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Review

Liquid metal technology for concentrated solar power systems: Contributions by the German research program

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Abstract: Concentrated solar power (CSP) systems can play a major role as a renewable energy source with the inherent possibility of including a thermal energy storage subsystem for improving the plant dispatchability. Next-generation CSP systems have to provide an increased overall efficiency at reduced specific costs and they will require higher operating temperatures and larger heat flux densities. In that context, liquid metals are proposed as advanced high temperature heat transfer fluids, particularly for central receiver systems. Their main advantages are chemical stability at temperatures up to 900 °C and even beyond, as well as largely improved heat transfer when compared to conventional fluids like oil or salt mixtures, primarily due to their superior thermal conductivity. However, major issues here are the corrosion protection of structural materials and the development of technology components and control systems, as well as the development of indirect storage solutions, to circumvent the relatively small heat capacity of liquid metals. On the other hand, using liquid metals might enable alternative technologies like direct thermal-electric conversion or use of solar high-temperature heat in chemical processes. This article aims at describing research areas and research needs to be addressed for fully evaluating and subsequently utilizing the potential of liquid metals in CSP systems. A second aim of the article is a brief overview of the liquid metal research capabilities of Karlsruhe Institute of Technology (KIT), their background and their relation to CSP and the aforementioned research pathways.

Keywords: concentrating solar power, high temperature heat transfer fluid, liquid metal, central receiver systems, liquid metal corrosion, liquid metal technology

1. Introduction

Concentrated solar power (CSP), and in particular central receiver systems (CRSs), can play a major role as a renewable energy source with the inherent possibility of including a thermal energy storage subsystem for improving the plant dispatchability. Next-generation systems have to provide an increased overall efficiency at reduced specific costs and they will require higher operating temperatures and larger heat flux densities. In that context, liquid metals are proposed as advanced heat transfer fluids in order to face those challenges and therefore largely contribute to the economics and deployment of future systems [1,2].

The use of liquid metal has been already considered in the past. Indeed, during the early years of the development of CRSs, sodium was one of the prominent heat transfer fluids under investigation, as evidenced e.g. by the tests summarized in Table 1. Although the main focus of research on CRSs has since then shifted towards other fluids (air, salts), this technology has continued to be investigated by several institutions around the world.

Sodium heat pipes have been widely studied for separating the solar receiver from a secondary heat-transfer area [3]. This concept has been studied and tested at a laboratory scale for applications like dish-Stirling systems [4] and solar methane reforming [5]. The main focus of those investigations was the decoupling of the heat transfer areas in order to provide an efficient heat transport system.

Table 1. Liquid metal (Sodium) based receiver test projects in the early 1980s.

Test facility	CRTF (US)	PSA (E)	PSA (E)
Type	External	Cavity	External
Developler	Rockwell Intl. (US)	Interatom (D)	Samprogetti (I)
Manufacturer	Rockwell Intl. (US)	Sulzer (CH)	Tosi Industriale (I)
Tset period	Oct 1981- Mar1982	1981-Apr 1983	1983-1986
Power, MW	2.5	2.5	up to 3.5
Peak heat flux, MW m^{-2}	1.53	1.4	2.5
Measured efficiency	90–96%	0.88	0.92
T inlet/outlet, °C	288/593	270/530	270/530
Aperture area, m^2	-	9.7	-
Aperture area, m^2	3.6	17	8.32
Thermal losses, Kw	?	500	230
Tube diameter, mm	21.4	?	14
Tube wall thickness, mm	1.2	?	1.0
Tube material	316 SS	316 SS	316 SS

In recent years, the international CSP-CRS community has acknowledged the need of advanced heat transfer fluids for next-generation plants and liquid metals have gained attention in several international research projects. Currently, two projects focused on LMs for CSP are funded by the US-DoE. First, in the framework of the Sunshot Initiative, UCLA is leading (with participation of UC-Berkeley and Yale) the thermo-chemical screening of candidate alloys which would fit the Sunshot-specific targets. For the most promising candidates, corrosion and heat transfer tests are envisaged. The second project foresees the development, by a consortium led by Georgia Tech., of an innovative hydrogen reactor based on molten tin as the heat transport medium. Further work as e.g. those reported in reference [6,7] have recently highlighted the attractive properties of liquid metals for CSP applications.

