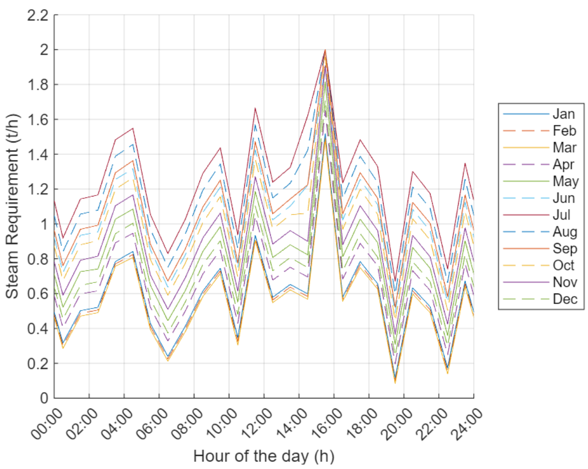

Figure 2. Daily load profiles for different months of the process heating required by the selected case study (derived from 13]).

2.3. Dynamic Modelling and Control Strategy

The dynamic model of the GEOSYN heat pump for the selected case study was developed using the MATLAB/Simulink platform [14] while all the thermo-physical properties were evaluated using CoolProp [15]. The corresponding Simulink model is schematized in Fig. 3. The heat exchangers were primarily developed using the System-Level Heat Exchanger block, which represented the heat transfer between two distinct two-phase fluid networks. In particular, the heat exchanger blocks were parameterized using the nominal operating conditions, and their sizing was adjusted to reproduce the specified performance at steady-state under these conditions. The nominal operating condition that was used to obtain system-level information of the heat pump corresponds to an evaporating temperature of 120 °C and a condensing temperature of 200 °C. Like heat exchangers, compressors were modelled as positive-displacement compressors using nominal operating conditions. For the current model, the pressure ratios of the first, second, third, and fourth compressor stages are 2.2, 1.7, 1.5, and 1.4, respectively. Saturated steam from the aforementioned geothermal well served as the heat source and was supplied to the evaporator. The mass flow rate of the geothermal steam was regulated by the circulation pump on the secondary fluid side of the evaporator to ensure complete condensation and subcooling by 5 K at the evaporator outlet. In the dynamic model, all pumps were modelled as ideal flow rate sources that do not perform work on the fluid or exchange heat, regardless of the resulting mass flow rate. The dynamic temperature profile of the geothermal steam was derived from the field measurements taken at a geothermal plant in Monterotondo Marittimo (Fig. 4). The electronic expansion valve (EEV) was modelled using the Local Restriction block, which models the pressure drop due to a localized reduction in flow area. The restriction area was controlled to maintain a constant superheating degree of 20 K at the suction of the first-stage compressor. Additionally, the compressor speed was modulated by a feedback controller to ensure the required sink outlet temperature of 185 °C at the condenser of the HTHP. The inlet temperature of the sink was kept at 102 °C [13] and the mass flow rate was dynamically varied by the flow rate source on the secondary fluid side of the condenser according to the heating requirement. Furthermore, the mass flow rate of the cooling fluid supplied to the intercoolers was regulated by three independent pumps to maintain a superheating degree of 20 K at the suction port of each compression stage. A summary of the controlled parameters and the corresponding manipulated variables is given in Table 2. All controllers implemented in the model were of the Proportional-Integral (PI) type. A simple set-point control might maintain steady-state conditions, it is generally insufficient for safely following dynamic steam demand or varying heat source temperatures, as it can lead to temporary violations of critical constraints or even system failure. Each PI controller independently tracks its set point to ensure that all operational constraints are maintained during normal operation. The major assumptions adopted in dynamic model development were:

- the isentropic, volumetric, and mechanical efficiencies of the compressor were assumed to be 75%, 85%, and 95% (as suggested by the compressor manufacturer: Dorin), respectively;
- heat losses/gains from/to all the components of the system were neglected;
- pressure drops across the heat exchangers were neglected;
- power consumption of the various pumps in the system was neglected;
- wall thermal mass of the heat exchangers was not considered.

The main objective of the control strategy was to maintain a superheating degree of 20 K at the suction port of each compressor, while ensuring that the discharge temperature remained below 270 °C (as specified by the compressor manufacturer).

