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Flow and heat transfer behaviors for double-walled-straight-tube heat exchanger of HLM loop

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ABSTRACT

Non-contacted double-walled-straight-tube heat exchanger has been designed for the Lead-Bismuth Eutectic (LBE) loop KYLIN-II, the flow rate and temperature distribution dramatically influence the performance of heat exchanger. The Computational Fluid Dynamics (CFD) and numerical heat transfer method has been used to build the three-dimensional model of the heat exchanger. Adopting the SST (Shear Stress Transport) k-omega model the flow rate and temperature distribution of the heat exchanger model has been calculated. The numerical simulation result shows that the non-uniform LBE flows don't affect TH performance of HX filled with powder in the gap between two tubes.

1. Introduction

Lead Bismuth Eutectic (LBE) is one of the most promising materials for coolant and spallation target for Accelerator Driven Systems (ADS). Since 2011 Institute of Nuclear Energy Safety Technology, Chinese Academy of Science·FDS Team has undertaken the R&D work of lead–bismuth cooled reactor in a "Strategic Priority Research Program" of Chinese Academy of Science named "the future of advanced nuclear fission energy system – ADS transmutation system", designing the dual-mode integrated pool-type reactor named China LEAd-based research Reactor (CLEAR-I) (Wu et al., 2016; Wu, 2016a). The ADS research includes low activation materials (Huang et al., 2013), liquid metal technologies (Wu, 2007), sub-critical system (Wu et al., 2011), advanced nuclear software (Wu et al., 2008; Wu, 2009; Wu et al., 2015). To support the design and construction of CLEAR-I, a large scale integrated non-nuclear pool type facility named CLEAR-S has been constructed (Wu, 2016b). For the non-nuclear technology experiment facility, KYLIN series lead–bismuth experiment loops have been built. Basing on the parameters of CLEAR-I, the Lead-Bismuth Eutectic (LBE) loop named KYLIN-II was designed for testing the material, thermal hydraulic and safety characteristics under LBE conditions (Wu, 2016c).

The heat exchangers with double wall tube were designed in CLEAR-I. The heavy liquid metal (HLM) loop KYLIN-II HX can be a candidate for primary heat exchanger of liquid metal reactor, so the HX study can provide technical rehearsal for this candidate. This type of heat exchanger is usually constituted by two (in this case it is generally straight tube type) or three (called double wall bayonet) concentric tubes. It is based on the concept to provide a double physical separation between two fluids: the coolant (i.e. water) and the hot fluid (i.e. LBE). There are three primary reasons for the separation of the fluids. The first is to maintain a given temperature drop between the hot fluid and the coolant. The second is to increase the safety margin of the unit by reducing the probability of interaction between the coolant and the hot fluid. Furthermore, this configuration allows the possibility to monitor eventual leakages from the coolant or from the hot fluid by pressurizing the annular region between the double walls.

However, few studies were conducted in the thermal-hydraulics (T-H) performances of double-wall bundle heat exchanger, especially for heavy liquid metal conditions. Based on the limited research of bayonet heat exchanger by ENEA, the conductivity of powders and annulus gap transfer effects on T-H performances had been simulated or experimented.

The double wall once-through bayonet tube bundle type was designed for the SG of ALFRED. The thermal–hydraulic assessment of the single bayonet tube was simulated to achieve the high temperature superheated steam by means of RELAP-5. If sintetic diamond or silicon carbide powders are used as high conductivity

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gap filler coupled with helium, the simulation agrees with the ANSALDO calculations and seems to match the design requirements. The conductivity of the powders is an important parameter that deserves experimental characterization (Rozzia, 2012). The experimental campaigns were developed in Tubes for Powders facility to characterize AISI-316 powder in support to the qualification of the NACIE-UP heat exchanger. The effect of loading procedure and thermal cycling on the conductivity of AISI-316 powder were investigated by series of experiment tests (Rozzia, 2015). More simulations were concentrated on the fuel pin bundle or the integrated experimental facility. RANS simulations of the 'Blocked' Fuel Pin bundle Simulator (FPS) that will be installed into the NACIE-UP facility are carried out by ANSYS CFX code. The effects of different flow blockage regimes (central, sector, side, corner) in a 19 fuel pin bundle were simulated. The elongated vortex phenomenon is evident behind the blockage area with a temperature rise both for coolant and the cladding (Marinari et al., 2017). A 2D axisymmetric FLUENT domain of the FPS was generated to be interfaced with its complementary region of NACIE facility modelled with RELAP5. Natural circulation condition, isothermal gas enhanced circulation and Unprotected Loss of Flow (FLOW) scenario of NACIE facility were simulated. Pressure, temperature and mass flow rate properly followed the RELAP5 stand-alone trends (Martelli et al., 2017a). CFD post-test analysis of the experimental campaign performed in the Integral Circulation Experiment configuration of the CIRCE facility were carried out. In order to reduce the computational time, the Shear Stress Transport (SST) k-omega model is selected to investigate the temperature field of the secondary flows in the FPS. RANS equation solved in the CFX Ansys commercial code with proper turbulent Prandtl number has proved to adequately simulate heat transfer phenomenon in fuel bundle cooled by LBE for engineering purpose (Martelli et al., 2017b). Remarkable effects on heat transfer performance of double wall tube occurred due to the powder material, fluid properties of both sides, structural features and operation condition of heat exchanger.