All heat transfer fluids used in current solar systems present individual advantages and limitations. For liquid metals, the main advantages are given by the combined efficient heat transfer capability and high-temperature stability, while a relatively low heat capacity and in some cases the corrosion issues represent the major limitations. As shown in Table 1, experiences with liquid sodium in the 1980s indicate that liquid metals allow an efficient operation from a thermal-hydraulic point of view. However, the overall operation had important drawbacks due to non-suitable monitoring, handling and technological standards, as well as lacking safety provisions, related to the chemical reactivity of sodium with water and air. In this respect, the state-of-the-art has evolved considerably ever since in other industries, although not yet applied to solar systems [8].

In the following sections, the research program on this topic in Germany is described in more detail. This program brings together two research centers of the Helmholtz Association, namely the Karlsruhe Institute of Technology (KIT) and German Aerospace Center (DLR). The article aims at describing research needs and potential research directions to be chosen in upcoming years, to reach a technical readiness level of liquid metals in CSP systems comparable to today's solar salt based systems. The article focusses on central receiver systems, as only with them, the full potential of liquid metals can be utilized and thus cost competitiveness might be achieved. Thermodynamic and system based economic considerations, behind that statement, are detailed in [9].

2. Research areas and research needs covered by the German program

2.1. Components and Control of Liquid Metal based CSP Systems

The use of a liquid metal (LM) as heat transfer medium in a CSP system requires dedicated designs of all components of the primary cooling loop, in particular the receiver, heat exchanger(s), pumps, control and monitoring systems. The latter include monitoring of the operational parameters, control valves, drainage systems, auxiliary heating etc. The valuable experience gained in other liquid metal applications as for instance accelerator based spallation targets or nuclear installations needs to be adopted and made useful for CSP system application. At KIT, a liquid metal based CSP demonstrator system including all mentioned components in a 10 kW range is under construction. This effort shall be accompanied by component tests like that of LM-based solar receivers in dedicated research infrastructures like the high flux solar radiation furnaces of DLR in Cologne, Germany. Basic research like determination of heat transfer and pressure drop correlations will also accompany the work where required.

2.2. Thermal Energy Storage Options in Liquid Metal based CSP Systems

Considering that thermal energy storage is a key component of the concentrated solar power technology and that liquid metals present a relatively low storage capacity, two possible systems are studied as working solutions.

First, an indirect approach, where liquid metals contribute towards improving the heat transfer efficiency, while a secondary storage medium (such as a non-expensive solid or phase change material) provides the low-cost storage capacity. This approach exploits role separation and thus avoids compromises which typically lead to non-optimum configurations. In addition to the selection of proper storage materials, research paths in this direction include the study of efficient power cycles including indirect storage, and the development of a cost-effective interface. In particular, heat exchangers for charging and discharging the storage subsystem will be required, and heat transfer enhancement techniques as well as direct contact options should be investigated.

Second, direct energy storage systems provide several advantages in terms of plant flexibility, buffering fast solar flux fluctuations in the time frame between minutes to one hour and allowing the CSP power plant to operate in load-following mode. Since in both cases the heat transfer fluid is a liquid metal, the additional investment has to be balanced by the gain in availability. The main focus of research in this respect is the development of efficient components such as buffer tank and heat exchanger or steam generator in the temperature range up to 800 °C. The integration of both systems into one device will possibly allow for investment reduction.

2.3. Direct Energy Conversion in Liquid Metal based CSP Systems

AMTEC (Alkali Metal Thermal Electric Converter) is one of the most promising devices for direct energy conversion (in Figure 1 an AMTEC prototype is shown). AMTEC is considered for implementation in CSP plants, either as stand-alone or as a topping system to conventional power conversion units. The physical principle is based on sodium-ion transport through a ceramic isolator driven by a temperature and pressure gradient. On the hot side, sodium is evaporated by solar thermal energy, allowing receiver temperatures up to 1100 °C. The sodium vapor is adsorbed at the ceramic surface and ionized: sodium-ions flow through, while the electrons produce direct-current power at an external load. Recombination of ions and electrons occurs at the cold side that operates at the sodium boiling point corresponding to a reduced pressure. A pump or a wick transfers the sodium back to the hot side. In this process, the excess energy can be transported by liquid metal to a storage device. Thermal-to-electric efficiencies in the range of 20–25% have been achieved in preliminary experiments, 30% and more are envisaged. Stable operation has been so far demonstrated successfully in previous research projects in small scale devices [2,10].

