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Construction of a test facility for demonstration of a liquid lead-bismuth-cooled 10kW thermal receiver in a solar furnace arrangement - SOMMER

J. Flesch[a]*, A. Fritsch[b], G. Cammi[a,c], L. Marocco[a,c], F. Fellmoser[a], J. Pacio[a], Th. Wetzel[a]

[a]*Karlsruhe Institute of Technology KIT, Hermann-von-Helmholtz-Platz 1, 46344 Eggenstein-Leopoldshafen, Germany*
[b]*German Aerospace Center DLR, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany*
[c]*Politecnico di Milano , Piazza Leonardo da Vinci 32, 20133 Milano, Italy*

Abstract

Liquid metals have been proposed in the past as high temperature heat transfer media in concentrating solar power (CSP) systems. Until the mid 80s test facilities were operated with liquid sodium-cooled central receivers. After a period of reduced interest in that approach, several new efforts have been reported recently, particularly from the US, South Africa and Australia. In addition, several recent publications have highlighted the attractive properties of liquid metals for CSP applications. A new contribution to this topic has been launched by Karlsruhe Institute of Technology (KIT) and the Solar Institute of the German Aerospace Center (DLR), combining their experience in CSP and liquid metal technology. The overall goals of this project are planning, design, construction and operation of a small concentrating solar power system in the 10 kW thermal range (named SOMMER) using liquid metal as heat transfer fluid for re-gaining operation experience and validating design methodology and providing a complete design concept for a large pilot CSP plant based on liquid metal technology, up to evaluation of O&M cost and levelized cost of electricity. This paper describes the current status of the work on the design and setup of SOMMER, the research goals of this facility, first results of numerical activities in view of the liquid metal cooled receiver design and the connection to the design activities for the pilot plant.

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Keywords: high temperature heat transport fluid, central receiver systems, liquid metal

* Corresponding author. Tel.: +49 (0)721 608-23421.
E-mail address: jonathan.flesch@kit.edu

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1. Introduction

Concentrating solar thermal power plants (CSP) with thermal energy storage have the advantage to generate power in periods without sunshine, e.g. during the passage of clouds over the mirror field or at night. Thus, the inherent fluctuations in the solar energy supply of the sun can be compensated by CSP plants without additional shadow power plant capacity. Although this is a principle advantage compared to e.g. photovoltaic power, for increased competiveness of CSP plants, the levelized cost of electricity (LCOE) generation still has to be reduced. One principal way to reach that goal is increasing the upper operating temperature limit of the plant and consequently the thermal-to-electric efficiency. A study performed by Kolb [1] indicates that operating temperatures up to 600°C could lead to higher efficiencies and reduced LCOE for super-critical steam cycles at 300 bar. According to a study performed by Singer et al. [2], future use of ultra-supercritical steam cycles at temperatures of 750°C and 350 bar could further reduce the LCOE [2]. However, these advantages in LCOE reduction require further development of plant components and technology, according to for example Kolb and Singer et al. [1, 3]. A particular challenge is the choice of suitable high temperature heat transfer fluids.

Nomenclature

Latin symbols

c_p	spec. heat capacity [kJ/(kg·K)]
D	inner tube diameter [m]
h	convective heat transfer coefficient [W/(m²K)]
k	turbulent kinetic energy [m²/s²]
k_θ	temperature variance [K²]
$\dot{m}$	mass flow rate [kg/s]
$\overline{T}_w$	average wall temperature [K]
T_b	average bulk temperature [K]
w	fluid velocity [m/s]
y^+	dimensionless first cell wall distance [-]
q''	thermal flux density [W/m²]

Greek symbols

α	thermal diffusivity [m²/s]
ε	dissipation of turbulent kinetic energy [m²/s³]
ε_θ	dissipation of temperature [K²/s]
η	dynamic viscosity [Pa·s]
θ	radial angle [rad]
λ	thermal conductivity [W/(m·K)]
ν	kinematic viscosity [m²/s]
ν_t	momentum diffusivity [m²/s]
ρ	density [kg/m³]

