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Numerical optimization of cold trap designs for the Karlsruhe Sodium Laboratory

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ABSTRACT

The present study is focused on the numerical analysis of three designs (basic, intermediate and optimized) for the cold trap considered for sodium purification in the KASOLA (KArlsruhe SOdium LAboratory) sodium loop. Given the complexity of the construction the present approach was based on CFD (Computational Fluid Dynamics). The comparison of the designs considered reveals that significant improvements have been obtained regarding the cooling and heat recovery systems. The CFD (Computational Fluid Dynamics) models considered a conjugate heat transfer approach in order to simulate both fluids (air and sodium) and the solid domains (stainless steel walls). The stainless steel wool packages were numerically modelled using a porous domain. For most of the cases the air flow is turbulent and was modelled using the Shear Stress Transport (SST) turbulence model, while the sodium flow was treated as laminar or turbulent, depending on the sodium flow rate. The effect of the turbulent Prandtl number and of the turbulence models (SST and Reynolds-stress models) on the heat transfer has been also investigated. The influence of the buoyancy forces has been also studied. The numerical results are found in very good agreement with the thermal balance analysis of the cold traps. The pressure loss for all designs is similar, nevertheless with a minor improvement for the optimized design. The study compares the advantages of each design and based on this analysis a design was identified and used for the cold trap that was manufactured and installed in the KASOLA facility.

1. Introduction

Liquid metals (LM) have recently received increased interest in the energy field since they are considered as a promising alternative to conventional heat transfer fluids (HTF) such as solar salts and oils [1–4]. Liquid metals have good thermodynamic properties (large thermal conductivity and large temperature range as liquids) making them efficient HTF in a wide range of applications [5]. Considering these advantages LM were proposed as HTF for next-generation CSP (Concentrating Solar Power) systems, particularly for power tower plants [1,2,5–8]. Furthermore, based on a successful test of a sodium receiver, the pilot CSP Jemalong Thermal Station using sodium as HTF is planned to be commissioned 2016 in Australia [8].

In this context the mid-size KASOLA facility having a sodium inventory of 7 m^3 has been erected at the Karlsruhe Institute of Technology in Germany [2,4,9,10]. It aims the experimental investigations of fundamental thermal-hydraulics LM flows, component development and testing for LM applications, code validation and safety assessment of LM operated systems, qualification of instrumentation and test of innovative LM-based thermoelectrical direct heat converters [11].

In sodium operated facilities, depending on the facility assignment, several impurities can arise during operation. The impurities can decrease the thermal transfer to the wall, alter the quality of the working fluid and of the structural materials and have the potential to block narrow flow passages. Among the most encountered impurities are oxygen, hydrogen, carbon, iron, chrome and tin. Typically, purifications systems are based on cold traps, where the LM is cooled below the saturation temperature of the impurities, so that they precipitate on metallic packing. For the KASOLA facility in particular, oxygen is the impurity monitored and controlled, since it leads to corrosion of the steel surfaces. Therefore, its concentration should be kept below 2–3 ppm [12], which is achieved by cooling the sodium close to its freezing point. In order to achieve this task as well as a performant design of the cold trap the heat transfer processes in the liquid sodium should be properly determined and are mandatory. This aspect motivated the present numerical investigation by CFD approach.

Liquid metals are characterized by Prandtl numbers $\ll 1$, i.e. the thermal boundary layer is much thicker than the viscous boundary

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Nomenclature

a	radius of the pipe of the helical coil [m]
A	area [m^2]
c_p	specific heat [J/kg K]
d	diameter [m]
f	friction factor
Gr	Grashof number
h	heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/m K]
l	length [m]
$\dot{m}$	mass flow rate [kg/s]
Nu	Nusselt number (h Dh/k)
P	pressure [Pa]
Pe	Peclet number
Pr	Prandtl number
$\dot{Q}$	heat transfer rate [W]
R	curvature of the helical coil [m]
Re	Reynolds number ((ρ Um Dh)/μ)
s	pitch of the helical coil [m]
t	time [s]
T	temperature [K]
U_{ov}	overall heat transfer coefficient [W/m^2 K]
v	velocity [m/s]
$\dot{V}$	volumetric flow rate [m^3/h]
w	wall thickness [m]
$y+$	non-dimensional distance to the wall [-]