Figure 1. AMTEC prototype element. Detailed description is given in [10]

Quite some challenges still exist for developing AMTEC into large scale applications in power conversion systems. The most critical issues are given by the development of the solid electrolyte (Beta Aluminate Solid Electrolyte, BASE) and its integration into the metallic housing, stable film boiling at the receiver, long term operation of the BASE, efficient high temperature electromagnetic pumps, and safe operation under transient conditions. All high efficient power conversion systems have to rely on the availability of adequate structural and functional materials at high temperatures. Compared to Rankine or Brayton cycles, which operate at 5–10 MPa, AMTEC can be run at almost ambient pressure, resulting in lower mechanical load for the material. Nevertheless, the research and qualification of innovative materials are main issues for the successful development of AMTEC systems. Furthermore, an optimization analysis will be necessary to assess the economics of integration of AMTEC as a topping cycle, its interface to the basic power conversion system and the storage subsystem.

2.4. Structural Materials Compatibility in Liquid Metal based CSP Systems

As for high-temperature systems in general, also for high temperature liquid metal heat transfer systems, corrosion and degradation of mechanical properties of structural materials represent major concerns. In principle, the main corrosion mechanisms for liquid metal systems (oxidation, dissolution and intergranular attack, etc.), and the main factors affecting them (temperature, composition, microstructure, etc.) are well understood. This knowledge has allowed the development of protective measures for both sodium (non-metallic impurities control) and lead alloys (oxygen control, addition of minor components to the liquid or solid for promoting the formation of protective layers). For lead and its alloys such measures have been investigated and proven up to approximately 650 °C. Investigations beyond this level and up to 750 or even 900 °C are under way, i.e. efforts to develop protection techniques that can improve the compatibility of high temperature steels and other common metallic materials are further investigated [11-16]. Proven techniques include the monitoring of diluted impurities as e.g. oxygen and carbon in liquid sodium, the active oxygen control for lead alloys and surface modification of materials in contact using surface alloying processes like GESA [15]. As these techniques are improved, the maximum operating temperature level is continually increasing. Based on previous promising results, materials compatibility research will continue to develop upon those pillars. Alternatively, advanced materials, such as refractories (W, Ta) and industrial ceramics (SiC, Ti_3SiC_2) might also allow extending the operating temperature range beyond 800 °C.

2.5. Operational Safety in Liquid Metal based CSP Systems

A priority aspect when considering the successful operation of energy systems is related to overall safety and consequences of undesired incidents upon the general public, the working staff and relevant infrastructure. While liquid-metal related accidents will not have widespread effects, their local consequences can be serious.

In the case of sodium and alkali metals, their vigorous reactivity with both air and water represents an inherent fire risk. This challenge is tackled following a three-step strategy: prevention, early detection, and fast response. A preventive action consist in minimizing the probabilities of sodium/air or sodium/water interaction considering all relevant plant states, such as transients, operation, and maintenance tasks as well as emergency events. Early leak detection, currently based on electrical sensors or on hydrogen monitoring systems, can effectively reduce the extent of an accident. Fast response systems, such as automatic draining and injection of fire suppression agents limit the consequences of an accident. Extensive knowledge has been accumulated in sodium safety systems and the current state of the technology is greatly improved compared to some decades ago. Research activities in this regard shall consider each of the three steps of this safety strategy.

Lead and its alloys are chemically inert in contact with air and water. Both the metal and its oxide are toxic when inhaled or ingested therefore prevention, early detection and fast response should be considered as well. Relevant safety measures are in this case proper ventilation, isolation and hygiene facilities. Moreover, the physical interaction of liquid lead and its alloys with water produces a fast evaporation with sudden volume expansion, and thus should be considered when designing e.g. steam generators. Research activities in this area shall be focused on developing guidelines and investigation of further aspects that may become relevant when a technology is scaled up from laboratory to industrial scale.

3. Infrastructure and experience with liquid metal heat transfer systems at KIT

Both in its large scale research (formerly Forschungszentrum Karlsruhe) and university sector, the Karlsruhe Institute of Technology (KIT) has extensive experience in the development and investigation of liquid metal based energy systems. The main competences and infrastructure relevant to liquid metal heat transfer systems and CSP are outlined here.