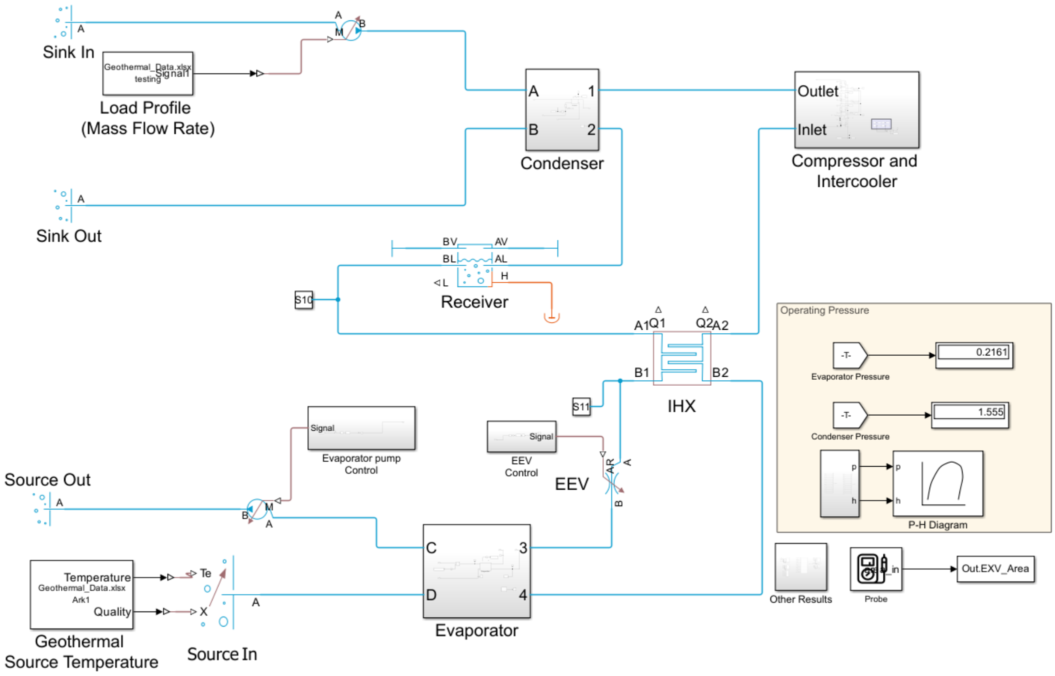

Figure 3. Simulink model of the GEOSYN HTHP.

Figure 4. Geothermal data logging facility at the GEOSYN geothermal well.

Table 2. Controlled parameters and manipulated variables in the proposed control system

Controlled Parameter	Manipulated Variable
Sink outlet temperature	Compressor speed
Source outlet temperature	Mass flow rate of the geothermal steam
1st stage degree of superheat	EEV restriction area
2nd, 3rd and 4th stage degree of superheat	Mass flow rate of the intercooler cooling fluid

2.4. Operating Cost and Environmental Impact Assessment

The operating cost and environmental impact of the proposed heat pump were assessed with respect to three countries, namely Austria, Denmark, and Italy. To estimate the heat pump operating cost in these countries, the hourly average electricity rate for June 2025 was obtained from the European Wholesale Electricity Price Data provided by Ember [16]. From Fig. 5, it can be observed that the hourly average electricity rate in Italy is significantly higher than that in Austria and Denmark. This is because the Italian energy mix depends primarily on natural gas and electricity purchased from other countries, whereas in Austria it is predominantly hydropower, and in Denmark it is wind energy. For all three countries, solar power serves as the secondary source of electricity, which leads to a substantial decrease in electricity rates during the daytime. The boiler operating cost was estimated based on the natural gas price of 40 €/MWh [17]. Three different scenarios were considered for the operating cost assessment, i.e., (i) actual electricity and natural gas prices (i.e., baseline scenario), (ii) electricity and natural gas prices increased by 20%, and (iii) electricity and natural gas prices increased by 40 %. Furthermore, the CO_2 emission factors for electricity generation in the considered countries, as well as for natural gas used in the environmental impact assessment, are presented in Table 3 [18].

