International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 437

FIRST RESULTS OF A NUMERICAL CHARACTERIZATION OF A FIELD SCALE CEMENT BASED THERMAL ENERGY STORAGE SYSTEM

Johannes Nordbeck[a], Sebastian Bauer[a], Andreas Dahmke[a], Hugo Gomes[b], Henok Hailemariam[a], Constantin Kinias[b], Kerstin Meier zu Beerentrup[a], Christian Smirr[b], Thomas Vienken[c], Frank Wuttke[a], Christof Beyer[a]

[a] Institute of Geosciences, University of Kiel, Germany
[b] Scheer Heizsysteme & Produktionstechnik GmbH, Germany
[c] Helmholtz-Zentrum für Umweltforschung – UFZ, Leipzig, Germany

ABSTRACT

This study presents the experimental and numerical simulation based characterization of a new modular solid-liquid sensible heat storage system. The field-scale storage prototype was constructed in the shallow subsurface and consists of 25 coupled 1.5 m³ storage units, each equipped with a helical heat exchanger in a cement based water saturated matrix. A charging and passive cooling experiment was performed over a period of 3 months, with a maximum storage temperature of 60°C and distributed temperature monitoring of the system.

A detailed 3D finite element model of the storage system was developed and parameterized in order to analyze the governing heat transfer processes and quantitatively characterize the storage behavior. Experimentally observed and simulated storage temperatures show a good agreement, with differences of less than 2.7 K, which proves the appropriateness of the model approach. Average loading rates of 14.6 kW during the first 2 days and 4.3 kW during the following 10 days of heat charging correspond to a used storage capacity of 660 kWh and 1310 kWh after 2 and 12 days, respectively. During passive cooling the storage temperature was reduced to approximately 30°C within 30 days, which corresponds to a heat loss rate of 1.4 kW during that time and demonstrates the necessity for proper thermal insulation of subsurface heat storages.

Keywords: sensible heat storage, subsurface, field scale experiment, storage characterization, numerical modeling

1. INTRODUCTION

Space heating and hot water supply have significant shares in the total energy consumption of private households and the trade sector, especially for countries in cold and temperate climates [1]. Balancing the temporal disparity between demand and availability of heat energy in order to increase the fraction of heat from renewable or alternative sources (e.g. solar thermal or industrial waste heat) calls for a strong extension of heat storage capacities, specifically in densely populated urban regions, where heat demand is largest [2]. In this context, a new modular and scalable, cement based solid-liquid sensible heat storage concept for operation temperatures of up to 90°C is presented here, which may contribute to this objective. The concept is particularly aimed at a flexible integration in heat supply systems of new or existing buildings in a space-constricted urban environment, e.g. in cellars, designated storage spaces or as "constructed" geothermal storages in the ground next to or below buildings. This study reports and discusses first results of a numerical simulation based evaluation and characterization of storage experiments performed with a field scale prototype of the new storage concept.

2. MATERIAL AND METHODS

2.1 *Cement based solid-liquid heat storage prototype*

The modular concept is based on coupled arrays of thermal storage units, which consist of tubular helical heat exchangers in a high porosity, fully water saturated

Fig 1 Installation of helical heat exchangers and temperature sensors in the excavation pit for the storage.

thermal filling material matrix. For the field scale prototype, 25 coupled 1.5 m³ storage units were arrayed in 5 parallel rows of 5 coupled units, respectively, and installed in the subsurface 0.2 m below ground level next to a building (Fig. 1). The composite storage has dimensions of 5.2 x 5.2 x 1.85 m and is insulated at the sides and the top with 5.2 cm and at the bottom with 10.4 cm of Steinothan (Steinbacher Dämmstoff GmbH). Its lower half is reaching into the groundwater at the test site. The thermal filling material consists of Füllbinder L (Schwenk Zement KG), which is a commercially available cement-based filling and sealing material with favorable mechanical properties and comparatively high thermal conductivity and heat capacity of 0.96 W/m/K and 3.4 MJ/m³/K under fully water saturated conditions [3]. For the heat exchangers, different tube materials (Al-PE, steel) and helix diameters were employed. Water is used as a heat carrier fluid and circulated through the heat exchangers.

