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Experimental and numerical investigation of a scalable modular geothermal heat storage system

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Abstract

In this work, an innovative modular heat storage system is investigated experimentally and by numerical modeling. A single storage module consists of a helical heat exchanger in a water saturated porous cement matrix. The experiment comprises a 5 day thermal loading stage, followed by 16.5 days of passive cooling, and was especially designed to quantify the thermal insulation efficiency. An inverse modeling approach was applied to successfully match temperature measurements within the storage by numerical simulation. The thus determined heat loss rates amount to 130 W for the fully loaded storage and to 50 W on average during passive cooling.

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Keywords: Helical heat exchanger; Seasonal heat storage; Numerical simulation; 2D axisymmetric model; OpenGeoSys

1. Introduction

The share of renewable energies (RE) on gross final energy consumption in Germany was 13% in 2016 [1]. The German government aims to increase the share up to 60% by 2050 [2]. Heat is a main factor for the energy market and the transition towards RE: Space heating, hot water and process heat account for more than half of the total energy demand and almost one fifth is used for space heating in residential areas [3]. But heat demand is seasonal, i.e. most

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heating occurs in winter [4], while production from RE (e.g. solar thermal) is highest in summer. Thus the main challenge is posed by the temporal disparity between production and consumption, which makes heat storage a key concept within the transition towards RE.

There are already numerous pilot heat storage sites in Germany using a variety of storage methods and mediums. Borehole thermal energy storage (BTES) sites using an array of borehole heat exchangers (BHEs) have been installed in Crailsheim and Neckarsulm [5,6]. Aquifer thermal energy storage (ATES) sites use a groundwater reservoir as storage medium and injection and extraction wells for storage and recovery of heat. Examples of ATES sites can be found in Rostock [5] and at the Reichstag in Berlin [7]. A seasonal thermal energy storage in Friedrichshafen is realized as hot-water thermal energy storage (HWTES) and in Eggenstein a gravel-water thermal energy storage (GWTES) has been installed [5].

This study is part of the IGLU project (intelligent geothermal long term heat storage with environmentally neutral behavior), which aims to develop a solar collector supplied energy storage system. It features a scalable, cement based, modular construction that can be integrated into heat supply-systems of new or existing buildings. An array of IGLU heat storage modules can be placed in a cellar, into the ground next to a building or, because the storage medium is cement, it can be installed as part of the building foundation. Heat storage systems require sophisticated methods to determine storage performance and heat loss. Experimental work and numerical simulations thus are a key part of the IGLU project. The experimental investigation aims to assess the storage performance and the heat loss of a prototype lab-scale IGLU heat storage module and to generate an experimental data basis for model validation. The simulation based design of the energy storage system serves as a tool for sensitivity analyses and optimization of material properties and system design (e.g. heat exchanger geometry) with respect to efficiency and environmental impacts. For the numerical simulation, the parameters of all parts of the storage module need to be known. Porosity, density and thermal parameters of the storage medium can be measured with good accuracy in the laboratory or are well known from manufacturer data. This is not true, however, for the storage insulation, which varies strongly in efficiency and parameterization depending on the details of the construction and installation. The insulation consists of two layers, one of fabric and of synthetic foam, coated with a plastic sheet from the outside. This makes it very difficult to determine the insulation properties with the required precision by analyzing the insulation materials. Instead, dedicated experiments to determine the insulation efficiency and parameters have to be conducted [8].

This study therefore presents an experiment specifically designed to generate a data basis for an inverse modeling approach to determine thermal conductivity and heat capacity of the storage insulation. For this, the experimental design, the obtained data, the specifically adapted modeling approach and the parameters inversely obtained are described here. Furthermore, the experimental results of this experiment are used to characterize the lab-scale IGLU heat storage module in terms of maximum heat loss, and cooling rates. The adapted parameters of the insulation along with the experimental data basis will be used in future numerical simulations for validation of a detailed 3D finite element model for sensitivity analysis and storage optimization.

2. Experimental investigation

2.1. Set-up

The thermal storage unit presented in this study has a volume of 1.1 m³, its height is 1.16 m and the diameter without insulation is 1.1 m. It consists of a helical heat exchanger (radius of 41 cm with a dip of 7 cm) and a plastic barrel, covered from the outside by layers of insulation. The insulation consists of a 12 cm thick mantle and lid insulation fabric and 10 cm of *Styrodur* plate at the bottom. The storage module is placed on a plastic palette. The storage medium is a fully water saturated cement (TVB; Schwenk, *Füllbinder L*). Fig. 1 shows a schematic of the experimental setup. Flow meter (magnetic inductive) and temperature sensors (type K thermocouples) in the inlet and outlet pipes are installed to determine the heat balance. For temperature distribution measurements, four profiles of five temperature sensors each are installed inside the storage medium. Additional sensors are placed between barrel and insulation, at the bottom part of the module and outside the system for room temperature measurement.

During the heat loading phase, a hot water bath, thermostat and a suction pump (Huber, model CC-215B) serve as a heat source. After an 18 h circulation period without heating to exhaust the air from the piping, the experiment continues with 5 days of thermal loading with an inlet temperature of 59.5 °C until the temperature inside the heat