ANALYSIS OF APPLICATION OF LIQUID METAL COOLANTS AS HEAT TRANSFER FLUID FOR CONCENTRATED SOLAR POWER SYSTEMS

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ABSTRACT

In the near future renewable energy sources should play an important role in reaching economic competitiveness with fossil fuel for a change in the global energetic scenario in view of the fight against climate change. Concentrated Solar Power (CSP) is into the portfolio of renewable technologies that are called to have a significant contribution to that future sustainable scenario. Nowadays, its economic competitiveness has a high improving potential due to technological development and scale factors that should be confirmed during the next decades. For reaching economic competitiveness with fossil fuel based systems and other power technologies, next-generation CSP must increase their operating temperatures and their receiver efficiencies by the substitution of conventional heat transfer fluids (HTFs) with more efficient ones. A more efficient HTF would make possible to enhance the heat transfer process by allowing higher heat flux densities while reducing the thermal losses, a fact which leads to a reduction of the dimensions of the receiver and consequently a reduction in the overall costs of the system.

The HTFs which are going to be employed in the next-generation of CSP systems might be based on molten salts and liquid metals. The aim of this work is to focus on the employment of liquid metals as HTF in CSP technologies. For this purpose liquid metal candidates have been chosen by their thermo-physical properties among three main groups: Alkali metals, Heavy metals and Fusible metals. Among these candidates some of them already had operational experience as coolants in other power plants as nuclear power reactors, namely sodium and lead-bismuth, while the others have never been tested in practice.

The purpose of this work is to analyse the potential performance of liquid metals as HTF, and the proposal to compare the performance of solar receivers with various coolant candidates. Computational Fluid Dynamics (CFD) tools may be applied to evaluate such performance describing the thermal and fluid-mechanic singularities of each fluid. In addition, the limitation of those tools into its application to low Prandtl HTFs, in which the common Reynolds Analogy is not valid, suggests the utilization of high configurable codes that could be customized to describe accurately heat transfer mechanisms.

INTRODUCTION

The environmental damage, in particular the emission of greenhouse gases, resulting from the production of energy by means of fossil fuels lead to a worldwide debate linked to the production of energy which involves economic operators, policy makers and public authorities. In the last decades, in fact, the regulatory provisions and agreements at the international level concerning the reduction of greenhouse gas emissions, energy conservation and promotion of renewable energy sources are continuing at a fast pace. There is no doubt that these sources will have a crucial importance in the near future. Among all of these, solar and wind energy are the sources which are characterized by the highest grow rates per year.

The focus of this work is on Concentrated Solar Power Systems (CSPs), which are considered a technology that has a high potential, by means of a scale up, to become competitive with fossil fuel systems [1]. CSP systems will need to work at higher temperatures, with higher heat fluxes, in order to reduce the Levelized Cost of Electricity (LCoE) by increasing the efficiency [1, 2]. In the meantime, the thermal losses should be minimized by the development and utilization of more efficient materials from the point of radiative properties, heat transfer and their stability at high temperatures (structural integrity), as well as their inter-compatibility (corrosion, etc). Capital and operational cost reduction should be achieved by the development of new concepts and new materials, increasing overall plant efficiency and reducing maintenance.

CRS (Central Receiver Systems) is a solar concentrating technology which consists of different components: a field of heliostats in which by means of a two-axis system each heliostat tracks the sun; a solar receiver, which is located at the top of the tower and has function to absorb the maximum possible radiation coming from the field; a working fluid circuit which receives the energy absorbed by the receiver. Compared to the other Concentrating Solar Power technology, CRS is characterized by higher concentrating ratios, thus temperatures and heat flux densities, and by a higher land use and initial costs [1]. This facts makes CRS the concept with higher potential for the implementation of heat transfer fluids with high thermal capacitance and long term stability at high temperatures (> 700 ºC).

For enhancing the performance of such a system the specific efficiency of the integration of receiver and the block of power must be improved. This can only be done by increasing the working temperature of the HTF (heat transfer fluid), which optimal value has been determined to be over the temperature of 900°C. Since this temperatures cannot be reached by conventional fluids, such as water or commercial solar salts, in order to improve the CRS system the choice is restricted to liquid metals and new mixtures of molten salts [3]. For the next generation of CRSs here follow the characteristics that heat transfer fluids will need to have. They will need to have attractive thermo-physical properties, i.e. a large thermal conductivity which improves the process of heat transfer, a low viscosity that minimizes the pressure drops, a large heat capacity in order to increase thermal inertia and avoid a secondary circuit for the thermal storage. They will need to be liquid and stable from the lowest possible temperature to more than 900°C; they will need to be compatible with the structural materials and chemically stable and safe [2, 4] In general liquid metals are more suitable for the next generation of HTFs if compared with conventional fluids, because of their wider operating temperature range and better thermo-physical properties. However, depending on the group of metals, the bigger challenge lays in solving the problems related to compatibility with structural materials or safety issues [4].