2.2 *Field scale experiment and monitoring*

The five rows of storage units were continuously charged with heat over a period of 33 days (i.e. from 12/21/17 to 01/22/18) with a supply temperature of 60°C and flow rates of 120-170 L/h for an assessment of technical feasibility and heat charging behavior. Once the storage temperatures reached a steady state, water circulation through the heat exchangers was stopped and the storage was allowed to passively cool over 60 days in order to quantify heat loss rates and the efficiency of the insulation. The average surface

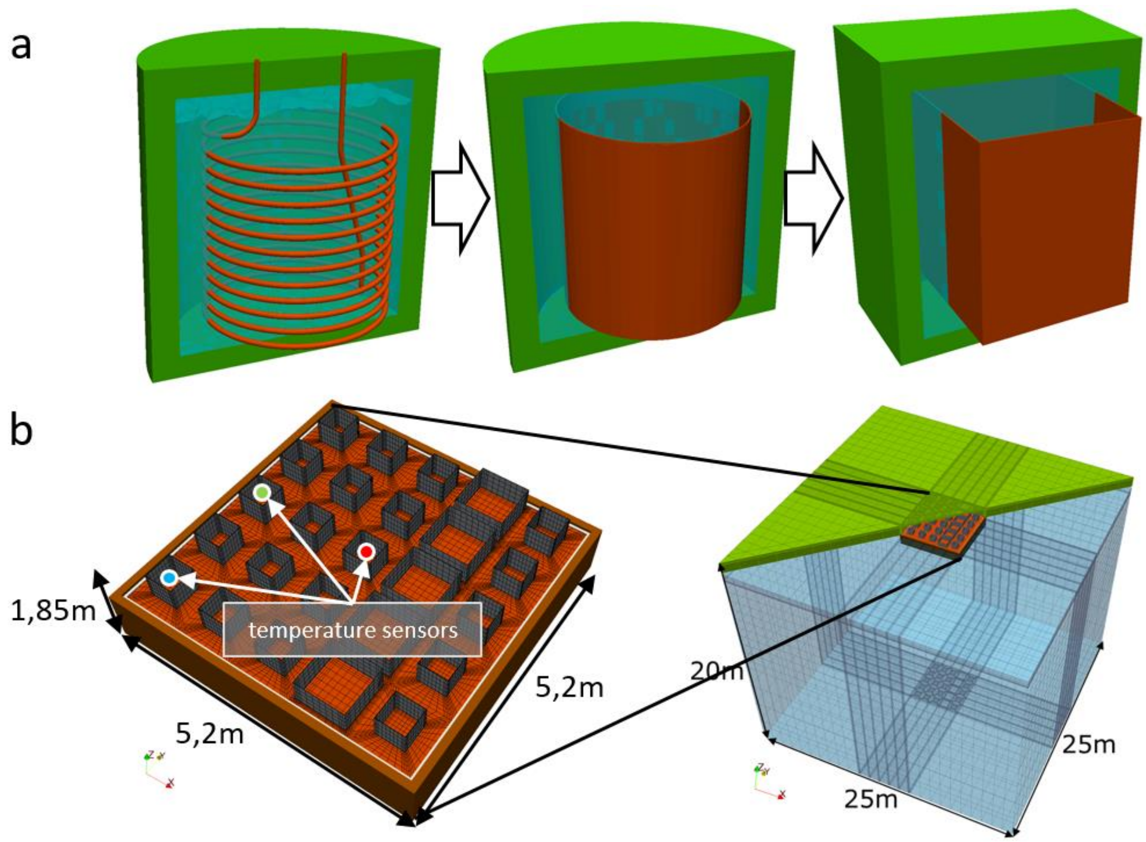

Fig 2 (a) Geometric transformation of the finite element grid of a fully resolved single unit with helical heat exchanger over equivalent hollow cylinder to a hollow cuboid; (b) composite subsurface storage model with 25 coupled units withing the surrounding soil and groundwater.

temperature during the whole experiment was 5°C. Storage temperatures were continuously monitored with distributed sensors within and below the cement matrix, and in a multilevel groundwater sampling well in the vicinity of the storage.

