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Conceptual study of central receiver systems with liquid metals as efficient heat transfer fluids

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Abstract

Concentrated Solar Power plants (CSP) provide several advantages to other energy conversion concepts. However, they are still not competitive in price, compared to conventional power plants. But there is still potential to reduce the cost. The higher heat conductivity of liquid metals leads to very high heat transfer coefficients – ten times higher as with molten salts. This big advantage could increase the efficiency and lower the cost of CSP plants. In order to optimize such a power plant regarding efficiency and cost, detailed information of each component of the system is necessary. This paper shows several system concepts in which liquid metals can be used as heat transfer fluid. In addition, several liquid metal pump types are investigated as well as thermal energy storage concepts. With the assumptions and boundary conditions taken in this model, direct thermal energy storage with liquid metal is prohibitive. But some innovative indirect storage systems with liquid metals show costs in the same range as with a 2-Tank molten salt storage.

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Keywords: Central Receiver System; Heat transfer fluid; Liquid metal; thermal storage.

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1. Introduction

One promising option of renewable power generation are Central Receiver Systems. Such power conversion systems often use molten salts both as heat transfer and thermal energy storage material. Examples for current solar towers with molten salt are SolarTwo (1995), Gemasolar (2011) and Crescent Dunes (2014). Molten salts are cost-efficient and not toxic. Furthermore, their high heat capacity and low costs make them suitable as thermal storage material. But they have also some disadvantages inherited. The melting point is above 200 °C. This means high parasitic losses for trace heating. In addition, the upper cycle temperature is limited to about 565 °C due to the chemical decomposition. In reality, the mean receiver outlet temperature is even lower in order to avoid local temperatures above the decomposition temperature in hot spots on the receiver. By using liquid metals these disadvantages could be avoided. The main advantage of liquid metals are their heat transfer coefficients, which are an order of magnitudes higher than that for molten salt [1]. This could increase the receiver efficiency. Moreover, the higher temperatures allow advanced power conversion cycles with increased efficiency. Therefore, the possibility of cost reduction exists, despite the higher costs of liquid metals. The ECOSTAR-study from 2005 estimates the levelized cost of electricity (LCOE) for a 50 MW_{el} solar tower plant with molten salt technology to 0.15 €/kWh_{el} [2]. Recent calculations of a power plant with the same power output combined with a liquid metal receiver with an ultra-supercritical steam cycles have indicated a reduction potential regarding LCOE of about 15 %, compared to the ECOSTAR molten salt concept [3].

In order to determine the LCOE, annual yields calculation of the particular concept is necessary. This requires efficiency values and cost data for all components of the power plant, especially for part load situations.

Nomenclature

D	[mm]	diameter of tube
u	[m/s]	velocity of flow
ε	[mm]	roughness of inner tube surface

2. Physical properties and advantages of liquid metals as heat transfer fluid

Figure 1 shows on the left the usable temperature range (liquid phase) of several liquid metals compared to solar salt. The alkali metals and the Lead-Bismuth-Eutectic have lower melting points. This means additional hours of operation during times of low radiation and therefore a higher capacity factor of the receiver, but also lower parasitic losses for trace heating. Above 565 °C, solar salt becomes decomposed. Liquid metals, however, stay chemically stable even at higher temperatures. This makes highly efficient thermodynamic power conversion cycles possible.

The main advantage of liquid metals is the heat transfer coefficient. Figure 1 shows on the right the temperature dependent heat transfer coefficient for a single tube with D = 12 mm, u = 1 m/s und ε = 0.1 mm. For a temperature of 400 °C, molten salt has about 4600 $W/m^2/K$, whereas over 50000 $W/m^2/K$ can be achieved with liquid sodium. In principle, there are two different options with a higher heat transfer coefficient: First, staying at the same heat flux density or increasing the latter.

At the same flux density, the higher heat transfer coefficient will decrease the thermal gradient of convection on the inner tube wall surface. This will also reduce tube wall temperature and the risk of temperature hot spots and thus pipe stresses as well. The lower tube wall temperature also increases life span at lower material costs [4]. The lower the receiver temperature the lower are thermal losses by radiation and convection, so higher receiver efficiency is obvious.

Higher flux densities lead to smaller receivers for the same power output. The reduction of absorber surface decreases material and manufacturing costs. According to preliminary receiver performance studies, liquid sodium leads to an absorber area reduction of up to 57 %, compared to solar salt [1]. In addition, due to the absorber area reduction, radiation and convection losses might also decrease. Hence, both options imply higher receiver efficiencies and performance.