Theoretical and Experimental Studies of Dual-Media Thermal Energy Storage with Liquid Metal

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Abstract. Liquid metals have remarkable heat transport capabilities and are, thus, promising heat transfer fluids in thermal receivers in solar thermal electricity systems with high heat loads, such as central receiver systems. For thermal energy storage, a dual-media storage system with solid filler material is proposed. This configuration increases the storage capacity and decreases the storage material costs compared with a direct two-tank system. It also improves the storage performance, when comparing with a single-tank thermocline system without filler. Theoretical results show that the discharge efficiencies are highest for the largest storage heights and higher for heavy metals (lead and lead-bismuth eutectic) compared with sodium, both due to the decreased axial heat conduction and thus, minimized degradation of the thermocline. At the Karlsruhe Liquid Metal Laboratory (KALLA) at the Karlsruhe Institute of Technology (KIT) a lab-scale prototype of a dual-media storage system with filler material and lead-bismuth eutectic (LBE) as the heat transfer fluid is currently taken into operation. The first results without filler material show a good agreement between the theoretical model and the experimental results. In parallel, the compatibility of filler material candidates with LBE is investigated by storing the material in stagnant LBE for several weeks at 500°C and afterwards examining the filler material with a scanning electron microscope (SEM). The results indicate that ceramics are the most promising candidates.

INTRODUCTION

Liquid metals, especially liquid sodium, are excellent heat transfer fluids and applicable in a wide temperature range. Therefore, they qualify for thermal receivers in solar thermal electricity plants [1,2,3]. As storage media, however, they are not preferred, mainly due to low energy densities. A previous evaluation proposed a dual-media storage configuration for liquid metal as the heat transfer fluid, as the thermal energy can be stored to large part indirectly in a filler with low material cost and high storage density [4]. In this storage configuration, hot and cold liquid is stored together divided by the thermocline.

It has further been shown that during cyclic operation liquid metals can be as efficient as salts in such a configuration, and, moreover, suitable for an extended temperature range [5]. In standby mode, however, the system has to be optimized regarding a low porosity and a large storage height to improve the stability of the thermocline [6]. Based on these results, a lab-scale storage system is built to demonstrate a dual-media storage system with liquid metal as the heat transfer fluid.

THEORETICAL STUDIES

Governing Equations and Storage Parameters

The temperature gradients in the dual-media storage system are determined by using a two-phase concentric dispersion model. The energy equations of the fluid (Eq. (1)) and solid phase (Eq. (2)) are solved by using the finite volume method. They are coupled by the heat transfer term (specific filler surface s_v multiplied by the heat transfer coefficient α) in the fluid energy equation and the boundary condition at the filler surface. In this study, radial heat conduction and heat losses to the environment are neglected. The boundary conditions, solution procedure and the validation with experimental data are presented in detail in Ref. [6].

$$u\varepsilon\rho_f c_{pf}\frac{\partial T}{\partial x} + \varepsilon\rho_f c_{pf}\frac{\partial T}{\partial t} = \varepsilon\lambda_f\frac{\partial^2 T}{\partial x^2} - s_v\alpha(T - T_s) \quad (1)$$

$$\rho_s c_s\frac{\partial T_s}{\partial t} = \lambda_s\left(\frac{\partial^2 T_s}{\partial y^2} + \frac{2}{y}\frac{\partial T_s}{\partial y}\right) \quad (2)$$

In order to compare the performance of different fluids in a dual-media storage system, a discharge efficiency is defined. Here, it is determined from the amount of useful energy ($T^*_{\mathrm{dis,out}} \geq T_{\max}$ - 20 K) that can be extracted by the fluid during discharge compared to the maximum energy that could be extracted, which is the storage capacity Q (Eq. (3)). It is calculated for the first discharge step starting with the storage system being fully charged.

$$\eta_{\mathrm{dis}} = \frac{\int_0^{t_{\mathrm{dis}}} m(c_{pf}T^*_{\mathrm{dis,out}} - c_{pf}T_{\min})}{Q} \quad (3)$$

Table 1 shows the storage parameters for a pilot-scale (1 MWh) storage system for different liquid metals and a small-scale (0.6 kWh) storage system. The storage capacity and the ratio of tank height to tank diameter is kept constant (H/D ≈ 3) for the 1-MWh storage configurations leading to different storage dimensions for the different heat transfer fluids and their operating temperature ranges. Furthermore, adiabatic conditions are assumed. The small-scale setup is more than a factor 1000 smaller, but the H/D ratio and the discharge velocity are similar.

