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Design, optimization and layout of a compact cold trap with high efficient heat recovery by a helical coil for the Karlsruhe Sodium Laboratory

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ABSTRACT

Three conceptual designs of a cold trap with integrated sodium-air HX (heat exchanger) and sodium-sodium HR (heat recuperator) were considered for the KASOLA (KArlsruhe SOdium LAboratory) sodium loop in Karlsruhe, Germany. All designs consist in the bottom part of vertically placed stainless steel wool packages used to retain the impurities from sodium. The upper part contains the sodium-air HX and the sodium-sodium HR. The purification function of the cold traps was laid out so that it can serve for the complete service life time of the experimental facility quasi maintenance-free. Regarding the sodium cooling and the heat recuperation three designs have been proposed and analyzed, and the best solution has been chosen. The study is focused on the layout and the optimization of the cold trap with respect to the optimal wire mesh dimensioning (e.g. wire mesh radial size, sodium residence time, pressure loss, etc.), optimal solution for the sodium heat recovery and for the air cooling system. The final design chosen has efficient sodium purification, larger purification rate, heat recovery of up to ~90% and low operating costs. This optimized design was further fine tuned and the cold trap was manufactured and installed in the KASOLA facility.

1. Introduction

Due to their favourable properties (large thermal conductivity, high temperature storage capability, low freezing temperature, etc.) liquid metals, such as sodium, have been employed for electricity generation mainly in the nuclear and solar fields. Recently, an innovative concept of a hybrid thermal solar power plant has been proposed by Hering et al. [1]. Some of the preliminary studies for this new concept are planned to be performed in the KASOLA loop [2].

The KASOLA loop is an experimental facility under construction at Karlsruhe Institute of Technology, with commissioning tests scheduled for 2016. The facility will serve for research activities on thermal-hydraulics for sodium (and sodium derivates) operated systems for transmutation (fast systems, normal operation, transient behaviour, testing of emergency cooling systems), development of accelerator targets, supporting heat transfer studies regarding the development of turbulent liquid metal heat transfer models for system and CFD codes. An innovative employment of the facility is a feasibility study for the usage of sodium in solar applications [1,3].

Depending on the type of the operated sodium facility several impurities can be released during operation, e.g. oxygen, hydrogen, carbon, iron, chrome, tin, bismuth, etc. In KASOLA facility, the major impurity monitored is oxygen, which can lead to the formation of sodium oxide (Na_2O). Oxygen can be introduced in the loop during the original loop filling or during maintenance procedures. The oxygen as an impurity leads to the corrosion of the steel surfaces. Other relevant impurities can originate from steel compounds (carbon, iron, chrome, tin). Hydrogen originates from the moisture in air and water vapour occurring in the cooling circuit and can diffuse through the steel pipes of the sodium-air heat exchanger, leading to the formation of sodium hydride (NaH). For water cooled reactor systems, the presence of NaH is particularly monitored since significant quantities suggest the presence of leaks in the pipes of the water-sodium steam generators. These impurities can lead to the plugging of the narrow passages in a facility and decrease the thermal performances of the device. Therefore certain concentration values have to be ensured, e.g. for oxygen the concentration should be lower than 2 ppm [4], while in France, Japan and India this limit is set to 3 ppm. The

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Nomenclature

a	radius of the pipe of the helical coil (m)
A	area (m^2)
c	concentration (mol/m^3)
c_p	specific heat (J/kg K)
C	cold trap capacity (m^3)
d	diameter (m)
De	Dean number ($Re\sqrt{a/R}$)
f	friction factor
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/mK)
l	length (m)
$\dot{m}$	mass flow rate (kg/s)
N	number of turns of the helical coil
Nu	Nusselt number ($h\, d_h/k$)
P	pressure (Pa)
Pe	Peclet number
Pr	Prandtl number
$\dot{Q}$	heat transfer rate (W)
r	purification rate (kg/s)
R	curvature of the helical coil (m)
Re	Reynolds number ($(\rho\ v\, d_h)/\mu$)
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)
V	volume
$\dot{V}$	volumetric flow rate (m^3/s)
w	wall thickness (m)