Dimensionless numbers

Nu	Nusselt number $\mathrm{Nu} = h \cdot D/\lambda$
Pe	Peclét number $\mathrm{Pe} = \mathrm{Re} \cdot \mathrm{Pr}$
Pr	Prandtl number $\mathrm{Pr} = \nu/\alpha$
Pr_t	turbulent Prandtl number $\mathrm{Pr}_t = \nu_t/\alpha_t$
Re	Reynolds number $\mathrm{Re} = (\overline{\mathrm{w}} \cdot D \cdot \rho)/\eta$

Liquid metals have been proposed in the past as high temperature heat transfer media in concentrating solar power systems. Indeed, during the 1980´s tests have been carried out on a demonstration plant (Plataforma Solar de Almeria) operated with a liquid sodium-cooled central receiver (Kesselring [4]). Unfortunately, the experiments have been stopped after a fire, caused by a sodium leakage during maintenance work.

Recently, after a period of reduced interest in that approach, several new efforts have been reported, such as thermo-chemical screening of candidate liquid alloys, as well as corrosion and heat transfer tests in the framework of the Sunshot Initiative in the US [5]. Further work, as e.g. those reported in Singer et al. [2], Kotzé et al. [6] and Boerema et al. [7] have recently highlighted the attractive properties of liquid metals for CSP applications.

A contribution to this topic has been recently launched by the Karlsruhe Institute of Technology (KIT) and the Solar Institute of the German Aerospace Center (DLR) and in the framework of the Helmholtz-Alliance LIMTECH [8], combining their experience in CSP and liquid metal technology. In a first step, both institutions reviewed the characteristics of various liquid metal options, aiming at identifying those fluids best suited for the application in CSP systems. The candidates were assessed regarding their thermodynamic properties and temperature limitations (thermal conductivity, heat capacity, viscosity, melting point, vapor pressure), handling problems, safety issues, hardware considerations (pumps, piping, valves, heat exchangers) and operating experience with liquid metal systems, see refs. [9], [10].

The further goals of the project are the following:

- Planning, design, construction and operation of a small concentrating solar power system in the 10 kW thermal range operated with liquid metals, called SOMMER (Solar Molten Metal Receiver). The facility will be located and operated on KIT grounds, with a liquid metal based receiver and intermediate storage.
- DLR will develop and assess a complete design concept for a large pilot CSP plant based on liquid metal technology, up to evaluation of O&M cost and levelized cost of electricity in order to compare the liquid metal system with conventional systems, e.g., based on molten salt.

This article presents the current status and preparation activities regarding the first project goal: the integration of a liquid metal loop within a solar furnace. The system description, as well as the research goals of this facility, is presented in Section 2. A major concern during the design process is the selection of an initial tube receiver design. Liquid metals are characterized by a high molecular thermal conductivity and a low Prandtl number. This results in a heat transfer mechanism different from that for ordinary fluids. As a consequence, the Reynolds analogy, which assumes a constant turbulent Prandtl number close to unity, cannot be applied to liquid metal flows. This prevents the applicability of conventional heat transfer correlations and turbulence models. Moreover, tubes of thermal receivers are exposed to circumferentially uneven high heat flux densities of the concentrated sunlight, which creates some doubt about the applicability of correlations developed for uniformly heated tubes. Thus, a liquid metal flow in a circular tube was simulated with an advanced turbulence model for two different boundary conditions, i.e. constant and sinusoidal heat flux along half of the circumference. The results of this numerical investigation are presented in Section 3. The investigation approach of DLR for the second project goal is briefly described in Section 4.

2. The SOMMER facility

A small concentrating solar power system in the 10 kW thermal range is under construction at KIT as a test facility for the investigation of liquid metals as heat transfer fluids (HTF) in CSP plants. A lead-bismuth-eutectic (LBE) mixture was selected, due to the extensive experience in handling it at KIT's liquid metal laboratory KALLA and according to the evaluation in [9]. Although sodium (Na) has even better heat transfer characteristics than LBE, it has been at this stage discarded because of the significantly more stringent safety measures related to it. However, Na remains a candidate for further research, as well as other fluids like for example tin (Sn).