The physical properties of the solid material are representative for filler materials: specific heat capacity of 700 J/kgK, density of 4000 kg/m³ and thermal conductivity of 5 W/mK. The porosity in the bed is assumed to be 0.4 with spherical particles of 5 mm.

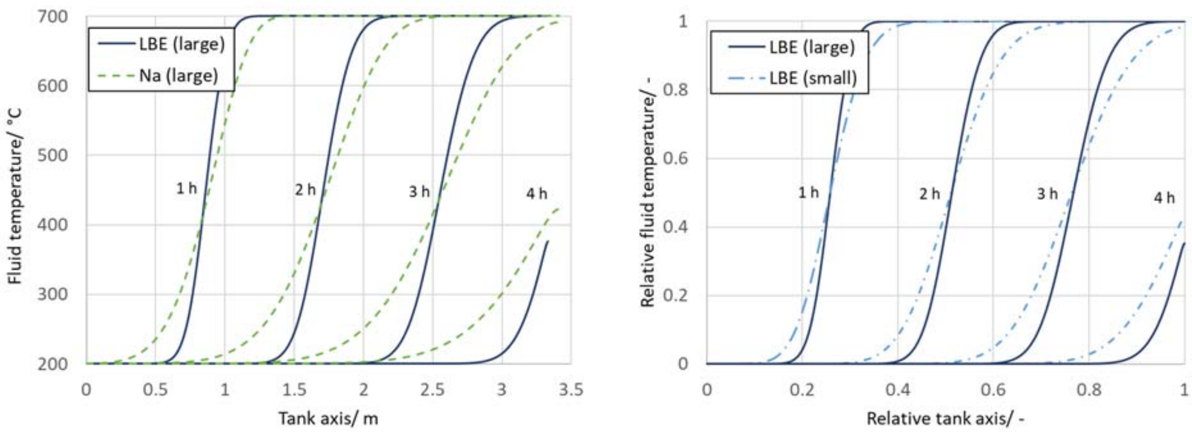
TABLE 1. Storage parameters of liquid-metal dual-media thermal energy storage systems

Parameters	Sodium (large)	Lead (large)	LBE (large)	LBE (small)
Capacity, kWh	1000	1000	1000	0.6
T_{min}/ T_{max}, °C/ °C	200/ 700	350/ 700	200/ 700	180/ 380
Fluid/solid mass, kg/ kg	1105/ 8303	18566/ 10926	12687/ 7761	19/ 11
H/ D, m/ m	3.4/ 1.1	3.7/ 1.2	3.3/ 1.1	0.37/ 0.13
Discharge time, h	4	4	4	0.1
Fluid velocity, mm/s	0.5	0.4	0.4	0.2

Theoretical Results

Figure 1a) presents the simulated fluid temperatures during discharge for LBE and sodium in the larger storage system with filler material (Table 1). Both heat transfer fluids can be used in the same operating temperature range. LBE shows a better stratification (higher slope) than sodium leading to higher discharge efficiencies. This is caused by the approximately four times lower thermal conductivity of LBE compared with sodium, which has a positive impact on the axial stratification.

Figure 1b) compares the fluid temperatures of LBE in the larger (1 MWh) and the small-scale (0.6 kWh) storage system, both with filler material (Table 1). For a direct comparison, a relative fluid temperature ($(T-T_{max})/(T_{max}-T_{min})$) and a relative tank axis (x/H) are chosen. It can be concluded that a larger storage system having a larger tank height is beneficial for a better stratification and thus, improved discharge efficiency. This is caused by the fact that it takes the thermocline zone a longer time to fill out a larger storage completely compared with a smaller one.



a) b)

FIGURE 1. Simulated temperature profiles along the vertical tank axis for four different time steps during discharge (1 h, 2 h, 3 h and 4 h); a) comparison between LBE and sodium; b) comparison between large and small storage system with LBE

In Table 2, the resulting discharge efficiencies (Eq. (3)) are presented. The dual-media storage system with sodium shows the lowest discharge efficiency among the liquid metals due to the high thermal conductivity of the fluid and thus, large axial heat conduction. Lead and LBE show similar discharge efficiencies, as they have similar physical properties. The storage system with lead shows a slightly higher discharge efficiency, however, only caused by the higher storage tank. The lab-scale storage system shows, as expected, a lower storage efficiency than the larger system due to the small tank height. Additionally, boundary effects and heat losses will play a more important role due to the small size of the lab-scale tank as well, which are neglected here.