3.1. Karlsruhe liquid Metal Laboratory (KALLA)

The Karlsruhe Liquid Metal Laboratory (KALLA) at KIT has long term experience in experimental investigation of liquid metal thermo-fluid dynamics, particularly in cooling of highly thermally loaded surfaces and materials selection and characterization. This scientific work is complemented by vast operating experience of small and large liquid metal systems, development of all necessary auxiliary equipment like heat exchangers, control systems, etc.

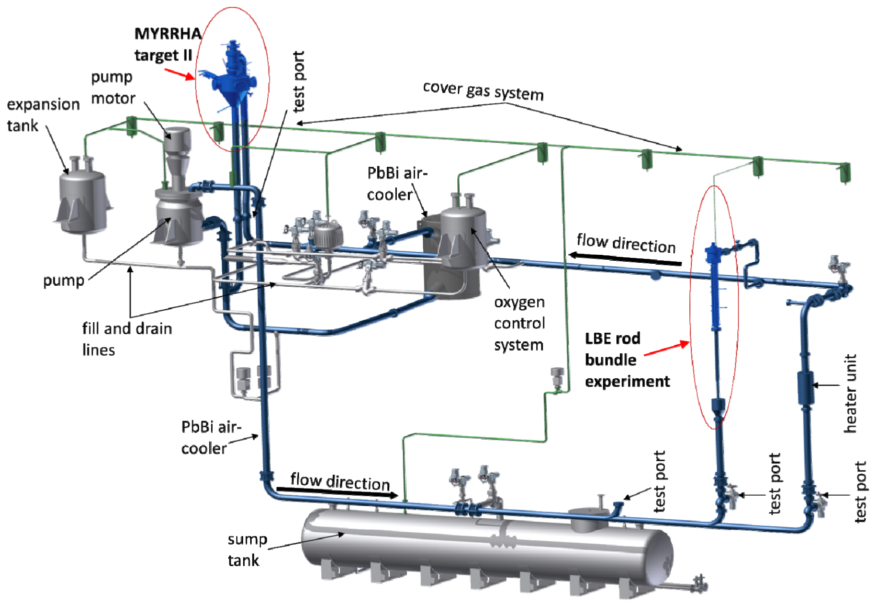

Figure 2. THEADES thermal hydraulics loop at KALLA: 44 tons of PbBi, 500 kW max. heating/cooling power, 47 m³/h, active oxygen control, 3.4 m usable height.

The liquid metals investigated in KALLA so far are lead-bismuth, lead, tin, indium-gallium-tin, sodium and sodium-potassium. A wide range of operating conditions is covered, from room temperature up to 550 °C and cooling capacity beyond 500 kW for high power densities in excess of 1 MW/m^2, in case of flowing liquid metals. For stagnant liquid metal testing devices, temperatures up to 900 °C have been applied as well. Several loop facilities are operated, covering different specific topics, such as thermal hydraulic and high-temperature corrosion studies, and development and testing of specific components and technological systems (e.g. instrumentation, pumping), see Figure 2. The experimental work is accompanied by thorough analyses of the data and development or improvement of physical models and numerical simulation tools [16,17]. A demonstration solar system featuring a liquid metal cooled receiver (SOMMER) is under construction. The accumulated knowledge has been utilized in international projects, contributing to improving the state-of-the-art in liquid metal systems.

3.2. Karlsruhe Sodium Laboratory (KASOLA)

KASOLA is a versatile liquid sodium facility, which allows various experiments at several ports covering different specific topics, such as thermal hydraulic and high-temperature material behavior studies, as well as development and testing of measurement techniques. As part of the Helmholtz Energy Materials Characterization Platform (HEMCP), KASOLA contributes to research and development of direct energy conversion systems, such as AMTEC (Alkali Metal Thermal Energy Converter). Based on the experimental findings, program development on various levels (CFD, system codes, details specific models, multi-physics analysis) accompanies experimental work to support experiment preparation, analyses and qualification of data. In order to thoroughly take into account daily thermal transients due to day/night conditions, material research aspects as fatigue and creep-fatigue have to be included to optimize design and material selections. Safety aspects are also taken into account from the beginning to allow low-risk operation and handling.