Solar power for the receiver will be provided by a solar furnace arrangement of a sun-tracking heliostat mirror and a concentrating parabolic mirror, see Fig. 1.

2.1. Research goals

One of the aims of the SOMMER loop is to (re)gain operation experience of a sun powered thermal system operated with liquid metals. This includes investigation of optimal thermo-hydraulic conditions of the receiver, by taking into account and validating results from computer simulations. The fluctuating nature of the sun as the source of energy will introduce system dynamics uncommon for state-of-the-art liquid metal loops. This refers to fast power and temperature transients as well as to the changing temperature levels due to 24 h operation under solar power source conditions. Current liquid metal experience, particularly with LBE, is based on a controllable and usually constant electric heat supply. Specific corrosion protection systems, designed to control impurities' partial pressures in the liquid metal, rely on almost constant temperature levels. Therefore power and temperature dynamics will be a challenge for the operation of SOMMER.

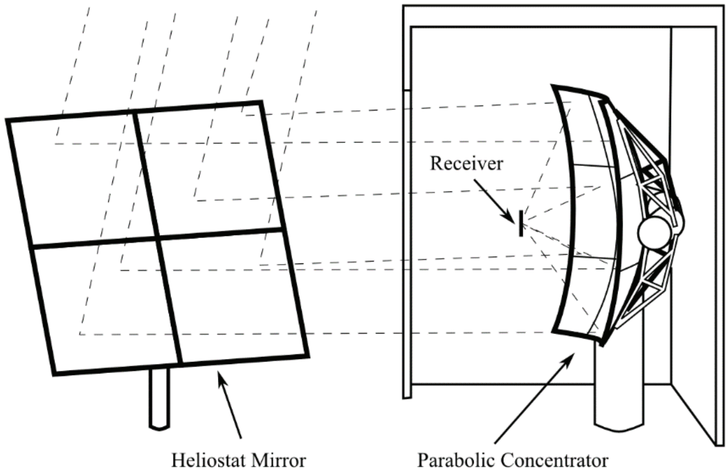

Fig. 1 Solar furnace arrangement of the SOMMER plant: A sun-tracking heliostat mirror reflecting the light onto a parabolic concentrator mirror. The parabolic concentrator is installed in a fix position and is protected from the environment by a building. A thermal receiver is installed in the focal point of the concentrating mirror and connected to a LBE loop.

A crucial aspect is the investigation and validation of receiver designs with LBE as heat transfer fluid. The design and testing of a liquid metal based intermediate energy storage is also a goal of this project. Due to the low specific thermal capacity of most liquid metals, and particularly LBE, hybrid solutions with solid or secondary liquid storage media need to be considered.

Furthermore, different pumping options should also be investigated. Indeed, electromagnetic pumps, for example, would have many technological advantages. However, in order to apply them to pilot or even bigger CSP plants, they need substantial further development in view of their limited efficiency. Procedures for safe liquid metal handling, operation guidelines etc. will be developed and documented such as to be transferable to larger plants.

2.2. Setup

The basic loop configuration will consist of a pump, a cooler, an electric heater and the thermal receiver. The possibility to expand it in order to accommodate a thermal energy storage system is also foreseen.

The thermal receiver of the SOMMER loop will be located in the focal point of a parabolic concentrator, the latter with a square aperture area of 16 m². The mirror has a focal length of 2.4 m and consists of nine glass facets with 3 mrad expected total slope error. This parabolic mirror is installed in a fixed position inside a building. Sunlight will be provided by a 32 m² heliostat mirror, equipped with a sun-tracking mechanism, located outside the building. Its total slope error is expected to be below 2 mrad. At a direct normal irradiance value of 800 W/m² this arrangement will nominally deliver 10 kW thermal power to a receiver with an area of 0.01 m². The expected average heat flux density is of 1 MW/m².