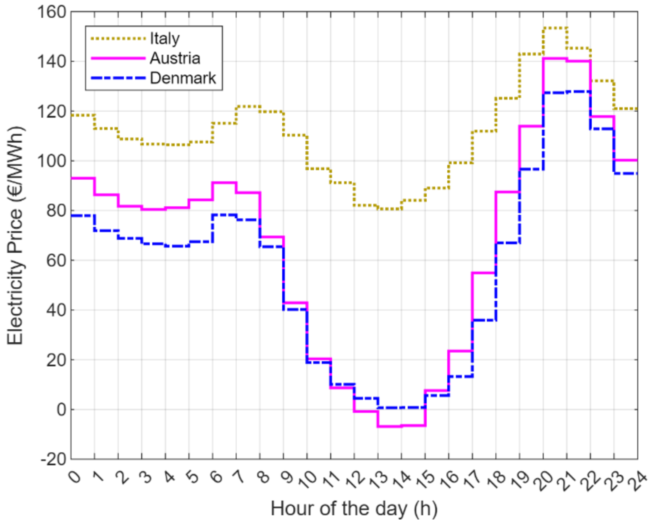

Figure 5. Hourly average electricity rate in June 2025 [16].

Table 3. GHG emission factor for the environmental impact assessment [18].

Parameter	Value
GHG emission factor of electricity in Italy	0.240 $kgCO_2$-eq/kWh
GHG emission factor of electricity in Austria	0.033 $kgCO_2$-eq/kWh
GHG emission factor of electricity in Denmark	0.094 $kgCO_2$-eq/kWh
GHG emission factor of natural gas	0.25 $kgCO_2$-eq/kWh

3. Results and Discussion

The performance of the HTHP for the proposed application was evaluated using two dynamic input parameters: the geothermal source temperature and the steam load profile, as illustrated in Fig. 6(a) and 6(b), respectively. Under the simulated conditions, the actual geothermal source temperature varied between 135.2 °C and 143.8 °C, while the steam demand ranged from 0.49 t/h to 1.91 t/h (0.14 kg/s to 0.53 kg/s). The system's performance was assessed over a 24-hour period, with the steam demand profile corresponding to the load requirements of the selected case study during the month of June. The steam demand in other months followed a similar pattern, so the conclusions drawn from the June profile can be considered broadly indicative. The variation in sink outlet temperature during the heat pump operation is presented in Fig. 6(c). It can be observed that, under varying operating conditions, the proposed system incorporating the compressor speed modulation was able to maintain a stable sink outlet temperature of 185 °C and thus meet the required temperature for the case study. Furthermore, the COP of the HTHP during operation ranged from 3.28 to 3.70, as shown in Fig. 6(d), with an average value over the 24-hour evaluation of 3.48. As expected, it can be observed that a higher geothermal source temperature combined with a lower steam demand resulted in an increased COP of the heat pump. The condenser heat rate was found to follow a trend similar to that of the steam load profile, as illustrated in Fig. 6(e), and vary between 0.32 MW and 1.25 MW. From the results obtained, it can be concluded that the implemented control strategy can steadily maintain the steam temperature required by the selected industry for varying heat loads. Beyond the steam demand represented by June's monthly profile, steam demands that are compatible with the compressor capacity and operating conditions can be met by the proposed system. Furthermore, the system is designed for a condensing temperature of 200 °C; therefore, sink outlet temperatures other than 185 °C are achievable with a realistic heat exchanger approach temperature.

