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MEDIUM-TEMPERATURE THERMOCHEMICAL ENERGY STORAGE FOR INDUSTRIAL PROCESS HEAT: DYNAMIC SIMULATION AND PREFOMANCE ANALYSIS

Summary

Thermochemical energy storage (TCES) is a promising option for decarbonizing industrial process heat, especially when waste heat is available, and electricity prices are volatile. This work presents a medium-temperature TCES-based thermal energy storage system (TESS) for process integration at 150–220 °C, which upgrades low-temperature waste heat and, unlike most existing concepts, utilizes the condensation heat released during desorption, directly or via an additional phase change material (PCM) storage. Dynamic simulations and sensitivity analyses quantify performance and are used for a techno-economic comparison with a reference system based on a high-temperature heat pump and thermal/electrical storage. The results indicate that medium-temperature TCES, combined with PCM storage and appropriate control, can provide a competitive and flexible solution for decarbonizing industrial process heat at the MW scale.

Keywords: Thermochemical storage, process heat, medium-temperature, waste heat, Zeolite Y

Field of application for the findings: Industrial process heat supply and waste heat recovery (150–220 °C, MW scale).

Addressed audience: Researchers and engineers in thermal energy storage and industrial process heat

1. Introduction / Background

The decarbonization of industrial process heat remains a significant challenge. Whilst electrification with renewable energies offers one potential solution path, it introduces inherent fluctuations in price structures associated with renewable electricity. Thermochemical energy storages (TCES) emerge as a promising solution, offering both an intrinsic heat pump effect and the capability for electrically driven charging.

Numerous review articles highlight the strong interest in TCES development (Ayaz et al., 2021; Krese et al., 2018; Kuznik et al., 2018; Lizana et al., 2018). A large share of this work targets residential applications with useful temperatures below 100 °C. Another research focus is put on high temperature application in solar thermal power plants with operating temperatures well over 300°C (Sunku Prasad et al., 2019) or for power-to-heat-to-power applications (Airò Farulla et al., 2020). Industrial waste heat utilization has also gained attention, but predominantly as a source for regeneration (Jarimi et al., 2019). Only few TCES run at medium temperatures including systems based on Magnesium Oxide/water, Methanol decomposition/synthesis, hydrogenation and Metal hydrides (Desai et al., 2020). Stengler and Linder (2020) demonstrated a laboratory-scale heat transformer upgrading heat from 180 °C to 280 °C using $SrBr_2/H_2O$ as working pair. Within the AMThES project, a fixed-bed reactor with zeolites (13X and NaY) reached adsorption temperatures of up to 180 °C (Füldner et al., 2025). A common limitation of these systems is that the condensation heat released during desorption appears at a low temperature level and is typically not utilized, although its effective use is crucial for achieving high overall efficiency.

This contribution presents an innovative thermal energy storage system (TESS) with a medium-temperature TCES as a core component, that combines electrical charging, heat pump effect and utilization of waste heat. It is designed for integration on process or supply level, which demands industrially typically steam production at temperatures of 150-220°C. Heat at this temperature level is delivered both during discharging process by upgrading waste heat as well as during charging process by condensation and is either directly consumed or stored for later use. Applying a working pair of a thermochemical material (TCM) and water, these operating conditions translate to saturation pressures of 7-23 bar – an exceptionally demanding regime for both materials and system design.

2. Methodology

To address these challenges, a novel system architecture was developed. A simplified stationary model was used for pre-assessment and support of the conceptual design. Based on this, a comprehensive transient system model was implemented in Modelica. The sorption reactor model as the key component incorporates heat and mass transfer resistances resulting from geometry and configuration of the TCM-water working pair in the storage.

Besides the reactor the TCES system comprises a heater, an evaporator to couple in the waste heat, a condenser providing heat to the process during desorption, a heat exchanger supplying the adsorption heat to the process, a heat recovery unit and a supervisory control system. Dynamic simulations of this integrated system were performed to support system design and feasibility assessment of practical implementation.

