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HIGH TEMPERATURE HEAT PUMP TEST BENCH WITH NATURAL REFRIGERANTS FOR STEAM GENERATION FOR DECARBONIZING INDUSTRIAL HEAT

Sebastian Benkert (corresponding author), Lukas Joos, Ursula Wittstadt, Lena Schnabel

Fraunhofer ISE

sebastian.benkert@ise.fraunhofer.de

Summary

This contribution investigates the potential of high-temperature heat pumps (HTHPs) to decarbonize industrial steam demand, particularly in sectors like chemicals and food. Using a test bench with natural refrigerants, the study simulates steam processes at 115 °C, utilizing waste heat sources between 30 and 100 °C. The setup has a thermal capacity of up to 125 kWth. Initial results indicate a coefficient of performance (COP) of 4 at low temperature lifts and 2 at high temperature lifts, with Carnot efficiencies ranging from 26% to 42%. The research also examines three operating modes and compares the performance of two different condensers for direct steam generation.

Keywords: High Temperature Heat Pumps, steam generation, natural refrigerants

Field of application for the findings: Sustainable Heat for Industrial Processes

Addressed audience:heating utility operators, HTHP manufacturers, end users, energy planners and consultants

1. Introduction

The demand for process heat predominantly relies on steam as an energy transport medium. Assuming a suitable heat source is available, a steam-generating HTHP can effectively decarbonize heat demand when operated with renewable electricity. Despite the increasing number of demonstrations of steam-generating HTHPs in laboratory settings (Vries et al. 2024, Marina et al. 2021) and real industrial applications (Amato et al. 2024, Hamacher 2023), there remains a significant gap in knowledge regarding the most efficient methods for steam production with HTHPs and the optimal design of necessary components.

Direct steam transfer offers several advantages, particularly concerning complexity and space requirements for lower steam temperatures around 120 °C in low-temperature steam applications (Arpagaus et al. 2026, Wilk et al. 2019). This article focuses on the direct steam generation capabilities of a Plate and Shell Heat Exchanger (PSHX), which combines the scalability of higher capacities and the robustness of Shell-and-Tube heat exchangers while requiring less refrigerant charge, similar to Plate heat exchangers. Additionally, the PSHX facilitates easy cleaning of the shell-side volume.

2. Methods

The heat pump test bench comprises a simple cycle featuring key components such as an evaporator, compressor, two condensers, and an electronic expansion valve, along with an internal heat exchanger. The flowchart depicting this setup is illustrated in Figure 1.

In the presented flowchart, the PSHX serves as the primary condenser while the second condenser, a Brazed Plate Heat Exchanger (BPHX), is passive. This means the BPHX is flowed through with refrigerant downstream to the PSHX but is not flowed trough with water on the secondary side. Therefore no heat transfer occurs

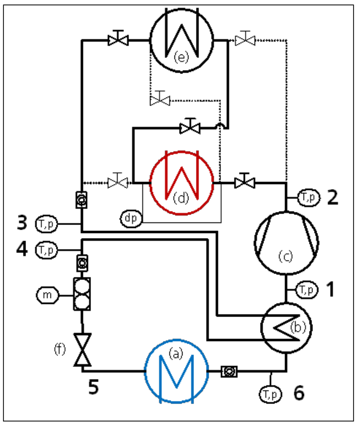

Fig. 1: Flowchart of the investigated heat pump: (a) evaporator, (b) internal heat exchanger, (c) compressor, (d) active condenser (PSHX), (e) passive condenser (BPHX), (f) electronic expansion valve.

and the BPHX is acting like an accumulator. The evaporator and internal heat exchanger are also designed as BPHX.

The hydraulic module facilitates control over water inlet temperature, mass flow, and pressure for both the heat source and sink. This allows the heat sink to function in various modes: pressurized water heating (PWH), wet steam generation (WSG), and dry steam generation (DSG).

During PWH, the water pressure is maintained above the refrigerant condensation temperature, allowing the water to enter as a liquid and exit at a higher temperature while maintaining its liquid state. For WSG, the pressure is adjusted to match the water saturation temperature, enabling the refrigerant to evaporate the water in the heat exchanger, resulting in a two-phase outlet. In DSG mode, further reduction of water mass flow leads to complete evaporation and slight superheating.

The PSHX outlet on the water side connects to a water-cooled plate condenser, where an energy balance determines the steam outlet quality during WSG mode. The compressor speed is adjustable via a frequency inverter but is fixed for the measurements at 90% of full speed.

3. Results and Discussion

Figure 2 illustrates the overall heat transfer coefficients plotted against steam outlet quality. As shown, an increasing trend in the overall heat transfer coefficient correlates with higher steam outlet quality. This is attributed to the reduced contribution of the sensible heating zone, where lower heat transfer coefficients are observed compared to zones with evaporating water.

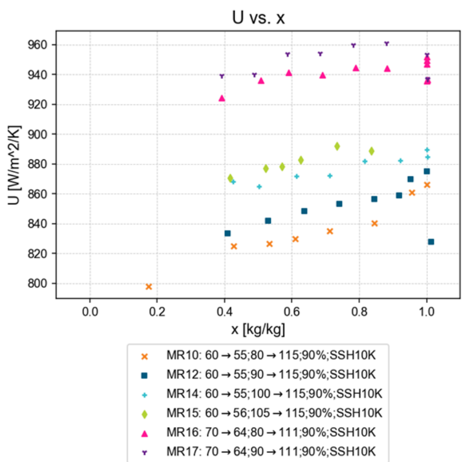

Fig. 2: Overall heat transfer coefficients U plotted against steam outlet quality x

For steam qualities nearing 1.0 or in slightly superheated conditions, a notable decline in the overall heat transfer coefficient occurs. This reduction is likely due to the volumetric occupation of steam within the heat exchanger, diminishing the surface area available for phase transitions.

Increasing the water inlet temperature corresponds with a similar trend; as the zone for water preheating diminishes, the overall heat transfer coefficient rises.

4. Conclusion and Outlook

This work presents experimental results from the HTHP test bench operating in both wet and dry steam generation modes, emphasizing heat transfer dynamics in the PSHX. Findings indicate that increasing steam outlet quality and water inlet temperature positively influence the overall heat transfer coefficient.

Future research will focus on more granular evaluations of heat transfer in individual zones, ultimately leading to enhanced design and operational recommendations for PSHX in direct steam generation applications utilizing HTHPs.

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