TABLE 2. Discharge efficiencies of dual-media thermal energy storage systems with liquid metal as heat transfer fluid

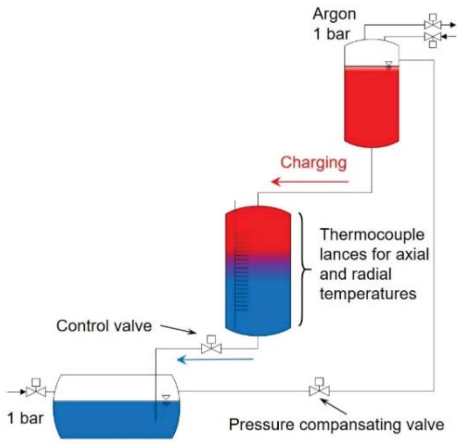
Parameter	Sodium (large)	Lead (large)	LBE (large)	LBE (small)
Discharge efficiency η_{dis}, %	78.0	88.3	86.2	83.1

EXPERIMENTAL STUDIES

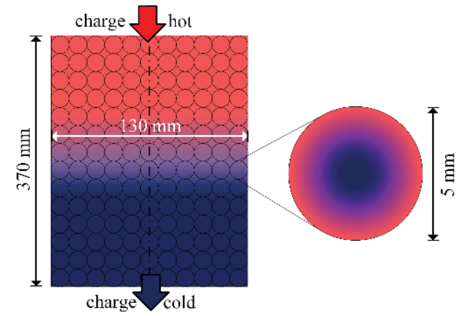
Experimental Setup and Filler Screening

At the Karlsruhe Liquid Metal Laboratory (KALLA), a lab-scale thermal energy storage is set up for demonstrating liquid metals as heat transfer fluids in a dual-media storage with solid filler material (Fig. 2b). In this setup, LBE is used as heat transfer fluid. In this small-scale storage, the heat transfer between filler and fluid can be investigated and valuable operational experience can be gained for a larger-scaled storage system, e.g. regarding filling, draining and temperature control. Additionally, the resistance of the filler material in terms of thermal shocks and cycling can be analyzed.

Figure 2a illustrates the arrangement of the three tanks in the setup: the “hot tank” with temperatures up to 380°C, the storage tank and the “cold tank”, which has a minimum temperature of 180°C because of the melting temperature of LBE of approximately 125°C [7]. The upper temperature of 380°C was defined due to limitations of the existing loop, in principle higher temperatures are possible when using LBE. During charging, the control valve is opened so that the hot fluid flows from the hot tank from the top into the energy storage tank due to gravity. For discharging, an overpressure is first applied to the cold tank. When the control valve is open, the cold fluid flows into the energy storage tank from the bottom up due to the pressure difference between the hot and cold tank. The storage tank material is austenitic stainless steel 1.4571.



a)



b)

FIGURE 2. a) Schematic flow diagram of the charging process including the "hot tank", the storage tank and the "cold tank"; b) schematic drawing of the storage test unit (volume ≈ 5 liters) with filler materials during a charging process

Furthermore, a filler material screening regarding the compatibility with the heat transfer fluid LBE is performed. Natural stones, glasses and ceramics are stored in LBE at 500°C under oxygen reduced atmosphere for several weeks. Afterwards, the filler materials are evaluated using different analyses, including scanning electron macroscopy (SEM).

Additional to the compatibility with LBE, the physical properties of the filler candidates are compared. A high density and specific heat capacity leading to a high storage capacity are preferred. Furthermore, a low thermal conductivity to buffer the expansion of the thermocline, especially during standby, are favored.

For a later industrial application, the specific cost of the filler material will be a key issue as well. However, for the first step of demonstrating this first-of-its-kind storage, well-defined geometries and properties of the filler material are more important.

Experimental Results

Before operating the storage system with filler material, test runs with liquid metal only are performed. Results of this measuring campaign are presented in this study. Figure 3 shows the temperature distribution of the LBE along the axis of the 0.37-m storage tank during a charge process starting from the whole tank being at 180°C without filler.

