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CHASE: Combined heat pump and thermal storage for energy efficient industry.

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Abstract

Industrial heating requires 66% of the total industrial energy demand in the EU. Heat electrification is one of the solutions to achieve the climate neutrality goals by 2050. However, the intermittent character of electricity generated by renewables is one of the main barriers to decarbonising industrial heat. Industrial heat pumps are one of the potential solutions to generate heat with electricity, and when these systems are combined with latent thermal energy storage, they could offer the ideal solution for periods of high peak thermal loads and in high peak electricity prices.
This study investigates the combination of a High Temperature Heat Pump (HTHP) with Latent Heat Thermal Energy Storage (LHTES) in a single lab-scale system. The system is currently in the manufacturing stage and is planned for experimental validation under real conditions, targeting thermal power output of 100 kW at 150 °C output, achieving >50% of Carnot efficiency. In addition, numerical modelling will validate its operation at 250 °C.
The future demonstration will allow to evaluate the feasibility of the system and its performance, flexibility, and response to fluctuations in both thermal load and power supply.

Keywords: Latent Thermal Energy Storage; High Temperature Heat Pump; Phase Change Material; Steam Compression; Industrial Heat;

1. Introduction

The EU is aiming for climate neutrality by 2050, meaning an economy with net-zero greenhouse gas emissions. A combination of different measures is planned to achieve the targets. On one hand, the efficiency of energy use should be increased, hence reducing the total energy consumption. On the other hand, the energy supply for transport, buildings and the industrial sector should be generated based on renewable sources. In addition, the installed renewable capacity should increase in the coming years, where the increase in renewable electricity is planned to be expanded to 592 GW solar PV and 510 GW wind by 2030 [1]. Looking at the global energy use, more than half is consumed in the form of heat. In the industrial sector, heat represents about 75% of the industry's energy demand globally (Approx. 23 610 TWh). Roughly half of this heat demand is in the temperature range below 400 °C.

In the EU, only 23% of the energy for heating and cooling across all sectors comes from renewable energy sources [2]. The main reason for the limited uptake of renewables is the intermittent character of wind and solar, and the need to produce heat at a competitive price. The latter can be achieved by using high temperature heat pumps (HTHP) as the heat output is a factor, expressed as the Coefficient of Performance (COP), higher than the electricity input. One of the challenges of HTHP is the relatively high capital expenses (CAPEX), which result in providing a heat output covering the base-load. The peaks in industrial heat demand, e.g. during startup or in batch processes, cannot be covered, nor can the heat pump be stopped during times of (renewable) electricity scarcity (and high prices) without losing the heat production. By combining the HTHP with a thermal energy storage (TES), peak heat demand and periods of electricity scarcity can be covered. As the COP of heat pumps is significantly reduced by increasing temperature lifts, latent heat thermal energy storage (LHTES) is the preferred type of TES because it has the highest thermal energy density over a few degrees temperature range. Although LHTES technologies are already available at commercial scale, HTHP systems present lower TRL (Technology Readiness Level) as their operating temperature increases. Therefore, integrating both technologies represents an innovative approach that has not yet been implemented at large scale [3].

The aim of the CHASE project, standing for "Combined Heat pump And thermal Storage for Energy efficient industry", is to enable efficient integration of renewable electricity providing heating of industrial processes by combining HTHP and LHTES at a relevant scale. This will be achieved by developing a heat pump capable of upgrading waste heat to deliver process heat, in the form of steam, at temperatures ranging from 150 °C to 250 °C. For this case, the selected system is a steam compression heat pump (SCHP), which is a HTHP that uses steam as a working medium. It compresses low pressure steam to a higher pressure, enabling its reuse in the process. The SCHP utilizes waste heat to evaporate steam, compress it and deliver it to charge thermally the LHTES as well as providing heat to the industrial process via existing steam systems, removing the need for additional heat exchangers and secondary loops. The latter means a slight reduction in CAPEX but more importantly, reduces the required temperature lift otherwise needed to transfer heat from the working medium to the steam system, resulting in a higher COP and thereby lower OPEX.