2.3 *Model development and parameterization*

A time efficient numerical simulation of storage systems with complex geometries like the field scale prototype, requires simulation grids optimized for size that do not compromise the accuracy and stability of the numerical solution. A geometric approach suggested by [4] was used here as a starting point, where the helical heat exchanger is transformed into a hollow cylinder (Fig. 2a). In a second step, the round structure is transformed into a cuboid type geometry. In this process, the volumes of all materials and thus the volumetric heat capacities are conserved, while the heat exchanger surface area changes and its thermal conductivity therefore must be corrected to match the thermal resistance [5]. This procedure allows a reduction of grid size by more than 99%. The equivalence of the three models was verified by comparing simulation results for various charging/discharging tests, which yielded a good fit with heat balance errors below 3%. Finally, the upscaling of the single cuboid to the field scale model is achieved by assembly and coupling of single unit models into the 5x5 array and integration in a model of the surrounding subsurface (Fig. 2b).

The thermal properties (density, heat conductivity and specific heat) of the different storage and subsurface materials were parameterized based on data sheet specifications, own measurements [3] and inverse modeling of the cooling phase of the experiment (Fig. 3b), which allowed an identification of the thermal resistances of the wooden lagging and insulation layers of the composite storage system, which deviate from data sheet declarations due to imperfect fitting and sealing. The procedure is detailed for a laboratory scale system in [6].

3. RESULTS AND DISCUSSION

The first experimental operation of the heat storage system was evaluated via measured temperatures and heat carrier fluid flow rates. After 12 days of continuous charging the thermal filling material reached maximum temperatures of 58.2°C throughout the storage system as shown by exemplary measurement data of three sensors (Fig 3) at the center, edge and corner storage units. During the remaining 21 days of charging, the temperatures within the storage remained almost constant, and the temperature spread in the heat carrier fluid between system inlets and outlets was between 1.8 - 3 K during this quasi-stationary phase of the charging experiment.

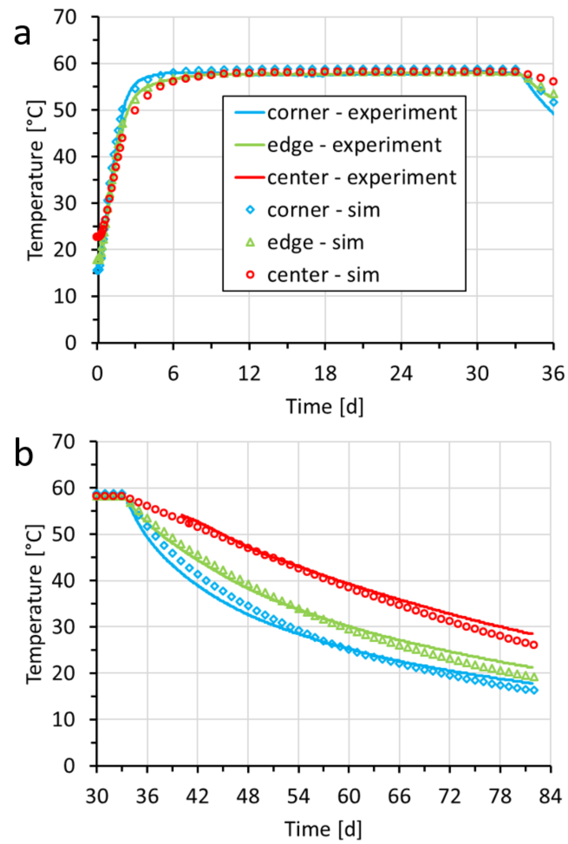

Fig 3 Measured and simulated temperatures at three selected positions within the storage material during 33 days of charging (a) and the following 60 days of passive cooling (b)