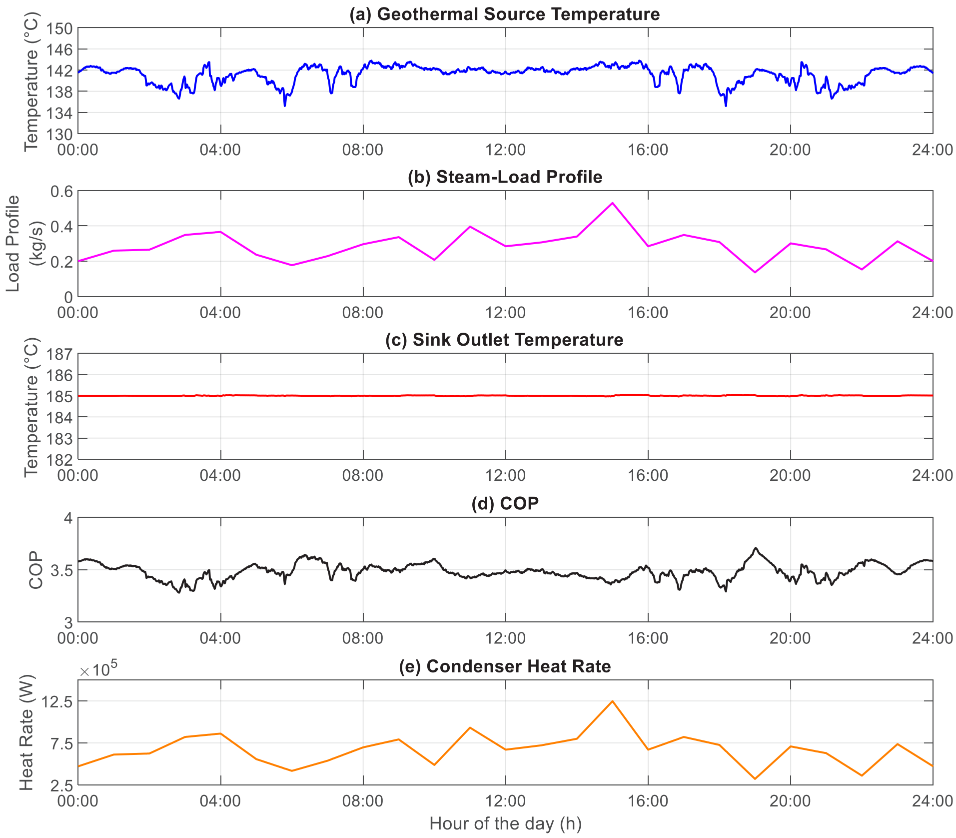

Figure 6. Key operating and performance parameters of the GEOSYN HTHP in the selected case study.

The impact of various control strategies implemented to safeguard the compressor operations is illustrated in Fig. 7. The primary objective of these strategies was to maintain a superheating degree of 20 K at the suction port of each compressor and ensure that all the discharge temperatures remain below 270 °C. The results obtained showed that all the discharge temperatures were maintained within the range of 241 °C to 261 °C, while the superheating degree across the suction ports of all compressor stages remained consistently around 20 K. Under design conditions, the highest discharge temperature was observed in Stage 4, followed by Stage 1, while Stage 3 consistently exhibited the lowest discharge temperature. This was due to the design pressure ratios of the different stages, and the assumption of negligible pressure drops in the heat exchangers. However, this sequence can be altered by factors, such as increased pressure drop across heat exchangers, reduced source temperatures, or elevated sink temperatures. These conditions may not only disrupt the temperature sequence but also lead to discharge temperatures exceeding the safety threshold of 270 °C. It can be concluded that under the investigated conditions, the proposed control mechanisms successfully achieved the targets of maintaining a 20 K superheating degree and limiting the discharge temperature to 270 °C. Further, the variation of the manipulated variables—namely the EEV restriction area, compressor speed, and source mass flow rate—is shown in Fig. 8. In the present study, no constraints were imposed on these variables. The EEV restriction area was found to vary between 5.10×10^{-6} and 1.90×10^{-5} m², while the compressor speed ranged from 730 to 3175 rpm. Under the simulated conditions, the geothermal steam (source) mass flow rate varied between 0.137 and 0.527 kg/s. All the manipulated variables were found to follow the same trend as the steam demand.

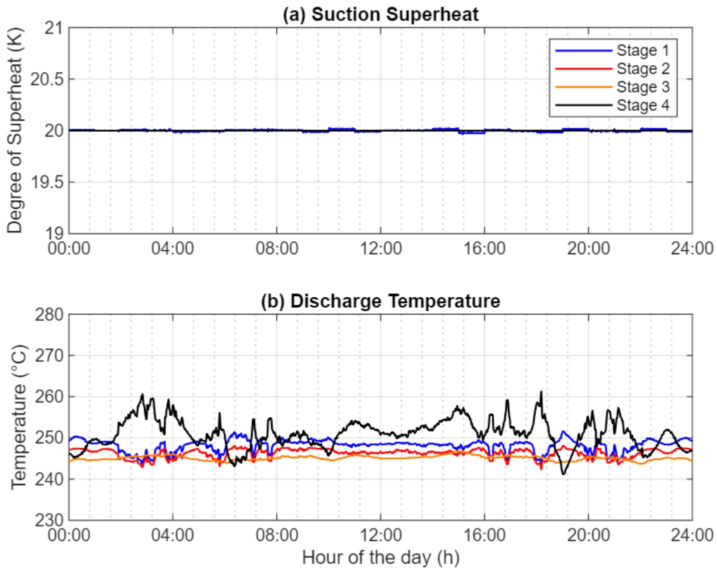

Figure 7. Variation of the superheating degree at the suction port and discharge temperatures of each compressor stage.