The aforementioned temperature levels are commonly required in sectors such as food processing, paper manufacturing, and the chemical industry. The SCHP will be coupled with the LHTES system, specifically designed to operate under the conditions imposed by the heat pump. The thermal storage will play a critical role in enhancing system flexibility and efficiency.

In order to determine the potential of this configuration, within the CHASE project, the combination of the SCHP and LHTES will be tested at a 100kW$_{th}$ and 100kWh scale in the lab. Boundary conditions with regard to the desired dynamic behaviour, data from industrial end users will be used to determine typical steam demand profiles as well as dynamic electricity price profiles based on day-ahead markets.

2. Conceptual framework

The CHASE configuration consists of two main systems: the SCHP and the LHTES. The SCHP system is developed in collaboration with Standard Fasel. The heat pump consists of two main skids: the vacuum boiler skid and the compressor skid. The vacuum boiler extracts heat from a water loop and consists of a vessel of 1.5 m^3 volume, with a circulating loop with a heat exchanger and a water pump. The water pump enhances heat transfer from the source and also ensures recirculation from the bottom of the boiler. The water level is maintained by a source of feedwater to the vacuum boiler. The compressor skid takes the produced steam from the vacuum boiler skid and compresses it to the desired steam pressure. It consists of two screw compressors connected in series, each with a maximum compression ratio of 1:5, allowing upgrading 200 mbar(a) to 5 bar(a) steam. In addition, the skid includes the electric motors, the oil management system and the water injection loop. The water injection helps in controlling the superheat of the discharged steam as compressing water vapour results in superheating.

Waste heat is transferred to the heat pump through the heat exchanger at the vacuum boiler. The heat delivered is at temperatures between 60 and 90 °C, and since the vacuum boiler is under sub-atmospheric conditions (0.2 – 0.7 bar(a)), water is evaporated. The low pressure steam generated is directed to the suction of the first compressor, which delivers steam at atmospheric pressure to the second stage. The discharge of the second compressor delivers steam at approximately 5 bar(a) to the process. The heat pump is capable of producing saturated steam with thermal capacity up to 250 kW$_{th}$.

The LHTES system has a latent thermal storage capacity of 100 kWh and operates at temperatures above 150 °C. It consists of a large vertical cylinder with small tubes inside, as seen in the section view shown in Figure 1. The tubes, each measuring 3 m length and 60 mm in diameter, are filled with adipic acid as the phase change material (PCM). To charge the LHTES, steam is supplied at the bottom of the storage tank and exits at the top. Heat is transferred from the steam to the tubes, the PCM melts, and the steam condensates drop to the bottom of the tank. Condensate from the bottom of the storage tank is recirculated partly to the top of the tank and partly to the laboratory's steam generation system. To discharge the PCM water enters from the top of the LHTES, flowing over the tubes generating steam. The steam temperatures for charging must be above the melting point of the adipic acid (152 °C) and below the melting point during discharge. The general overview of the CHASE configuration is presented in Figure 2.

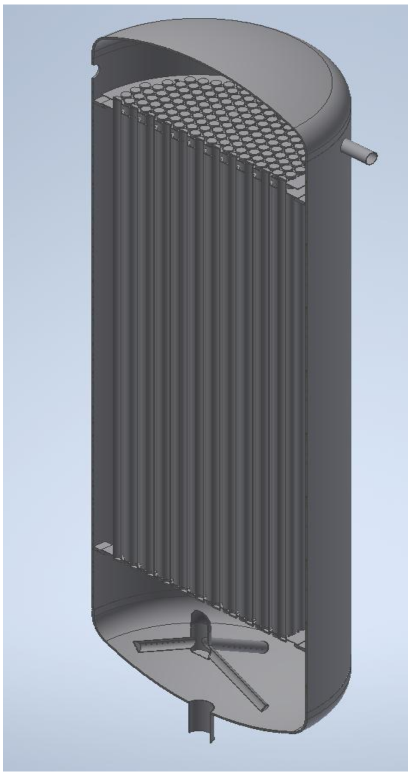

Figure 1. Section view of the LHTES 3D drawing showing the pressure vessel and the PCM tubes. Connections at the top and bottom show the steam supply and outlet ports.