3. Results

As a key performance indicator (KPI) a COP is defined that is essentially driven by the three temperature levels (desorption, useful and waste heat temperature), as well as by dimensions and the resulting ratio of sensible to adsorption heat. Further KPIs are the required electrical charging power and duration and condensation heat. A sensitivity analysis shows the performance for a variety of operating conditions.

The entire TESS (Fig. 1) extends the TCES storage system by an additional phase change material (PCM) storage as to flexibilize the temporal use of heat that is released during desorption. A comparison of the system against competing technologies was carried out, based on the results of dynamic system simulations. The reference model incorporates a high-temperature compression heat pump, thermal storage, and electrical battery storage to support load shifting and peak shaving, alongside optional backup generation and rule-based control strategies governed by electricity price signals and storage states. The techno-economic analysis addresses system sizing, operational boundaries, performance evaluation, and economic assessment including time varying energy prices. The simulation framework examines two typical industrial contexts: continuous thermal loads and significant opportunities for waste heat integration, like they can be found in pulp and paper industry, and batch-type processes reflecting for instance the food industry.

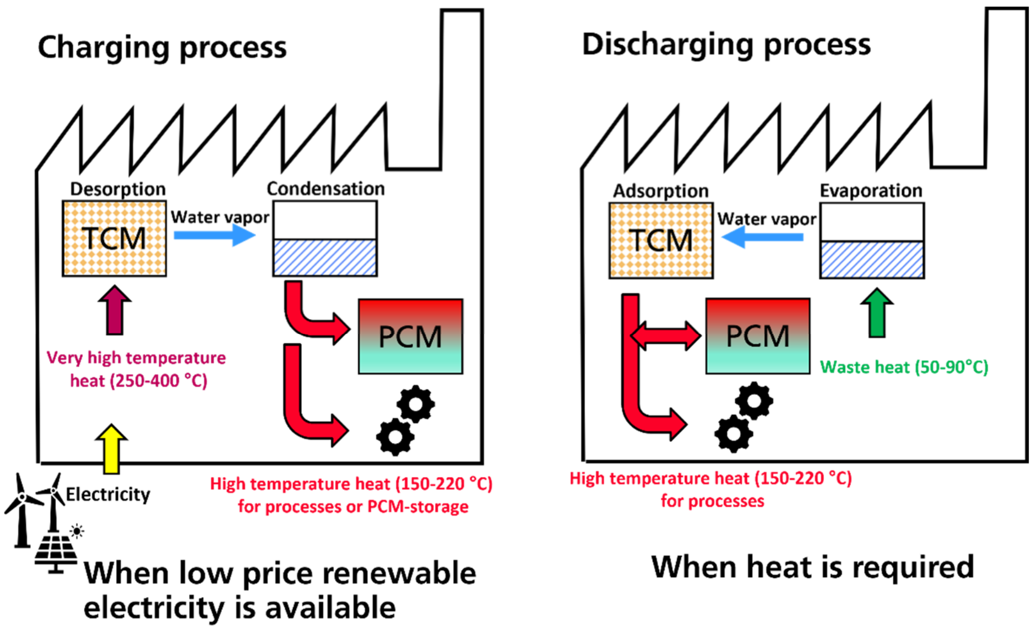

Fig. 1: The TESS principle with TCES and PCM storage

4. Conclusions

The presented results offer valuable insights into the integration of medium-temperature thermochemical storage for industrial applications in MW scale. The analysis demonstrates the potential of advanced TCM in demanding high-temperature and high-pressure regimes and highlights the importance of effectively utilizing condensation heat to achieve high overall efficiency. In combination with PCM storage and appropriate control strategies, the Muspell concept enables flexible integration of waste heat and temporal decoupling of heat supply and demand, making it a promising option for the decarbonization of industrial process heat.

5. References

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