Development of high-performance air heater based on an inductively heated packed bed

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***Abstract* — Electrical Energy Storage supports the expanding integration of intermittent renewable energy sources. However, capital costs of existing storage concepts are still too high for an economical operation. Therefore, the implementation of additional Power-to-Heat (PtH) unit into a Compressed Air Energy Storage (CAES) is proposed to increase system's energy density and thus reduce capital costs. This paper discusses an experimental study with associated simulations based on a modeling approach for a novel PtH concept comprising an inductively heated packed bed. The objective is to gain a greater understanding for the power transmission from the inductor via packed bed to the adjacent airflow and to quantify the process efficiency. First, an experimental laboratory setup has been realized. Second, experiments with various flow rates and induced power densities have been carried out. Afterwards, an appropriate electro-thermal model for the PtH concept has been applied to investigate the power transmission to the packed bed. At the end, this modeling approach is compared to the experimental results, which confirm high efficiencies for the proposed PtH concept.**

Keywords—Induction heating, Power-to-Heat, aerated packed bed, air heater

I. Introduction

Utility-scale Electrical Energy Storage (EES) supports the expanding integration of intermittent renewable energy sources allowing a reliable and flexible supply of low-carbon or even zero-carbon electricity. Emerging EES technologies introduced in Fig. 1 (left) are considered adiabatic due to the implementation of thermal energy storage (TES) following the adiabatic compression in a Carnot heat pump cycle. On the one hand, such adiabatic EES concepts are highly efficient due to the temporarily stored heat inside the TES. On the other hand, the capital costs of these concepts are still too high for an economical operation in future electricity transmission systems.

To decrease the capitals costs we propose to increase the energy density of the EES through an additional integration of electrically generated high temperature heat. Fig. 1 (right) shows exemplarily this integration in a heat pump cycle of a Compressed Air Energy Storage (CAES) system. Such a process hybridization through the integration of Power-to-Heat (PtH) decreases the round-trip efficiency on the one hand, but, opens up the potential for improvements in flexibility as well as cost efficiency on the other hand. To this end, we are developing a high-performance PtH unit based on an inductively heated packed bed of spheres to heat up the working fluid (air) to temperatures of up to 700 °C.

Induction heating of a packed spheres bed allows high power densities and a uniform heating procedure. Moreover, the high number of spheres leads to a large surface area enhancing the convective heat transfer to the airflow.

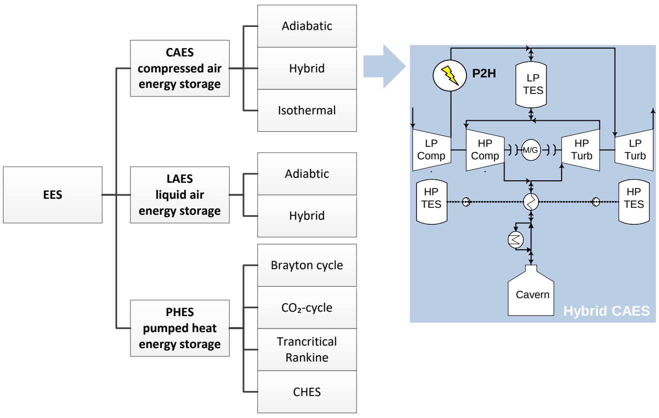

Fig. 1. System level: Electric Energy storage technologies (left) and hybrid concept of CAES (right)

These conceptual advantages have together with the specific advantages of induction heating the great potential for a promising application in the power generation sector.

II. Conception

A. System configuration

The technical system from Fig. 2 comprises a pressure vessel and an inductively heated and aerated spheres bed placed inside a ceramic tube. Dry air flows from the top of the pressure vessel through a flow straightener inside the inductively heated porous zone where convectional heat is transferred to the air. This laboratory setup enables with its installed power of 40 kW outlet temperatures up to 800 °C with associated flow rates up to 350 Nm^3/h. The solenoid used for the experimental as well as for the numerical investigation has the diameter of 0.140 m, the length of 0.40 m and comprises 10 windings.

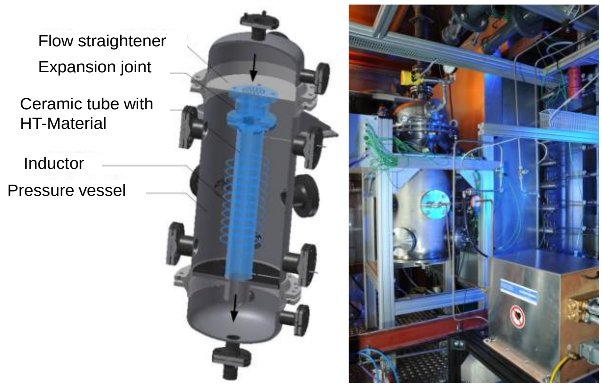

Fig. 2. Component level: CAD-model (left) and experimental setup (right) of the air heater unit based on induction heating of packed bed

B. Conceptual arrangement

Previous conceptual investigations of induction heating concepts for air heating purposes have shown large potential for the PtH concept of inductively heated packed bed. Fig. 3 shows experimental results of the air outlet temperature for various concepts with an electric input of 5.0 kW and a flow rate of 25 Nm^3/h. Highest temperature and thus exergetic values are obtained for the packed bed.