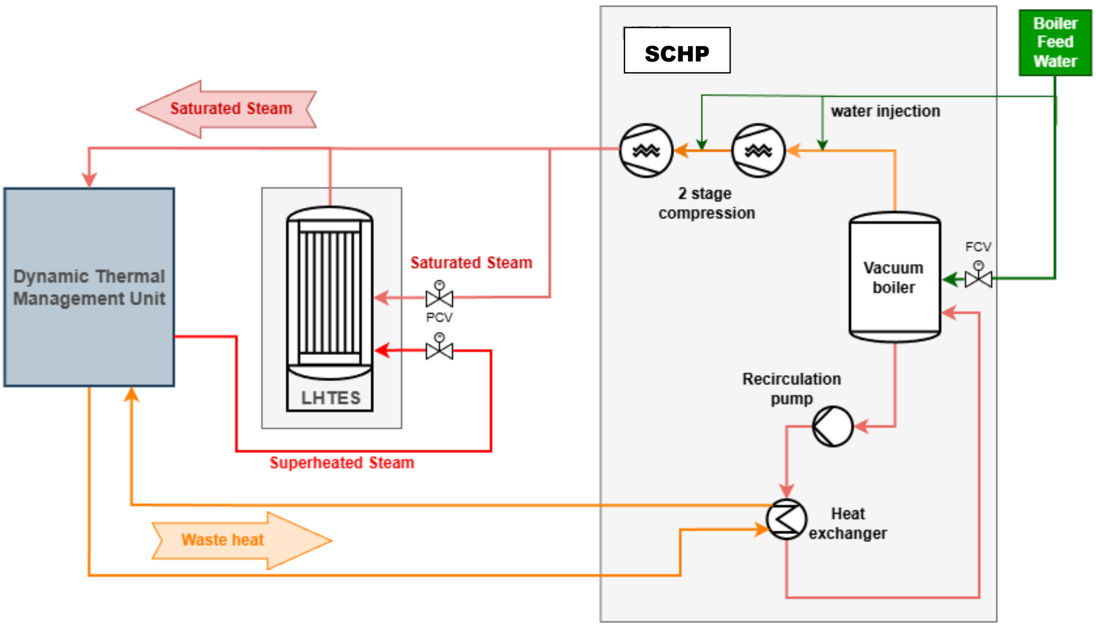

Figure 2. Schematic diagram of the CHASE setup consisting of the heat pump and the LHTES.

3. Expected performance and challenges

The SCHP and LHTES systems are an evolution of earlier design concepts that have been studied theoretically and experimentally. Building on these previous developments, it is possible to predict certain performance characteristics as well as identify potential challenges that could arise during implementation.

Steam Compression Heat Pump

A prototype of the steam compression heat pump (SCHP) was previously developed and tested under different temperature and steam flow conditions. The analysis of the results revealed issues that have been addressed in the redesigned system [4]. One of the main performance drawbacks was related to the vacuum boiler, which showed a large temperature difference between the waste heat and the steam generated by the vacuum boiler. By using a plate-based evaporator, it is expected to reduce this temperature difference and also reduce the setup footprint. In addition, the maximum steam outlet temperature of the previous SCHP was limited to 150 °C, primarily due to the relatively low steam pressure generated in the vacuum boiler and the limited power driving the electric motor of the first compression stage. Replacing the motor with a larger unit will enable the generation of higher steam pressure, increasing the previous thermal output from 250 kW_{th} to 300 kW_{th}. Increasing the temperature and thermal capacity will also enable the reduction of the charging time of the LHTES. Reaching a steam outlet temperature of 160 °C, the theoretical charging time results in 40 minutes, while at 170 °C, the charging time could drop significantly to 15 minutes, as shown in Figure 3.