Behind the receiver, at a high point of the system, an oxygen control system (Lefhalm et al. [11], Konys and Schroer [12]) will potentially be installed in order to control oxygen partial pressure in such a way, that both, reduction of the oxide layer at the inside of the tubing, as well as oxidizing the LBE are being prevented. The corrosion mechanisms are fairly well understood and investigated up to temperatures around 600 °C (Zhang et al. [13], Weisenburger et al. [14]). Downstream of the oxygen control unit will be a conventional air cooled heat exchanger. Between pump and receiver, there is an auxiliary heater installed, which can be used to assist investigations of power-temperature transients or to decouple the temperature increase along the receiver from the flow rate, to expand the power and temperature transients. Such a heater would of course not be part of a liquid metal based CSP system. The system is currently under construction and is supposed to start operation in 2015.

3. Numerical investigations

The heat flux on the tubes of a solar receiver is typically varying along the tube axis and the tube circumference, causing high thermal stresses in the tube walls when, for example, only one half of the tube circumference is exposed to the solar irradiance. The magnitude of the resulting stresses depends on the cooling effect of the heat transfer fluid. For a proper thermo-hydraulic, as well as a mechanical design of the receiver, good knowledge of the local wall temperature and convective heat transfer coefficient is therefore required.

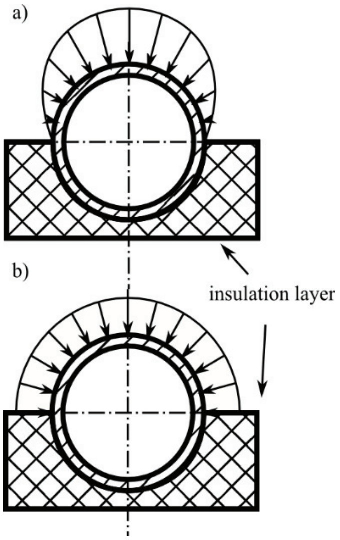

Fig. 2 Circumferential thermal boundary conditions for the CFD simulations – circumferentially varying heat flux distribution with half of the tube's surface adiabatic and on the other half an applied a) sinusoidal varying heat flux; b) constant heat

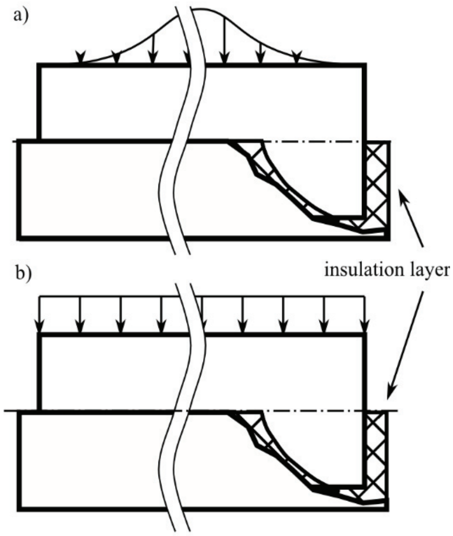

Fig. 3 Longitudinal boundary conditions – half of the tube's surface adiabatic and on the other half an applied a) sinusoidal varying heat flux and b) longitudinally uniform heat flux distribution (used for the CFD simulations)

The effect of a non-uniform heat flux on fluid heat transfer in circular tubes has been recently investigated for a high Prandtl number fluid, water, by Chang et al. and Okafor et al. [15],[16]. Indeed, a sinusoidal heat flux distribution along half of the circumference, as shown in Fig. 2a, was numerically investigated in [16] with two cases of longitudinal heat flux distributions as indicated in Fig. 3a and Fig. 3b, while a constant heat flux along half of the circumference (Fig. 2b) was experimentally investigated in [15] for water and Reynolds numbers ranging between 13×10^5 and 32×10^5 and with a longitudinal heat flux distribution as depicted in Fig. 3b. The results have shown that for the investigated Pr numbers the mean heat transfer coefficient can be evaluated with the Nusselt (Nu) number correlations valid for uniformly distributed heat flux on the wall.

