Summary of the doctoral dissertation

Title: Thermal–fluid analysis of a packed-bed Thermal Energy Storage for application in an Adiabatic Compressed Air Energy Storage System

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The transformation of the Polish Power System, aimed at the decarbonization of the generation sector, generates an increasing demand for large-scale energy storage systems. The research plan forming the basis of this doctoral dissertation was developed on the foundation of a patented concept that utilizes a post-mining shaft as a compressed gas reservoir in an adiabatic compressed air energy storage system (A-CAES). According to this concept, the mining shaft simultaneously serves as the installation space for a thermal energy storage (TES), whose geometry significantly differs from conventional technological solutions in terms of its slenderness.

The high slenderness ratio of the thermal energy storage unit with a fixed packed bed, resulting from the limited diameter of the mining shaft, was identified as a key research gap. The dissertation encompasses three principal research areas: (1) experimental studies of the thermal energy storage tank in three geometric variants, (2) multivariate numerical analyses and optimization of the TES design, and (3) numerical investigations of the adiabatic compressed air energy storage system.

The experimental studies were conducted on a in-house test stand comprising three thermal energy storage tanks with identical packed bed volumes but differing slenderness ratios. The measurement campaign was extended to include tests using basalt rocks as the storage material with two different particle size distributions. The wide range of laboratory configurations enabled a detailed analysis of the influence of design and operational parameters – such as storage tanks slenderness, particle size of the storage material, and mass flow rate of the heat transfer fluid – on the operational characteristics of the TES. The analysis included, among others, the pressure drop of the airflow through the bed, the time required to reach the threshold outlet loss, the dynamics of the state of charge during the charging stage, and the evolution of the thermocline region as well as maximum and minimum temperature zones.

The multivariate numerical studies of the laboratory-scale thermal energy storage unit were performed using a modified model developed in ANSYS Fluent, the accuracy of which was validated against experimental results for all tested configurations. The numerical simulations extended the conclusions from the experimental campaign, particularly regarding

the development of the thermocline region as a function of the TES operating parameters. The obtained results were also used to determine the energy and exergy efficiencies of the TES cycle and the overall energy storage system.

In the optimization process, the maximization of the TES exergy efficiency was adopted as the objective function. The selected optimal configuration was analyzed under cyclic operation, considering the effect of residual heat on the achievable energy and exergy efficiencies. Based on the performed simulations, a methodology was proposed for determining the target state of charge that marks the completion of the charging stage, thereby minimizing outlet losses from the storage tank.

The numerical analyses of the adiabatic compressed air energy storage system were carried out for three models differing in the level of detail used to describe heat transfer and airflow processes within the packed bed. The obtained operational characteristics of the large-scale TES enabled multivariate analyses of the A-CAES system.

The results of the experimental and numerical investigations clearly demonstrated the influence of key TES parameters – such as its slenderness and the particle diameter of the packed bed material – on the operational performance of the system. Furthermore, the potential for implementing A-CAES systems utilizing post-mining shafts in Poland that meet the minimum geometric requirements was assessed. It was shown that the development of a network of energy storage facilities based on post-mining infrastructure could significantly contribute to enhancing the flexibility and stability of the Polish Power System.