The third improvement relates to the control of the water injection required in the compression stages. In the previous SCHP prototype, the stability in the control of the water injection was difficult. A new control system will be used in this prototype, allowing stable operation and increasing the performance of the compressors.

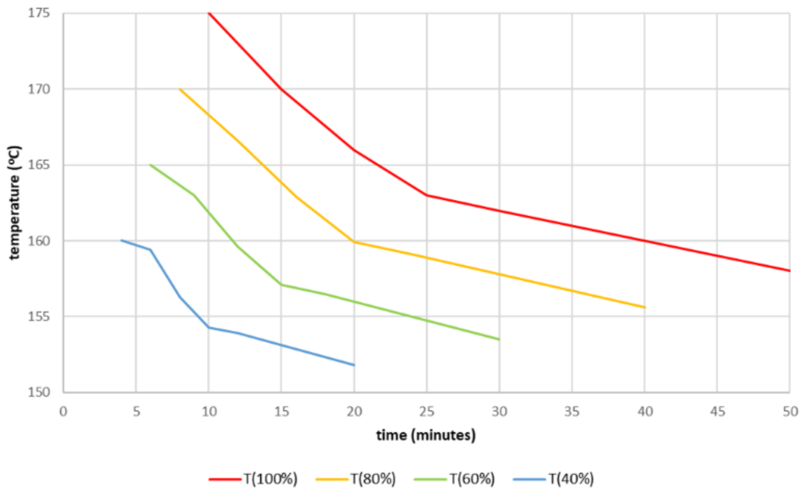

Figure 3. Relationship between saturated steam temperature and the time required to reach various states of LHTES charge, expressed in percentage.

LHTES

A smaller LHTES prototype version was previously tested and evaluated. This previous prototype consisted of 19 tubes, each 2 m long and 50 mm in diameter, filled with a PCM-graphite mixture. The setup was tested in laboratory conditions connected to a steam generating system and a thermal management system. The tubes were filled with adipic acid, and graphite was added to enhance the material’s thermal conductivity [5]. However, during the experimental campaign, it was observed that the charging rate surpassed the target of completing a full charge (0 - 100%) within 1 hour, while maintaining a 10 K temperature difference. The results from the validated numerical model developed in the previous study indicate the influence of the diameter on the charging performance and duration, as seen in Figure 4, [6]. This could have an impact on the charging performance of the system, considering that the diameter of the tubes in the new LHTES is larger [7]. Further analysis and inspection of the tubes revealed significant air entrainment within the PCM-graphite mixture, possibly originating from the filling process (Figure 5). To address this issue, the filling method of the PCM mixture will be improved, optimizing the type and amount of graphite, employing specialized equipment, and adjusting external conditions during the charging procedure.

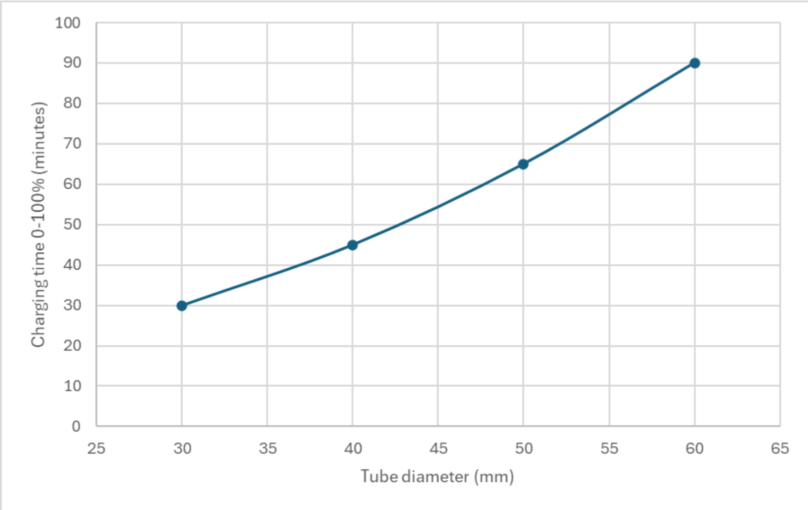

Figure 4 - Effect of tube diameter on PCM tubes charging rates (10 K driving force)