LIQUID METAL CANDIDATES

Six liquid metal candidates have been chosen from the Heavy, Fusible and Alkali metals group. The candidates have been chosen based on their thermo-physical properties, which are shown in the following table 1 [5]:

Of these six candidates only Sodium and Lead-bismuth have had operational experience during the last decades in nuclear power plants. The other candidates have no experience and their thermo-physical properties and compatibility with materials have not been studied yet across the entire temperature range [2].

The Alkali group, from which Sodium and Lithium have been chosen, are characterized by relatively low fusion point, low cost and good compatibility with materials. However they present serious safety problems because of their high exothermal reactivity with air and water which may result in toxic leaks and explosions [4]. Regarding the thermo-physical properties lithium is more attractive because of the higher boiling point, higher conductivity, lower density and higher capacity, which makes it suitable for direct thermal storage.

The Heavy and Fusible metals groups are similar regarding compatibility with materials and safety issues. From the first group Lead-bismuth has been chosen, while from the second Gallium, Tin and Galinstan have been chosen. Both the groups are characterized by extremely low safety risks and high corrosion rates, with the Fusible group being more problematic from this point of view. Gallium is the metal candidate with the best thermo-physical properties: it is liquid at room temperature, has the widest operative range, one of the highest thermal conductivities and the highest heat capacity. The drawback of Gallium, and in general of the Fusible group, is the extremely high cost [2]. The advantage of Lead-bismuth lays in his operation experience in nuclear plants, in the good thermo-physical properties and the low cost [2].

HTF	Tfusion [°C]	Tboiling [°C]	Cp [kJ Kg-1 K-1]	λ [W m-1 K-1]	ρ [Kg m-3]	μ [mPa s]	Heat Capacity [ρ*Cp]	Cost [USD kg-1]
Molten Tin (Sn)	232	2687	0.24	33.8	6330	1.01	1519,2	15.9
Gallium (Ga)	29.8	2403	3.75	59.5	5673	0.69	21273,75	252
Sodium (Na)	98	883	1.26	57.5	761	0.16	958,86	2
Lithium (Li)	180	1347	4.16	63.3	436	0.20	1813,76	11.82
Lead-bismuth (44.5Pb-55.5Bi wt%)	125	1638	1.46	17.7	9710	1.33	14176,6	13
Galinstan (66Ga-20.5In-13.5Sn wt%)	-19	> 1300	0.29	16.5	6440	2.4	1867,6	450

Table 1: Themo-physical properties of candidate liquid metals [5].

EVALUATION OF LIQUID METAL PERFORMANCE

The application of liquid metal technology to the design of energy equipment, as it is the case of a solar receiver, is very reduced and the engineering tools that are used for the sizing of plants components are low qualified for the description of the physical phenomena that are involved, specially thermal-fluid-mechanics. For instance, the utilization of multipurpose codes based on finite element solutions for Navier Stokes equations and the usual treatment of boundary layers around wetted surfaces are affected on its performance by the low Prandtl number of most of the liquid metals, that make very difficult to fulfil some of the approximations that should be done for a practical resolution of the energy and momentum equations.

For that reason, the validation of fluid-mechanic codes on its application to liquid metal application should be done in the conditions that are expected in the operation of a solar receiver. A central solar received is expected to work with temperatures in the 200-600 ºC range when designed for molten salts. This range is close to the temperature range of many nuclear application of liquid metals, mainly lead and lead-bismuth reactors [6]. This fortunate circumstance implies that the state-of-the art of common engineering tools have a reasonable grade of confidence for the design of equipment as heat exchanger or pumps.

The comparison of the performance of liquid metal technology applied to CRS should be done by the evaluation of the efficiency and other operational variables of a central receiver in the range of temperatures in which at least some low-Prandtl fluid has been tested. In particular we have chosen the work of Rodriguez-Sanchez et al. (2014) [7] as a reference case. In parallel, some work should be done to establish the validity range of fluid-mechanic models implemented in common CFD codes. If the comparison between molten salts and molten metals suggests that the application of the latter could be positive, further analysis could be done to extent the design of central tower receiver to higher temperatures with liquid metals, taking into account critical issues as corrosion and material compatibility that are expected to be significant at that stage.