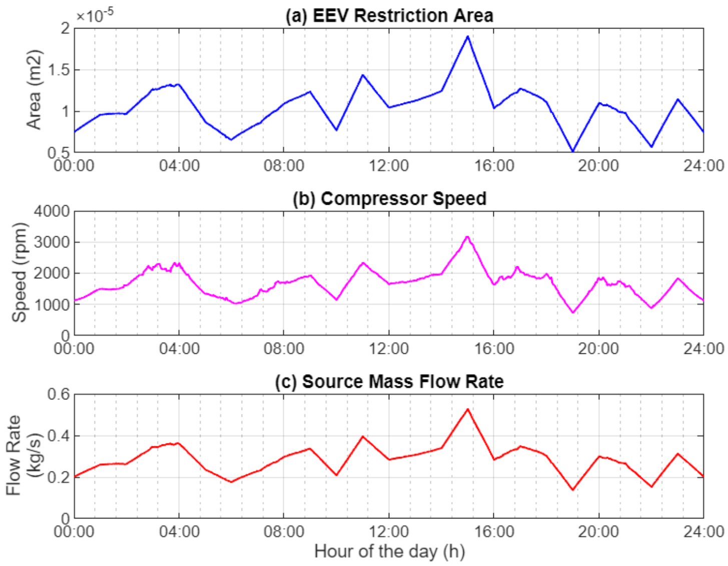

Figure 8. Variation of the manipulated parameters (a) EEV Restriction Area (b) Compressor Speed and (c) Source Mass flow rate.

Fig. 9 illustrates the operating costs of the heat pump and the boiler under different scenarios. It can be observed that, in the baseline scenario, the GEOSYN heat pump achieved a reduction in operating cost compared to the boiler when assessed under the electricity and gas price conditions of Italy, Austria, and Denmark, with reductions of 25 %, 59 %, and 64 % , respectively. The relatively higher operating cost of the heat pump in the Italian scenario is attributed to the higher average hourly electricity price compared to those in Austria and Denmark. Furthermore, even with a 20% increase in the electricity cost, the boiler operating cost remained 12%, 103%, and 132% higher than that of the GEOSYN heat pump when evaluated under the price conditions of Italy, Austria, and Denmark, respectively. If the electricity price increases by 40% and the natural gas price by 20%, the operating cost of the boiler still remains 15%, 109%, and 139% higher than that of the GEOSYN heat pump in the corresponding country scenarios. It can be concluded that the GEOSYN heat pump provides significant economic benefits over the boiler during operation.

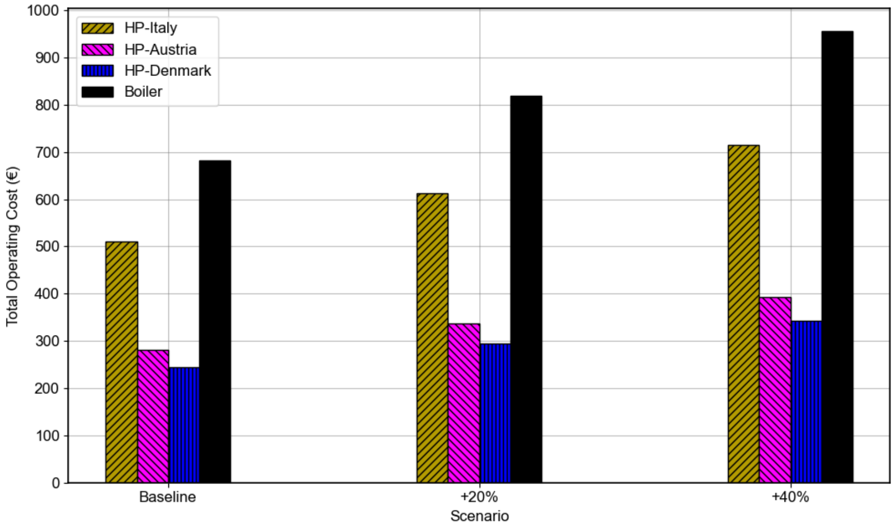

Figure 9. Comparison of the operating costs of a boiler and the GEOSYN HTHP in the selected case study.