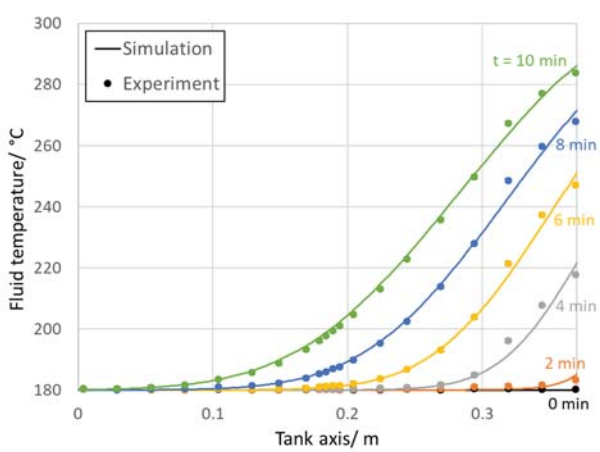


FIGURE 3. Fluid temperature distribution (experimental results=marks, simulation results=solid line) along the tank axis for every two minutes during a 10-min charge process

It can be observed that the flange at the top of the tank hinders the fluid to enter at the temperature of the upper "hot tank". Due to the relatively large heat capacity of the tank flange compared to the capacity of the lab-scale tank, heat is lost and the inlet temperature is decreased. Nevertheless, the experimental results (marks) and the simulated results (solid line) show a good agreement. As the inlet temperature for the simulation the temperature measured at the top of in the tank, just below the upper flange, is taken.

The investigations regarding the filler material compatibility with LBE show that, in general, ceramics have the best results. The filler materials that are examined are natural stones (quartz and filter gravel), glasses (borosilicate and soda-lime), and ceramics (alumina, zirconia, zirconium silicate and steatite). Figure 4 presents some pictures of the fillers after being taken out of the LBE. It can be observed that both quartz (Fig. 4a) and borosilicate (Fig. 4b) glass were affected by the LBE, the zirconium silicate (Fig. 4c), however, had no visible damage.

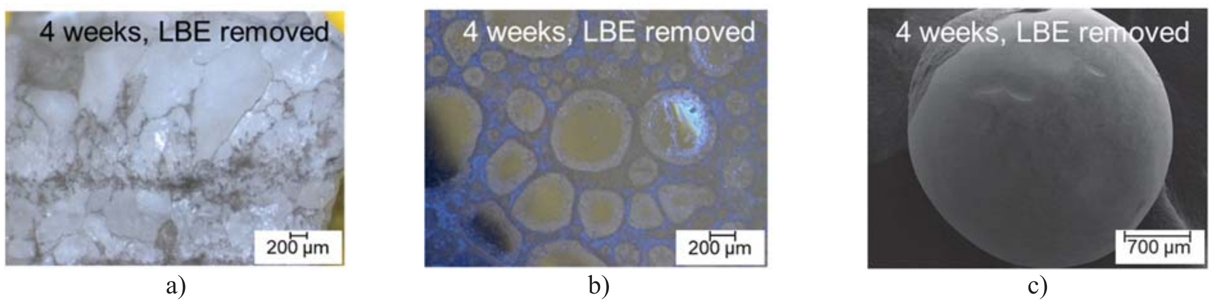


FIGURE 4. a) Picture of quartz after being stored in LBE for 4 weeks; b) picture of borosilicate glass after being stored in LBE for 4 weeks; c) SEM image of zirconium silicate after being stored in LBE for 1 week (SEM image: Esther Heil/KIT)

CONCLUSIONS

Liquid metals are investigated as heat transfer fluids in a dual-media storage system at the Karlsruhe Liquid Metal Laboratory (KALLA) at Karlsruhe Institute of Technology (KIT). Simulation results show good discharge efficiencies for liquid metals and heavy liquid metals, such as LBE, in particular. Currently, a lab-scale storage system is taken into operation to demonstrate a liquid metal dual-media storage system with filler material. For this purpose, filler material with suitable storage properties (high storage capacity and low thermal conductivity) and compatibility with LBE are screened.

First pre-test results of the storage system with LBE only show a good agreement of the simulated results with the experimentally obtained temperatures. The screening of the filler materials leads to the result that ceramics are best suited as filler materials regarding compatibility issues.

As a further step, after gaining experience with operating the lab-scale storage system with filler material, a pilot-scale storage system (100 kWh) is planned to be integrated in an existing liquid metal loop at KALLA.

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