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LOW-PRANDTL NUMBER HEAT TRANSFER FLUIDS IN PACKED-BED HEAT STORAGE

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1. ABSTRACT

In this contribution, low-Prandtl number fluids are investigated for the use as heat transfer fluid in packed-bed heat storage systems. At the Karlsruhe Liquid Metal Laboratory (KALLA), liquid metals, mostly heavy metals such as lead-bismuth or tin, are used. They are excellent heat transfer fluids and are used in concentrating solar power plants or in nuclear power plants, where high heat loads are supposed to quickly and efficiently be cooled. Above that, KALLA is looking into using liquid metals as heat transfer fluids in packed-bed heat storage systems, making use of their excellent heat transport capabilities and the wide liquid phase temperature range. This work highlights the ongoing work with regard to experimental demonstration of the technology and related fundamental heat transfer investigations.

2. INTRODUCTION

The Prandtl numbers (Pr) of the liquid metals used at KALLA are approximately 0.01 (see Table 1). This is significantly lower than for example for water (~ 1–10) or air (~ 0.7) [1]. The Prandtl number is defined as the ratio of momentum diffusivity ($\nu = \eta/\rho$) to thermal diffusivity ($a = \lambda/(c_p\,\rho)$) and is given in Eq.1.

$$\mathrm{Pr} = \frac{\nu}{a} = \frac{\eta c_p}{\lambda} \qquad (1)$$

If Prandtl numbers are << 1, it indicates that the thermal diffusivity is significantly higher than the momentum diffusivity. Thus, the thermal boundary layer is larger than the viscous boundary layer and because of that difference, similarity rules cannot be used [2]. In Table 1, Prandtl number values of some exemplary liquid metals are given.

Table 1 Prandtl numbers of selected liquid metals (at 600 °C) [3]

Liquid metal	Prandtl number
Sodium (Na)	0.006
Lead (Pb)	0.012
Lead-bismuth eutectic ($Pb_{44.5}Bi_{55.5}$)	0.013
Tin (Sn)	0.007

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The superior heat transfer of those fluids is being investigated for packed bed heat storage systems at KALLA. Such packed bed systems have already been proposed in the 1980s [4] but without any experimental demonstrations. Up until now, the minimum Nusselt number of Nu = 2 had to be assumed for the heat transfer in the packed bed due to the lack of suitable correlations for packed beds in the combination with low-Prandtl heat transfer fluid [5].

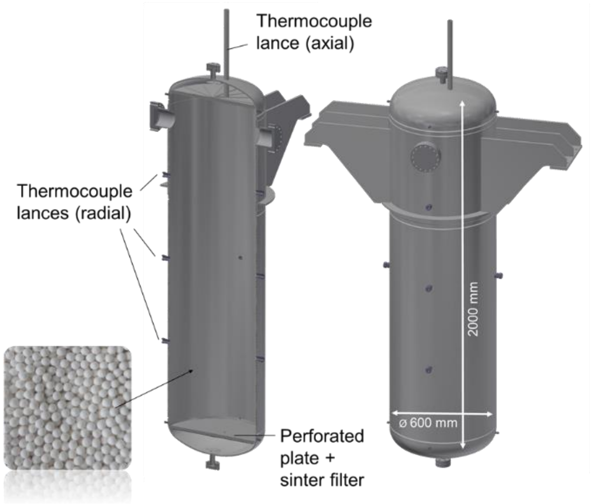
3. METHODOLOGY

After having tested the concept on a lab-scale (1 kWh) to gain knowledge about suitable filler material and measurement techniques [6], a pilot-scale heat storage is currently under construction in order to demonstrate the technology. An existing liquid metal loop at KALLA using eutectic lead-bismuth is utilized for that purpose.

In parallel, a project funded by the German Research Association (DFG) within the Priority Programme 2403 on Carnot Batteries aims to take a closer look at the heat transfer in the packed bed. In a separate experiment, the heat transfer coefficients in a packed bed using liquid metals as heat transfer fluids will be analysed.

4. RESULTS

Figure 1 (left) shows a 3D design of the heat storage tank. An axial thermocouple lance with approximately 100 thermocouples will measure the temperature in in the vertical direction. Additionally, four radial thermocouple lances are installed to record the temperature in horizontal direction in the tank. Figure 1 (right) shows a photo of the thermocouple lance used in the lab-scale experiment with 0.5-mm thermocouples protruding from it for measuring the fluid temperature in the tank.



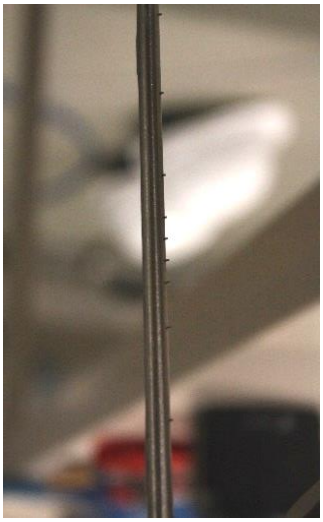


Fig. 1 Left: 3D design of the pilot-scale heat storage DUOLIM (design: Fellmoser and Daubner), right: example for thermocouple lance with 0.5-mm thermocouples (photo: Dieterle)

Approximately 1.5 tonnes of spherical zirconium silicate material will be used as the packed bed. The storage material is kept in place by a perforated plate (for stabilization) and a sinter filter. The latter also ensures that even fine particles do not enter the liquid metal loop.

In parallel, a test section will be designed and the applicability of conventional heat transfer correlations for packed-beds will be tested. However, given the low Prandtl number, it is assumed that they will have to be adapted, as this is the case for the heat transfer of liquid metals in other geometries. In the literature, no Nusselt number correlations for packed beds that is valid for low-Prandtl number fluids is available to the authors' best knowledge.

5. CONCLUSIONS

Low-Prandtl number fluids, such as liquid metals, are promising for the application in packed-bed heat storage systems. However, until now, the concept has not been demonstrated on a larger scale. Therefore, a 100-kWh heat storage experiment is set up at KALLA using eutectic lead-bismuth as the heat transfer fluid and ceramic filler material as the storage medium. For such low-Prandtl number fluids, heat transfer correlations for packed beds are not yet available. Thus, a dedicated experiment will test and adapt the heat transfer correlation of conventional fluids. This will enable a better simulation and improved design of such heat storage systems.

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REFERENCES

[1] VDI e.V., *VDI Heat Atlas*, 11th edition, Springer Berlin Heidelberg (2013).

[2] NEA No. 7268, OECD, *Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies* (2015). Chapter 10: Low Prandtl number thermal-hydraulics.

[3] Pacio, J. and Wetzel, Th. Assessment of liquid metal technology status and research paths for their use as efficient heat transfer fluids in solar central receiver systems. *Solar Energy*, 93 (2013) 11–12.

[4] Pomeroy, B.D. Thermal Energy Storage in a packed bed of iron spheres with liquid sodium coolant, Solar Energy 23 (1979), 513-515.

[5] Niedermeier, K., Marocco, L., Flesch, J., Mohan, G., Coventry, J. and Wetzel, Th. Performance of molten sodium vs. molten salts in a packed bed thermal energy storage. *Applied Thermal Engineering*, 141 (2018) 368–377.

[6] Müller-Trefzer, F.; Niedermeier, K.; Daubner, M.; Wetzel, T. *Experimental investigations on the design of a dual-media thermal energy storage with liquid metal*. Applied Thermal Engineering, 213 (2022), 118619.