Fig. 10 illustrates the GHG emissions from the boiler and the heat pump with respect to different countries. The proposed heat pump reduced the GHG emissions by 74%, 96%, and 90% when compared to the boiler. The highest reduction in GHG emissions was observed for the scenario representing Austria, followed by that of Denmark. This reduction can be attributed to the significant share of renewable energy sources in the electricity mix of these countries, which results in lower GHG emission factors associated with electricity generation. It can be concluded that the proposed HTHP offers a significant reduction in operating costs and GHG emissions compared to conventional boilers in textile-industry applications.

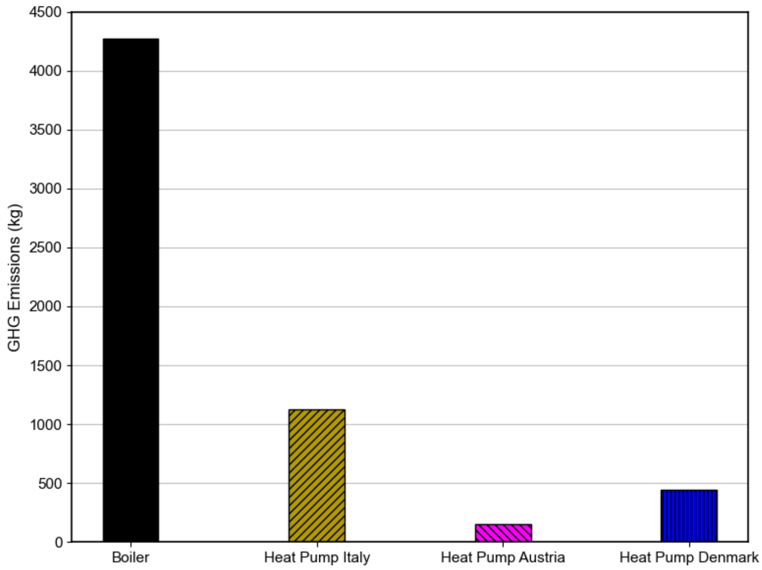

Figure 10. GHG emissions from a boiler and the GEOSYN heat pump in the selected case study.

4. Conclusions

High temperature heat pumps offer a promising solution for decarbonizing industrial sectors by replacing fossil fuel-based boilers and providing the heat required for various thermal processes. Geothermal heat is a promising heat source for HTHPs to support process heating applications that demand temperatures in the range of 180–200 °C. This study presents the dynamic analysis of a geothermal R718 HTHP in the context of the replacement of a natural gas-fired boiler in a textile industry, which requires steam at 185 °C and 11 bar for different process heating applications. The dynamic model of the proposed heat pump was developed in the MATLAB/Simulink platform, along with control strategies for limiting the compressor discharge temperature and achieving the required sink outlet temperature. The model was based on dynamic field measurements from an actual geothermal well as well as the dynamic steam load profile of the industry.

It was found that proposed HTHP can achieve an average COP of 3.48 and a reduction in operating costs ranging from 25% to 64% compared to natural gas-fired boiler during June 2025 in the Austrian, Danish and Italian scenarios. Furthermore, the results suggest a potential reduction in GHG emissions of up to 96% under the same conditions. Finally, the proposed control strategy effectively maintained the superheating degree and the discharge temperature within the compressor's safe operating limits, while achieving the desired sink outlet temperature of 185 °C.

This study supports the advancement of HTHP technology through an improved understanding of control methods and integration approaches with geothermal energy systems. It is important to emphasize that validating this model is essential, particularly by refining assumptions made in the present study, such as constant compressor efficiencies and negligible heat exchanger pressure drops. Future work will focus on improving this preliminary dynamic model (and the related control strategy) of the heat pump through calibration and validation using the data from the prototype developed within the GEOSYN project as well as through the investigation on the dynamic behaviour of the heat pump during start up, shut down and ramp up.

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