Greek letters

δ	height of corrosion layer (m)
η	efficiency (–)
λ	thermal conductivity of the fluid (W/mK)
μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)

Subscript

CP	cold point
$crit$	critical
h	hydraulic
LM	logarithmic temperature gradient
imp	impurity
in	inlet
out	outlet
ov	overall
r	residence
sp	straight pipe
tot	total
w	wall

Abbreviations

AMTEC	Alkali-Metal Thermal-to-Electric Converter
CFD	Computational fluid dynamics
CT	Cold trap
KASOLA	Karlsruhe Sodium Laboratory
HEMCP	Helmholtz Material Characterization Platform
HR	Heat recuperator
HX	Heat exchanger
LIMTECH	Helmholtz Alliance on Liquid Metal Technology
MHD	Magnetohydrodynamic pump

accepted amount for hydrogen ranges between 50 ppb [4] in India and 100 ppb in France.

An overview of the purification techniques is given by Hinze [5]. The most widely used procedure is the precipitation method, which relies on the fact that the solubility of the impurities (Na_2O, NaH) decreases with temperature. By lowering the sodium temperature below the saturation temperature, the impurities precipitate on the metallic surfaces of a packing, which consists of wire meshes.

Some of the most important design parameters for cold traps (CT) are the capacity and the profile shape of the trapping temperature, the residence time of the sodium in the wire mesh (i.e. the flow Reynolds number), and the geometrical layout of the wire mesh (i.e. wire diameter, radial size, granularity, etc.). As discussed by several authors (Latgé et al., [6,7]; Zhao and Ren, [8]; Hemanath et al., [4]), dividing the cold trap in two parts allows an improvement in the purification efficiency. The upper part contains the cooling circuit (with possible heat recuperation) and NaH trapping can occur on cold walls as discussed in [7], while the bottom part is held at isothermal conditions and most of the Na_2O purification occurs in the wire mesh packing. However, it is to notice that both upper and bottom parts contribute to sodium purification.

One of the most important design parameter is the residence time of the dissolved impurities, i.e. oxygen and hydrogen in the wire mesh. The trapping efficiency is improved with decreased flow Reynolds number [6,9,10]. According to Grundy [11], the trapping efficiency is direct proportional to the residence time and reaches almost unity at a value of 10 min, estimated for a cold trap using knitted stainless steel wire mesh, having a vertical flow from bottom to top, where the heat exchanger is placed.

Especially for sodium oxide the trapping efficiency, defined in Eq. (1) depends on the sodium flow, while for sodium hydride the efficiency is flow independent, since NaH trapping occurs on the cold walls, where the growth rate is not limited by diffusion through a boundary layer, but by the integration in the crystal lattice [6,12]. This difference is consistent with the fact that the diffusion coefficient of oxygen in sodium is much smaller than for hydrogen. This distinction in the crystallization mechanisms motivates the concept of a two-zones cold trap, the upper part optimized for sodium hydride and the bottom part for sodium oxide.

Up to about 10% improved efficiency is reported by Murase et al. [10] if the packing is held at isothermal conditions, i.e. the wire mesh exhibits a flat temperature profile. Furthermore, for wire mesh packing with thinner wires a higher trapping efficiency is reported.

Porous metal packing was also tested as trapping device, but did not perform satisfactory [9]. Due to their fine granularity metallic packing tend to plug quickly and do not offer a large crystallization surface. Therefore, the interest shifted to metallic wool packing that offer larger flow passages, which decreases the risk of plugging, and larger surface.

Several authors [13,14] report that depending on the local conditions, the deposition of the sodium oxide can occur on all metal surfaces of the cold trap (e.g. pipes, walls) and not just in the wire meshes from the packing. This can lead to possible flow blockages in narrow passages. Small deposits are reported on the walls located prior to the wire mesh, while large deposits are reported at the bottom of the trap, where generally the temperature is at its lowest point and the sodium flow is almost stagnant. Plugging of the outlet pipe has been reported for several cold traps to occur