Greek letters

λ	thermal conductivity of the fluid [W/m K]
μ	dynamic viscosity [kg/ms]
ρ	density [kg/m^3]

Subscript

ave	averaged
crit	critical
h	hydraulic
LM	logarithmic temperature gradient
ref	reference
w	wall
t	turbulent

Abbreviations

CFD	Computational fluid dynamics
KASOLA	Karlsruhe Sodium Laboratory
LRR-QI RS	Launder Reece Rodi Quasi-Isotropic Reynolds-stress turbulence model
HEMCP	Helmholtz Material Characterization Platform
HR	Heat recuperator
HX	Heat exchanger
LIMTECH	Helmholtz Alliance on Liquid Metal Technology
SSG RS	Speziale Sarkar Gatski Reynolds-stress turbulence model

layer. This implies that the classical Reynolds analogy approach is not valid for turbulent flows of liquid metals [13] and special care should be taken for the numerical modelling of LM flows.

Numerical modelling of certain cold trap configurations has been developed by McPheeters and Raue [14], which report good comparison against experimental data. It is argued that a desirable design would have a large, packed annulus region and a relatively small, unpacked central region. In agreement with this finding, Zhao and Ren [15] used their mathematical model to investigate the optimal wire mesh layout, suggesting that a low surface at the upper part and a large surface at the bottom part should enhance the trapping efficiency. They determined the optimal air cooling passage form to have a divergent shape with the base at the bottom.

Besides the geometrical configuration, the operating thermodynamic conditions have a strong influence on the purification process. As discussed by several authors [16–18], the purification efficiency is improved with decreased flow Reynolds number, since the residence time of the dissolved impurities in the packing is increased. Khatcheressian et al. [19] report the mathematical modelling of crystallization process of sodium hydride and sodium oxide in a cold trap coupled to transfer phenomena. The simulations reported revealed a strong interaction between these physical phenomena. The thermo-hydraulic conditions influence the crystallization of the impurities, while the crystal deposits influence the flow streamlines and heat flux distribution.

Several cold trap designs reported in literature [20–23] gather the packing and the cooling system in a one-body configuration. However, several authors [12,15,16] argue the fact that dividing the cold trap in two regions leads to efficiency improvement. The cooling circuit and possible heat recuperation systems are placed at the upper region, while the packing for sodium purification are placed at the bottom and held at isothermal conditions. Therefore, such configurations have been considered also in the present study, which is focused on the numerical analysis of the thermo-dynamical flow field of three designs considered for the cold trap of the KASOLA facility.

The study is structured as follows: in the second section the KASOLA sodium loop and the cold trap are described, in the third section the numerical setup is discussed, in the fourth section the numerical results are presented, in the fifth section the installation of the cold trap is presented and the main conclusions of the study are summarized in the last section.

2. KASOLA experimental loop and layout of the cold trap

The Karlsruhe Sodium Laboratory contains three subsections: (a) base loop with purification section, (b) two test ports with experiments and (c) the storage tank in a separated building, as presented in Fig. 1. In the base loop is incorporated the versatile test section, which has a height of nearly 6 m above the MHD pump and can be used for a large range of experimental tests at high mass flow rates. The facility is located in a three floor, 12 m high steel containment. The base loop contains a magneto hydrodynamic pump that can provide a maximum liquid sodium mass-flow rate of 150 m^3/h. The maximum operating temperature allowed in the base loop is 550 °C. Additional information related to the loop can be found in [4,9,10].

Before entering the purification system, where the cold trap is located, the sodium is cooled in the Na-air heat exchanger from the base loop so that it can enter the cold trap at a temperature of about 200 °C.

The main design requirements for the cold trap are efficient purification (which can be achieved by cooling down sodium below the saturation temperature of the impurities and by allowing a large residence time in the packing), a quasi maintenance-free operation for the entire lifetime of the KASOLA facility, an efficient sodium waste heat recovery, a safe and robust design as well as low operating costs.