3.1. Research goals

When considering liquid metals as heat transfer fluids in concentrating solar power plants the Nu number correlations for high-Prandtl number fluids cannot be used since they do not apply to such low Pr number fluids

(Pr~ O(10^{-3} – 10^{-2})). As previously mentioned, the heat transfer mechanism differs from that of fluids with medium-to-high Pr number. Indeed, the thickness of the thermal viscous sub layer is considerably greater than that of the hydrodynamic viscous sub layer. Therefore, specific Nu number correlations for liquid metals have to be used, while the well-established Gnielinski or Dittus-Boelter correlations, (Shah et al. [17]), are not suited to this kind of fluids. A recent review of the available Nusselt correlations appropriate for fully developed forced convection to liquid metal flows in tubes can be found in Pacio et al. [18].

Presently, according to the authors´ knowledge, there are no investigations for liquid metal flows subject the non-uniform heat flux as shown in Fig.3. In order to overcome this, own numerical simulations at different Péclet numbers ranging from 3×10^2 to 6×10^3 have been carried out. The results are compared with the correlation of Skupinski et al. as suggested in [18], valid for uniformly distributed wall heat flux.

3.2. Numerical model

All the simulations have been done with the CFD software FLUENT v.15, by numerically solving the steady-state Reynolds averaged form (RANS) of the conservation equations for momentum, energy and turbulence quantities.

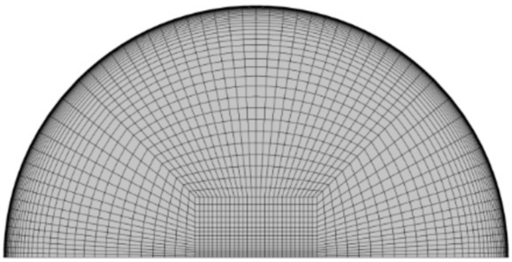

Fig. 4 Section of the medium mesh used.

For the pressure-velocity coupling the SIMPLE algorithm has been adopted, while a second-order upwind discretization scheme has been used for all variables [19]. No-slip boundary conditions have been enforced at the wall. The heat fluxes have been imposed according to Fig.3, neglecting possible variations of them in the axial direction (only boundary condition b in Fig. 3 was considered).

Because of symmetry reasons, only half of the domain has been simulated. The flow and temperature fields have been considered as fully developed. Therefore, cyclic boundary conditions have been applied to the inlet and outlet domain´s faces. The momentum diffusivity, ν_t, has been evaluated according to the model proposed by Abe et al. [20], by solving a transport equation for the turbulent kinetic energy, k, and one for its dissipation rate, ε. This model belongs to the category of *low-Re* turbulence models and therefore requires a y^+ value at the first near –wall cells less than 1.

As previously discussed, the Reynolds analogy, and thus a constant unitary turbulent Prandtl number, Pr_t, cannot be applied to liquid metal heat transfer problems. Recently Manservisi et al. [21] have proposed a new model to overcome this problem and to directly compute the turbulent thermal diffusivity of heat, α_t from the solution of two additional turbulence transport equations, namely one for the temperature variance, k_θ, and one for its dissipation, ε_θ. These are not already implemented in the standard version of FLUENT and have been therefore separately coded and coupled to the software through user-defined-functions (UDF).

The simulations have been performed for Reynolds numbers ranging from $10^4 \leq \mathrm{Re} \leq 2 \cdot 10^5$, neglecting buoyancy and viscous dissipation and assuming constant thermo-physical properties, resulting in a Prandtl number value of 0.028. Because of the latter assumption, the momentum and energy equations are decoupled, allowing thus to solve the flow and temperature fields, together with their respective turbulence quantities, separately. Both the values of the residuals of the different equations as well as physical computed parameters of relevant interest have been monitored in order to determine a convergence criterion for the simulations. Indeed, once the wall shear stress and the wall heat transfer coefficient remained constant for hundred iterations, the solution was considered to have reached convergence. A mesh sensitivity analysis has been also done for three different numbers of volume elements. The difference of the previous mentioned physical quantities computed with the medium and fine mesh was less than 2%. As shown in Fig. 4, the grid has been refined close the wall to obtain a dimensionless first cell wall distance of $y^+ \leq 1$ and sufficient cells inside the viscous and buffer layer.