3.3. Research on Materials Compatibility and dedicated Infrastructure

Materials compatibility, in terms of resistance to corrosion and mechanical properties degradation with liquid metals, is one of the main issues for technological realization. E.g. in liquid Pb or Pb-Bi based systems, the solubility of metallic components (especially of steel alloying elements) and non-metallic elements are essential parameters to be considered. Indeed, in case of reducing potential (meaning a liquid metal with low oxygen content), the solubility of elements as Ni is high, thus putting into question the use of Ni based alloys or austenitic steels in high temperature components; while under the same conditions refractory metals such as W, Mo and Ta (up to 800 °C) show very low solubility. In the case of liquid sodium, the solubility of most elements is significantly smaller and therefore most conventional high temperature steels can be applied up to 650 °C as long as the oxygen content is kept at low values.

Several research groups at KIT perform coordinated activities devoted to improve the performance of candidate structural materials thus allowing for their practical implementation in high-temperature systems. Liquid lead and its alloys allow for adding oxygen, thus forming an oxide scale on the steel surface which minimizes the degradation due to dissolution or the degradation of the mechanical properties. Oxide formation and dissolution rates are evaluated in both loop-type and stagnant facilities. Furthermore, the instruments and methods of controlling the oxygen concentration during the experiments are constantly improved, which is essential for producing meaningful data in the material tests. Under the umbrella of KALLA, a number of different corrosion test facilities are operated in KIT [12,14]. The corrosion test-loop CORRRIDA is operated with lead alloys up to 550 °C and the recently constructed TELEMAT targets test temperatures up to 750 °C. Stagnant test set-ups like COSTA employed for corrosion screening of materials are operated up to 900 °C, see Figure 3. Facilities that combine corrosion tests with additional loads like fretting (FRETHME), erosion (CORELLA) and creep-to-rupture (CRISLA) are in operation as well.

Figure 3. COSTA up to 900 °C corrosion test setup (left) and CRISLA creep-to-rupture test setup for structural materials in lead alloys (right): two examples out of a complete set of materials compatibility research facilities.

In order to tackle the sodium activities especially at the envisaged high temperatures, a set of new loop type facilities are under design and construction. These set-ups will allow to test materials regarding its high temperature compatibility with sodium (up to 850 °C) and to simulate in-situ realistic stress strain scenarios including thermal cycling. Life time behavior simulation, aging, joints performance and reliability of modified surfaces (coatings and surface alloys) are to be addressed using all available experimental and simulation capabilities.

KIT has many years of experience in corrosion investigations and corrosion mitigation. Modification of surface properties by surface alloying using pulsed electron beams (GESA process [15]) and impurity control in heavy liquid metals like lead (Pb) and eutectic lead-bismuth (PbBi) are some of the processes used. All required post-test analysis methods are available in the metallographic laboratories at KIT. Simulation of material transport in liquid metals and of the surface modification processes are employed to support the experimental analysis. The acknowledged expertise of the researchers is demonstrated in the active participation in European and international projects and cooperation.

4. Summary

Liquid metals represent a promising option for high temperature heat transfer fluids in central receiver CSP systems. Their main advantages are chemical stability at temperatures up to 900 °C and even beyond, as well as largely improved heat transfer when compared to conventional fluids like oil or salt mixtures, primarily due to their superior thermal conductivity. The beneficial heat transfer capabilities contribute to significant efficiency gains and subsequently to lowered levelized cost of electricity.

However, there are some key challenges to be addressed for the large scale application of liquid metals at very high temperature. Major issues here are compatibility (in terms of corrosion and mechanical resistance) of structural materials with the liquid metals and the development of technology components and control systems, as well as the development of indirect storage solutions, to circumvent the small heat capacity of liquid metals. Safety is another important concern. Although necessary measures are well known from other applications, a careful evaluation is needed for the transfer to CSP. Vast operating experience with liquid metal systems has been gathered from the nuclear as well as other scientific areas like liquid metal spallation targets in elementary particle sources or even industrial applications like glass production or electronics cooling. Using liquid metals might enable alternative technologies like direct thermal-electric conversion or use of solar high temperature heat in chemical processes.

The home institution of the authors, Karlsruhe Institute of Technology, Germany, hosts experienced research teams and dedicated laboratory as well as large scale infrastructure for all described research aspects related to application of liquid metals in CSP.

Conflict of Interest

All authors declare no conflicts of interest.

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