REFERENCE CASE

The reference design of solar receiver on which the CFD simulations have been conducted has been taken from [7], where the flow of Hitec molten salt has been studied. The proposed design is an alternative to the traditional external tubular solar receiver and is called bayonet receiver. The receiver, which is 10.5m high and has a 8.4m diameter, is composed by 18 panels, each of which composed by 22 tubes. As shown in figure x. in each panel the fluid rises from the inlet header into the inner tubes, flows upwards and heats up itself, then turns direction in the upper part and flows in the outer tubes before being collected at the bottom in the outlet header.

Parameter	Value	Parameter	Value
Receiver height [m]	10.5	Wind velocity [m/s]	0
Receiver diameter [m]	8.4	Ambient pressure [bar]	1
Number of flow paths	2	Ambient temperature [°C]	30
Total number of panels	18	Relative humidity [%]	60
Number of tubes per panel	22	Global absorptivity of the tubes	0.93
Total mass flow by the panels [kg/s]	290	Tube material emissivity	0.84
External diameter of the outer tube [mm]	60.3	Sky emissivity	0.895
Wall thickness of tubes [mm]	1.65	Refractory wall emissivity	0.2
Tube pitch [mm]	2	Ground emissivity	0.955
External diameter of the inner tube [mm]	52	Temperature of the liquid at inlet of the receiver [°C]	290

Table 2: Reference case design parameters [7].

We have initiated the modelling of this reference case with OpenFoam, generating the mesh shown in Figure 2. Because of the symmetry of the geometry and in order to reduce the computational time of the simulations, a 2-D axisymmetric geometry has been created.

The mesh has been divided in three regions: two solid regions, one for the inner tube walls and one for the outer tube walls, and one fluid region. For every region the mesh has been structured in order to have a finer mesh in the bottom region, where inlet and outlet are located, in the upper region, where the flow changes direction, and near the walls, which is a critical part of the solution for turbulent flows. Since the height of the receiver is extremely big and would result in a too large computational time, in the middle of the geometry, where the solution also does not change from meter to meter, a coarser mesh has been created with cells measuring 0.1 meter in the y direction.

We are working in the evaluation with our model of the performance on this reference design with molten salts, to compare with the existing data available in the literature [7]. In a second stage, we will estimate the performance with various liquid metal candidates to assess the technological diagnosis about its applicability and its potential technical improvements.

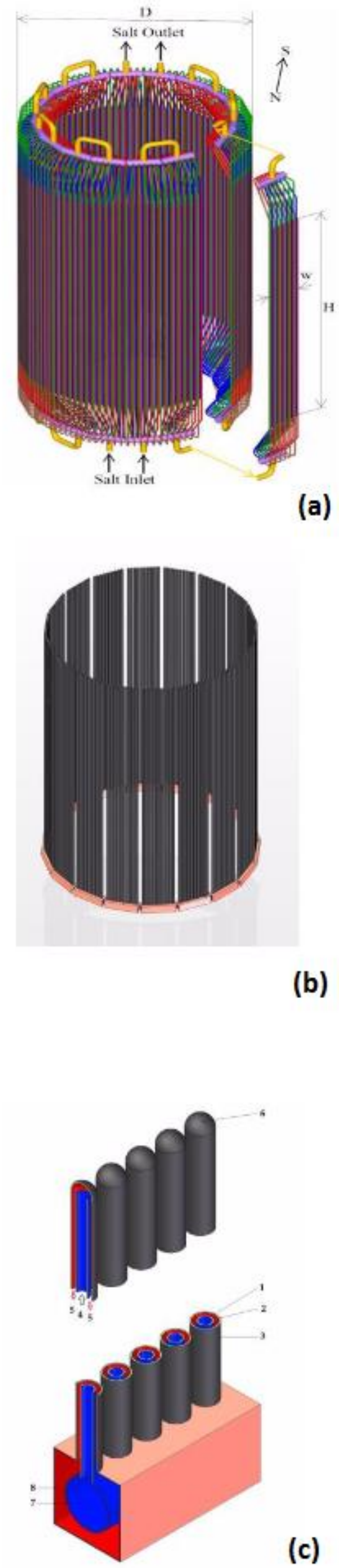

Figure 1: Reference case design: (a) shows the conventional external tubular solar receiver design; (b) shows the innovative bayonet tubular receiver design; (c) shows the structure of the tubes for each panel [7].

