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

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. Abstract

In Germany, approximately 50% of total energy demand is attributed to heat, with 470 TWh required for process heat, primarily generated from fossil fuels. The industrial sectors, including chemicals, food, and paper, present significant opportunities for decarbonization, with potential reductions of at least 64 TWh achievable through the adoption of high-temperature heat pumps (HTHPs) [4]. Currently, the majority of market solutions rely heavily on synthetic refrigerants, which are projected to be phased out due to environmental regulations.

This study aims to explore the potential of HTHPs in meeting industrial steam demand sustainably. Through the use of a test bench designed for a steam-generating HTHP utilizing the natural refrigerant n-butane (R600) and a Plate and Shell heat exchanger (PSHX), the performance of the system is evaluated for producing heat in the form of pressurized water or steam at 115 °C. This process harnesses waste heat sources ranging from 40 to 80 °C, thereby maximizing energy efficiency.

The experimental setup features a prototypical open-type piston compressor with a motor power of 31 kWel and a thermal capacity of up to 125 kWth. The coefficient of performance (COP) observed aligns with findings from prior studies in the literature. The HTHP operates in three distinct modes: pressurized water heating (PWH), wet steam generation (WSG), and dry steam generation (DSG). Notably, the efficiency of heat transfer shows a marked increase when steam is generated, indicating the system's adaptability and effectiveness.

2. 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 ([3],[6]) and real industrial applications ([1],[5]), 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 ([2],[7]). This article focuses on the direct steam generation capabilities of a 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.

3. Methods

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

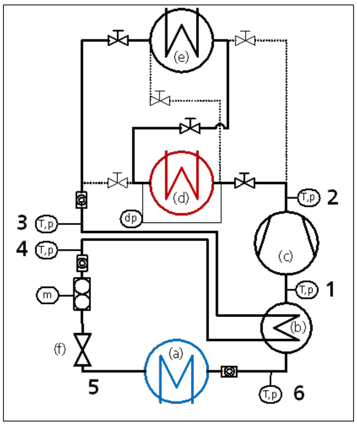

Fig. 1: Flowchart of the investigated heat pump: (a) evaporator, (b) internal heat exchanger, (c) compressor, (d) active condenser (PSHX), (e) passive condenser (BPHX), (f) electronic expansion valve.

The PSHX serves as the primary condenser while the evaporator and internal heat exchanger utilize Brazed Plate heat exchangers (BPHX). The study operates the heat pump using the PSHX with a series-connected BPHX acting as a liquid accumulator.

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. 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 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.

4. 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.

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.

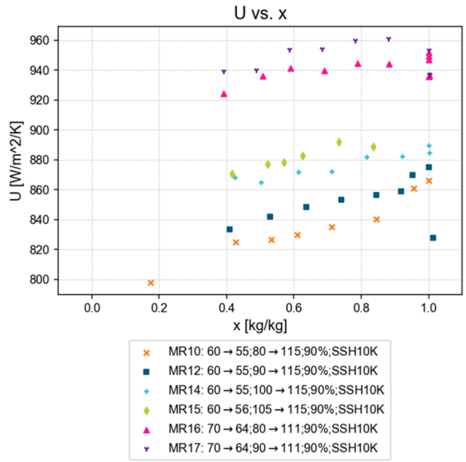

Fig. 2: Overall heat transfer coefficients U plotted against steam outlet quality x

5. 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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