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A review on the application of liquid metals as heat transfer fluid in Concentrated Solar Power technologies

*Nikola Lorenzin**, *Alberto Abánades*

[a] *Universidad Politécnica de Madrid, Escuela Técnica Superior de Ingenieros Industriales, Departamento de Ingeniería de la Energía, Calle de José Gutiérrez Abascal, 2, 28006 Madrid, Spain*

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ABSTRACT

Among all renewable energy sources Concentrated Solar Power (CSP) systems are considered a technology that will play an important role in future energetic scenarios and that will become economically competitive with conventional fossil fuel power systems. As an example, among the next generation of CSP systems, Solar Central Receiver Systems (CRS) is a technology that is considered to have a high improving potential, especially if rising the operating temperature at about 1000 °C in order to increase the efficiency and thus reduce the dimensions of the receiver and the overall costs of the system. In order to achieve these temperatures liquid metals may be proposed to replace conventional fluids, namely water, air and molten salts, as a new generation of heat transfer fluids.

Five candidate liquid metals with the best thermophysical properties have been selected among the Alkali, Heavy and Fusible metal groups: molten tin (Sn), gallium (Ga), lithium (Li), sodium (Na) and lead-bismuth (PbBi). The last two already have operational experience within the field of nuclear power engineering, while the other have no operational experience and their thermophysical properties have been calculated only in a limited temperature range.

In this work the state of the art has been reviewed and the main critical issues (safety, compatibility with structural materials and integration with CFD software) have been analyzed and discussed. Future work and developments have been outlined, namely the need of extending the calculation of the thermophysical properties at the ideal operating temperature of 1000 °C, of further tests regarding the compatibility with structural materials both in dynamic and static conditions and of testing correlations and numerical methods for a better integration into CFD software.

Introduction

Nowadays the awareness of the environmental damage resulting from fossil fuels use, first of all the increase of the greenhouse effect, maintains a very high level of attention of public authorities, economic operators and policy makers towards issues linked to the production of energy. There is no doubt that renewable energy, not only in the near future but also in a much longer period of time, will play an increasingly

* *Corresponding author.*
E-mail address: nikola.lorenzin@alumnos.upm.es (N. Lorenzin).
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important role in the economic and energetic landscape worldwide. Among all renewable energy sources Concentrated Solar Power (CSP) is gaining increasing interest worldwide and is considered to be a technology which will play a crucial role in the future thanks to its rising economic competitiveness with fossil fuels [1].

In order to increase efficiency, thus lower the costs, next generation CSP systems will need to scale up, working at higher temperatures and with higher heat fluxes [2]. Due to their higher working temperatures, concentrating ratios and their higher potential of developing the state of the art and reducing the LCoE (Levelized Cost of Electricity) at large scales, Solar Central Receiver Systems (CRS) are considered one of the best choices among all CSP technologies [1,2]. This is confirmed by the trend which sees CRS systems overcoming the other CSP technologies for what regards under-construction and under-development projects [1].

CRS, also known as Tower Solar Power, is a concentrating solar power technology consisting of a heliostat field where each heliostat tracks the sunrays by means of a two-axes system and concentrates them on a solar receiver located at the top of a tower. In the receiver the HTF absorbs the heat flux and transfers it to the working fluid in order to produce electrical energy. The CRS system includes different configurations of the heliostat field which aim is to increase the optical efficiency by reducing the shading and blocking effects. Compared to the other CSP systems the CRS is a technology which allows higher concentrating ratios and heat flux densities but which requires a wider land use and higher initial costs, thus is preferred for large scale projects [1].

In order to improve the efficiency of a CSP system the performance of its receiver must be enhanced, which is mainly done by increasing the operating temperature of the heat transfer fluid (HTF). There is a maximum operating temperature for which the thermal receiver efficiency is maximized. This optimum has been found to be over the temperature of 900 °C, a temperature which cannot be reached by conventional fluids (water, nitrate salts and gases) employed until now in CSP systems [3]. Increasing the operating temperature and changing the HTF implies that changes in the different components of the system must be done, specifically in the following: solar receiver, circulating system, heat exchanger, control system and instrumentation. Regarding liquid metals, which are the HTFs taken into consideration in this work, the experience gained by sodium and lead-bismuth in nuclear power systems can be applied for the next generation of CSP [2].

Pacio and Wetzel and Pacio et al. [2,5] indicate the characteristics which need to be taken in consideration in order to choose the most suitable HTF for a CSP system. The fluid needs to be stable and in liquid phase ideally from ambient temperature and above 900 °C. The fluids physical properties need to be attractive: a large thermal conductivity improves the heat transfer process; a low viscosity minimizes the pressure drops; a large heat capacity makes possible to store the exceeding energy directly. At last, the compatibility with materials and respective safety issues must be accounted and tested properly.

Comparison with conventional fluids

There are six groups of HTFs which may be used in CSP systems: gases (air, helium and super critical CO2), water/steam, thermal oils, organic fluids, molten salts and liquid metals. The following table summarizes the respective advantages and drawbacks of the different groups of HTFs that can be employed in CSP systems [6].

Taking in consideration the information summarized in the table it is clear that conventional fluids are not able to further improve CSP systems efficiency by scale-up, a fact which suggests the employment of liquid metals as a new generation of HTFs [2,4,5]. The only HTFs which could be competitive with liquid metals for the new generation of CSPs are the new mixtures of molten salts (alkali-fluoride and carbonates LiNaK) which extend the temperature range up to 900 °C [6]. However this operating temperature is still lower than that of most liquid metals and the high melting point of 400 °C suggest that liquid metals are more promising as new generation of HTFs. Moreover the HTF and storage costs (in case of direct thermal storage) are only an initial cost in case of liquid metals while in the case of molten salts they need to be renewed since molten salts need to be reintegrated continuously during the process. Concluding and summarizing, the advantages of liquid metals respectively to conventional fluids as heat transfer medium are the following [5]:

- Wider operating temperature range (above 1000 °C).
- Lower melting point, thus lower energy consumption for keeping the fluid above this point.
- High boiling point which allows the operation at high temperatures.
- Large thermal conductivity which implies wider heat transfer coefficients for elementary geometries (more than two orders of magnitude for the same physical and geometrical conditions).
- Higher allowable heat fluxes. The improved heat transfer leads to improved receiver efficiency, reduced wall superheating thus lower radiation and convective losses and thermo-mechanical stresses.

On the other hand when compared to other HTFs, especially the conventional ones, these are the main disadvantages of liquid metals [5]:

- Big corrosion issues at relatively high temperatures. This problem is shared with molten salts and can be compared only with air, helium, sCO2 and water/steam because for what regards thermal oils and organic fluids no data is available in the literature.
- High costs when compared with air, helium, sCO2, water/steam and molten salts.
- Impossibility of direct thermal storage for some of the candidates.
- Safety issues when taking in consideration the Alkali metal group, especially liquid sodium.