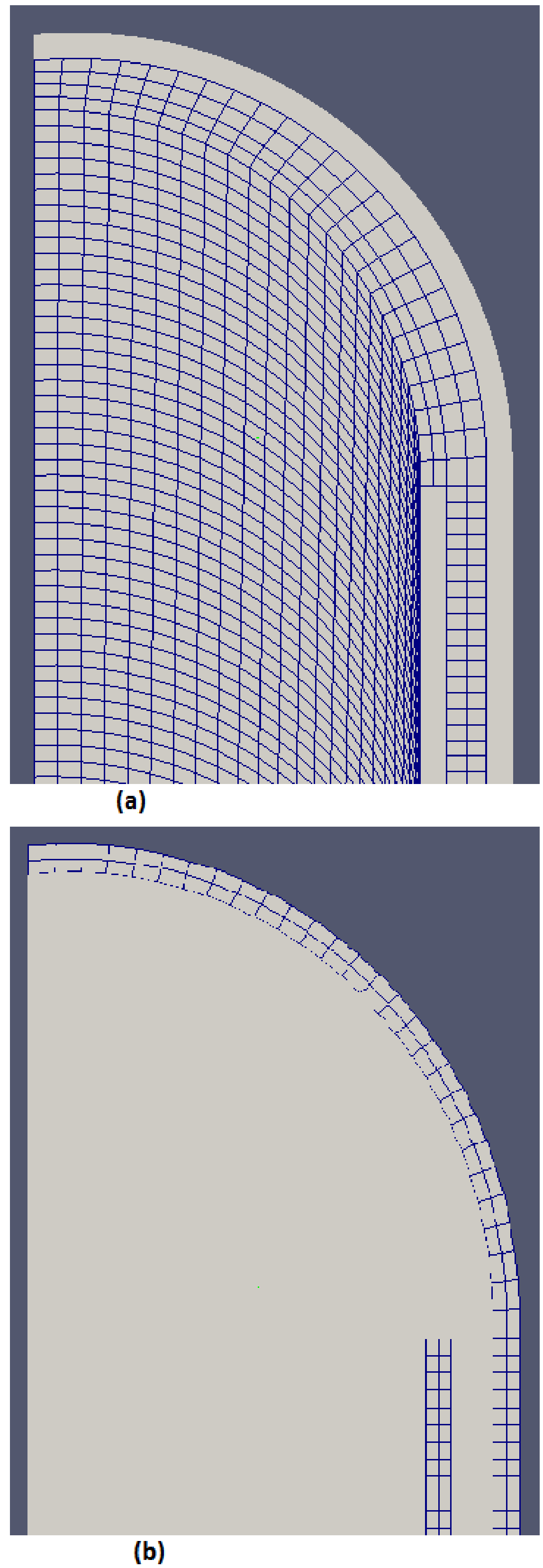

Figure 2: Mesh of the three regions modelled within OpenFOAM: (a) the mesh of the internal and external walls; (b) the mesh of the heat transfer fluid.

CONCLUSIONS

For increasing the efficiency and becoming competitive with fossil fuel based systems the next generation of CSP plants, more specifically Solar Power Tower systems, will need to operate with HTFs which can withstand higher temperatures and admit higher heat fluxes. For this purpose liquid metals and new mixtures of molten salts are the best choice.

Six liquid metal candidates, the ones with the best thermo-physical properties, have been chosen from the Alkali, the Heavy and the Fusible metals groups. These are: Sodium, Lithium, Lead-bismuth, Gallium, Tin and Galinstan. These candidates are going to be adapted, tested and compared by means of the Computational Fluid Dynamics (CFD) software OpenFOAM. For this purpose a design of an external tubular solar receiver working with molten salts has been taken as reference.

A physical model is being built and simulation are in the process of being conducted. At the end the results are going to be compared and discussed for all the candidates.

REFERENCES

[1] Baharoon, D.A, et al., "Historical development of concentrating solar power technologies to generate clean electricity efficiently – A review", Renewable and Sustainable Energy Reviews 41, 996-1027 (2015).

[2] 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, 11-22 (2013).

[3] Pacio J, et al., "Thermodynamic evaluation of liquid metals as heat transfer fluids in concentrated solar power plants", Applied Thermal Engineering 60, 295-302 (2013).

[4] Pacio J, et al., "Liquid metals as efficient coolants for high-intensity point-focus receivers: implications to the design and performance of next generation CSP systems", Energy Procedia 49, 647-655 (2014).

[5] Lorenzin N and Abanades A, "A review on the application of liquid metals as heat transfer fluid in Concentrated Solar Power technologies", International Journal of Hydrogen Energy (2016).

[6] Georgy Toshinsky and Vladimir Petrochenko , "Modular Lead-Bismuth Fast Reactors in Nuclear Power", Sustainability 4, 2293-2316 (2012).

[7] Rodríguez-Sánchez M.R., et al., "New designs of molten-salt tubular-receiver for solar power tower", Energy Procedia 49, 504-513 (2014).