3.2.1. Dimensionless numbers

The average Nusselt numbers are computed as follows:

$$\overline{\mathrm{Nu}} = \frac{\frac{D}{2\pi}\int_0^{2\pi} q''(\theta)d\theta}{\lambda\,(\bar{T}_w\ - T_b)} \tag{1}$$

$$\bar{T}_w = \frac{1}{2\pi}\int_0^{2\pi} T_w(\theta)d\theta \tag{2}$$

$$T_b = \frac{\int_0^{2\pi}\int_0^R \rho\cdot w\cdot T\cdot r\;dr\;d\theta}{\dot{m}} \tag{3}$$

In the above equations q'' is the heat flux density as a function of the radial angle θ, D is the tube diameter, λ the thermal conductivity, $\bar{T}_w$ is the circumferentially averaged wall temperature and T_b the bulk temperature for constant thermo-physical properties. Simulations have also been performed for air at $\mathrm{Pr} = 0.71$ and with a turbulent Prandtl number $\mathrm{Pr}_t = 0.85$ which is an adequate value for air, as shown by Kawamura et al. [22].

According to a dimensional analysis applied to the forced-convection problem, it can be deduced that the Nusselt number (Nu) has a functional dependence on Re and Pr. Within the LM-range (Pr<0.05), however, Nusselt numbers are presented in term of the Péclet number, as presented by Pacio et al. [18].

3.3. Results

Average Nusselt numbers computed for a pipe flow at $\mathrm{Pr} = 0.71$ (air) with two different boundary conditions are compared with those computed with Gnielinski´s correlation. In one case the whole tube circumference was heated with uniform and constant heat flux, while in the second case only one half of the tube was heated with a constant heat flux (Fig. 2b). The simulation results, shown in Fig. 5a, confirm that the calculated average Nusselt numbers for uniform heat flux over the whole surface and over only half of it (refer to Fig. 2b) agree well with those evaluated with the Gnielinski correlation. The latter can thus be used for both kinds of boundary conditions.

For liquid metals both boundary conditions of Fig. 2 together with longitudinal heat flux of Fig. 3b were considered in the simulations. As shown in Fig. 5b, also in this case the calculated average Nusselt numbers closely agree with those evaluated with the Skupinski correlation, valid for uniformly distributed heat flux.

This is a first indication, that Nu number correlations for fully developed flow in uniformly heated tubes can be used for that kind of flow in non-uniformly heated flow. However, some work will have to be done to investigate the full range of boundary conditions, e.g. the influence of developing flow in real receiver configurations like the relatively short tubes of the experimental receivers.

Parallel to these simulations, and in order to validate the numerical model, an experimental campaign will be conducted for the liquid metal flow in a pipe with constant heat flux applied on only half of the tube´s surface. This will be accomplished by building a dedicated test section to be added to KALLA's small thermal hydraulics test loop GALINKA. The latter is operated with an eutectic composition of Indium-Gallium-Tin, referred to as MCP11, which has a melting point of 11°C at ambient pressure. Therefore experiments at moderate temperatures can be carried out. Many of this fluid's thermo-hydraulic properties have recently been published in [23]. Experience gained over the course of this project will support the work at DLR for large scale system design concepts. On the other side, KIT will base the design of the components and the selection of the equipment for the SOMMER facility on the know-how of DLR.