For the model simulation, inlet and outlet temperatures as well as fluid flow rates were used as boundary conditions of the field-scale storage system. The comparison of experimental data and upscaled and calibrated model results for the charging as well as the cooling phase shows good agreement: Maximum temperature deviations are smaller than 1 and 2.7 K, respectively. Model results for the charging phase show charging rates of 14.6 kW during the first 2 days and 4.3 kW during the following 10 days. After this time span, the storage array has been charged with 1310 kWh and thus was at more than 90% of its maximum capacity (i.e. for a maximum charging temperature of 60°C). During the 21 days of the quasi-stationary phase most of the supplied heat is lost across the insulation to the surrounding subsurface at an average rate of 2.1 kW.

The inverse modelling of the cooling phase (section 2.3) allowed the identification of the systems insulation properties. The average heat loss rates during the cooling phase were determined as 2.1 kW directly after deactivating the heater and then declined to 1.8 kW during the first 10 days and 1.2 kW during the following 20 days. The simulation also shows, that the highest heat losses, i.e. more than one third of total losses, occur across the top surface of the storage, which means additional insulation would best be installed here.

4. CONCLUSIONS

The combination of experimental investigations, temperature monitoring and numerical simulation on a validated model allowed for a detailed characterization of the new modular thermal energy storage system. Overall, the following conclusions can be drawn from this work:

- The new cement based heat storage system was successfully tested on a field-scale setup by extensive temperature monitoring and a detailed numerical simulation.
- A model concept was developed which significantly reduces the computational effort for the simulation of a field scale system with multiple storage units.
- The comparison between experimental and numerical results shows a good agreement, thus the upscaling strategy from high resolution single-unit models to the coupled multi-unit model of the test site was successful.
- The combination of experimental data and quantitative simulation based interpretation allowed to derive the field-scale systems key characteristics, i.e. storage capacities, charging and heat loss rates. The calibrated and validated model can therefore be used for prognoses of storage behavior in different charging / discharging scenarios.
- The modelling approach described in this paper can be further applied for the layout and operational optimization of cement based, modular thermal energy storage systems of the presented type for specific applications and settings.
- Installation of heat storage systems in the subsurface requires an assessment of long term heat emissions into the surrounding ground and potential environmental impacts. Monitoring data collected in the vicinity of the presented field-scale storage system will help to validate and apply the model for such analyses.

REFERENCE

[1] AGEB – AG Energiebilanzen e.V. Anwendungsbilanzen für die Endenergiesektoren in Deutschland in den Jahren 2013 bis 2017. Study commissioned by the Federal Ministry for Economic Affairs and Energy, 2018. Berlin.

[2] Kabuth A, Dahmke A, Beyer C, Bilke L, Dethlefsen F, Dietrich P, Bauer S. Energy storage in the geological subsurface: dimensioning, risk analysis and spatial planning: the ANGUS+ project. Env Earth Sci 2017, 76:23. https://doi.org/10.1007/s12665-016-6319-5

[3] Miao XY, Beyer C, Görke UJ, Kolditz O, Hailemariam H, Nagel T. Thermo-hydro-mechanical analysis of cement-based sensible heat stores for domestic applications. Env Earth Sci 2016:75. https://doi.org/10.1007/s12665-016-6094-3

[4] Moch X, Palomares M, Claudon F, Souyri B, Stutz B. Geothermal helical heat exchangers: comparison and use of two-dimensional axisymmetric models. Appl Therm Eng 2014:73:691-698.

[5] Boockmeyer A, Bauer S. Efficient simulation of multiple borehole heat exchanger storage sites. Env Earth Sci 2016:75:1–13.

[6] Nordbeck J, Beyer C, Bauer S. Experimental and numerical investigation of a scalable modular geothermal heat storage system. *Energy Procedia* 2017:125: 604–611.

ACKNOWLEDGEMENT

We gratefully acknowledge funding provided by the Federal Ministry for Economic Affairs and Energy (BMWi, Grant 0325547B) and the support of the Project Management Jülich (PTJ).