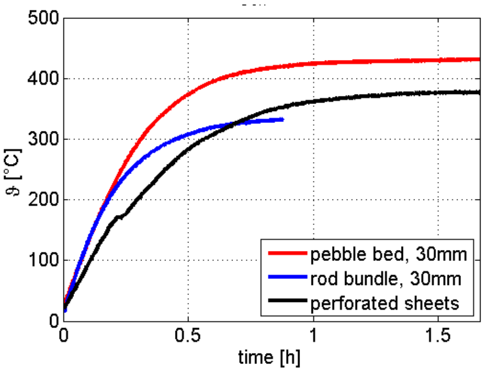

Fig. 3. Experimental results for air outlet temperature of various PtH concepts operated with f=24 kHz, P_{Gen}=5 kW and V=25 Nm^3/h

Therefore, this concept combined with induction heating has been chosen for the development of the air heater. Its conceptual arrangement is schematically illustrated in Fig. 4. To meet the requirements for high efficiency and power density during the heating process in a CAES heat pump cycle, the ferritic stainless steel X10CrAlSi7 has been chosen for further experimental investigation.

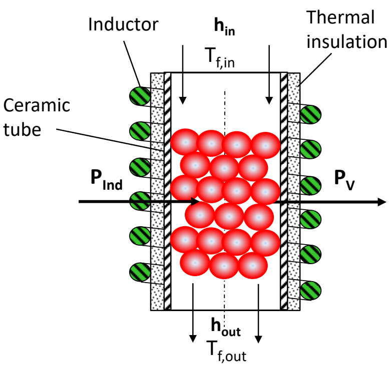

Fig. 4. Conceptual arrangement of the inductively heated packed bed

III. Experimental and Numerical Investigation

The objective of the experimental study is to analyze the efficiency of the proposed PtH concept. This investigation is accompanied with a simulation study based on the modelling approach derived from Duquenne et al. [1]. This approach presupposes an equal heat generation inside a pile of well-ordered spheres to the cylindrical rod with identical heat capacity and mass. This analogy has been proven on the basis of results from a 2d FEM simulation using a simplified sphere arrangement from Fig. 5. Thus, this analogy allows calculating the induced power with an analytical approach for cylindrical bodies described by Baker et al. [2]. This power is implemented in a thermodynamic 1d-model given by Belik [3] to calculate the temperature fields for Fig. 6.

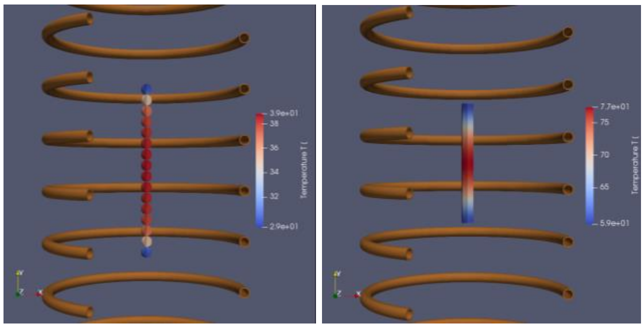

Fig. 5. Results for sphere arangement and mass equivalent cylindrical rod at I_{coil} =250 A and f=25 kHz using CENOS simulation software

Experimental and numerical results from Fig. 6 clarify the energy-efficient use for air heating purposes, since process efficiencies greater than 80% has been achieved for flow rates up to 100 Nm^3/h. Here, the use of smallest particle diameters results in high thermal efficiencies due to the large heat transfer area. The comparison between simulation and experiment in Fig. 6 shows moderate deviations to the experimental results. Reasons for these deviations are in particular the neglected thermal radiation losses from the packed bed to the cooled inductor windings and the insufficient Nusselt correlation for Reynold numbers < 2000 [3]. Nevertheless, the used modelling approach is suitable for further investigations of the efficiency and power density in large-scale CAES application.

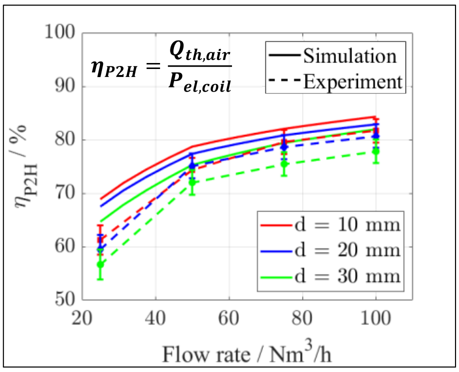

Fig. 6. Validation of the 1d electro-thermal model [3] at f = 25 kHz and I_{coil} = 250 A: Results for PtH efficiency of the laboratory 10 kW-setup

IV. Conclusions

The present contribution focusses on an experimental study with associated simulations based on a modelling approach for a novel PtH concept comprising an inductively heated and aerated packed bed. The electro-thermal model is validated on the basis of an experimental study since acceptable deviations occur due to neglected thermal radiation losses. In conclusion, a greater process understanding has been established and a process efficiency > 80% has been demonstrated for this novel PtH concept.

References

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