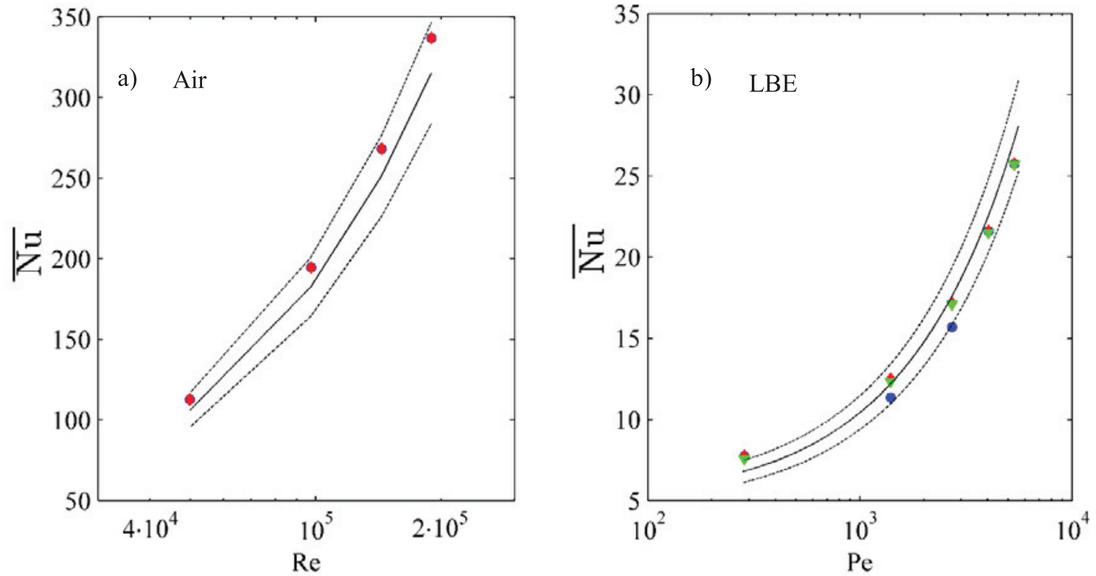

Fig. 5 Average Nusselt numbers a) $Pr = 0.71$ (line) Gnielinski correlation; (dotted line) $\pm10\%$ deviation from correlation - (circle) $q(\theta)$ of Fig. 3b; (diamond) $q = const$ over entire perimeter b) $Pr = 0.028$ (line) Skupinski correlation; (dotted line) $\pm10\%$ deviation from correlation - (circle) $q(\theta)$ of Fig. 3b; (diamond) $q(\theta)$ of Fig. 3a; (triangle) $q = const$ over entire perimeter.

4. System design

Parallel to the small demonstration system, preliminary designs for a commercial scale receiver (incl. solar field layout), the power cycle, piping and balance of plant for a large pilot plant are under development at DLR. These activities will address parameters important for commercial application as well as several options for thermal energy storage, both direct and indirect, technological approaches, interface connections, cost aspects, and safety issues. Also a thermal and economic optimization of the selected configurations, according to the specific characteristics of LBE and other metals, will be addressed. As a result, detailed annual performance characteristics will be obtained, like annual electrical energy yield, parasitic power consumption and capacity factor.

For the selected system components the cost will be estimated in order to obtain the total investment cost. With estimates for the O&M cost, the LCOE will be calculated from the annual net electrical energy output. The results of the analysis will be compared with reference systems, based on molten salt (state of the art and new developments) and/or particle receivers. For all these systems comparable assumptions will be made. The comparison shall consider LCOE, operational aspects and safety issues. The current state of these activities is being presented in [24] (to be published in this edition of the Energy Procedia).

5. Conclusions

As a reaction on the demand for technologies capable to reduce the LCOE and increase the efficiencies of CSP plants, activities have been started at KIT and DLR to investigate in liquid metal heat transfer fluids. At KIT an experimental test loop and solar furnace are under construction. The operation conditions in that system will be subject to high natural fluctuations in energy supply from the sun which are untypical for state-of-the-art liquid metal applications. The layout of the complete facility and particularly the liquid metal loop have been described in the paper. For the thermal design of components such as the receiver, good knowledge of the heat transfer is required. An idealized boundary condition for the receiver has been studied numerically: fully developed turbulent flow in a circular tube with heat flux along half of the tube circumference, while the other half is considered adiabatic. The results of this study indicate that Nusselt number correlations developed for a uniformly distributed heat flux on the wall can be applied to all Prandtl number fluids also in the case of circumferentially varying and non-uniform heat flux.

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