In addition, the construction material selection of the components of the LHTES are underway. Issues such as durability, corrosion and cost are considered for this selection phase. Replacing stainless steel with carbon steel would not only reduce the tubes' cost but also simplify post-processing and facilitate system integration. Initial static test analysis measurements indicated some influence of the construction materials, both with and without graphite present, but the magnitude of the observed effects requires further examination. Moreover, the orientation, control and operating conditions have also studied and defined. The vertical orientation of the tubes as in the previous prototype, will remain. However, the system will be adapted to operate under both a steam-filled vessel and in a fully water-filled vessel. The latter will increase the required temperature difference to charge/discharge the system, but water adds a significant sensible heat component, which results in increased heat storage capacity.

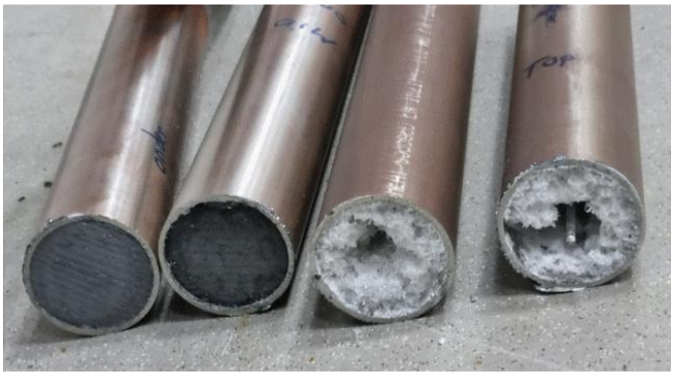

Figure 5. Post test analysis of LHTES tubes with adipic acid/graphite mixture, showing two sections of the tube, in the middle (left tubes) and at the top (right tubes).

The experimental campaign of the CHASE system consists of testing the SCHP and the LHTES individually and then as an integrated system. The system will be installed in the Carnot laboratory of TNO which will be integrated with a purpose-built test rig. This test rig consists of a cooling unit and a water tank, allowing the generated steam to condense and return the latent heat to the water tank. In this way, the heat generated by the system will be reused as a heat source for the SCHP, and any remaining heat is released to the ambient.

The SCHP tests will be conducted under varying conditions, including different water supply temperatures, steam pressures, as well as full and partial compressor loads. Dynamic tests will also be performed, such as ramp-up and ramp-down sequences and measuring the overall performance of the system at cold and hot starts. The tests on the LHTES will include full charge/discharge times for a range of charging and discharging temperatures and for a range of steam flow rates, measuring part-load charge and discharge times and the impact of standby times on performance, especially for part-load conditions.

After testing each unit individually, both setups will be tested together as the CHASE system to assess their interaction, performance, and identify strategies for optimizing combined operation, focusing on stability and efficiency.

The final step involves translating the combined system's energy performance into a techno-economic assessment. This evaluation will compare the benefits of combining the SCHP and LHTES, with conventional gas-boilers and with setups combining e-boilers with thermal energy storage. The analysis will determine whether and to what extent the SCHP and LHTES provide added value for industrial decarbonization.

4. Conclusions

This paper presents an approach to determine the impact of combining a steam compression heat pump and latent heat thermal energy storage for industrial applications. Experimental validation at the 100 kW scale is planned to evaluate their individual and combined performance, along with all the practical implementation challenges. Future work will match the validated performance of the system with industrial heat demand profiles and/or dynamic electricity prices to establish feasibility.

Acknowledgements

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