The flow rate and temperature distribution of the heat exchanger are main factors affecting the performance of heat exchanger. In this paper adopting computational fluid dynamics (CFD) and numerical heat transfer method, three-dimensional flow and heat transfer mathematical and physical model are built for the heat exchanger.

2. Main features of KYLIN-II

The goal of KYLIN-II experiments consist of the evaluation of the Heat Transfer Coefficient (HTC), the check of the presence of hot spots and peak temperature points, the evaluation of the axial thermal stratification of the coolant fluid and its entrance length along the bundle sub channels, overall mixed circulation experiment.

The KYLIN-II forced circulation loop is a LBE rectangular loop as depicted in Fig. 1. The KYLIN-II loop basically consists of two vertical pipes connected by two horizontal pipes. The vertical pipes are working as riser and down comer. In the bottom part of the riser a Heat Source (HS) of about 250.0 kW is installed, while the upper part of the downcomer is connected to a Heat eXchanger (HX). An expansion vessel is installed on the top part of the loop, coaxially to the riser. The circulation height is 2 m between the centerline of HS and HX. Gas-lift and mechanical pump are both installed to research the driving force on LBE. The loop is made of stainless steel (AISI 316) and can use both lead and the eutectic alloy LBE as working fluid. It has been designed to work up to 550 °C and 1 MPa (Tarantino et al., 2008).

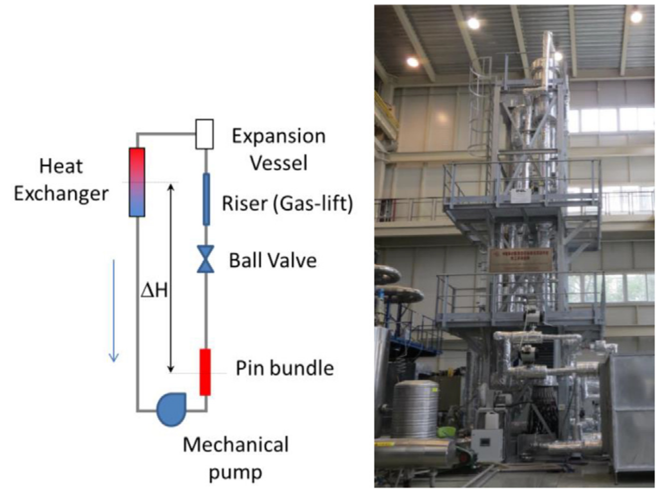

Fig. 1. Scheme and view of the KYLIN-II loop.

3. Structural model of KYLIN-II HX

The whole 7 tubes are placed within the shell in a regular hexagonal configuration also with a central tube. The symmetry model was used due to the geometry properties of the heat exchanger (Fig. 2).

Each tube bundle is constituted of two tubes, and the gap between two tubes is filled with stainless steel AISI 316L industrial powder. Thermal conductivity of the powder is about 1.5 W/mK from experience on NACIE loop (Rozzia, 2015).

Reactivity feedback of physical properties due to the temperature variation both for LBE and water is neglected. Physical properties at 400 °C and 125 °C were chosen for LBE and water, respectively. The properties of LBE at 400 °C are shown in Table 1 (Kumari and Khanna, 2017; OECD/NEA, 2007; Dwyer, 1970; Todreas and Kazimi, 2001).

3.1. Numerical models and methods

AYSYS CFX 13 is a practical fluid engineering analysis tool for simulating fluid flow and heat transfer problems, which was used to carry out the HX simulation.

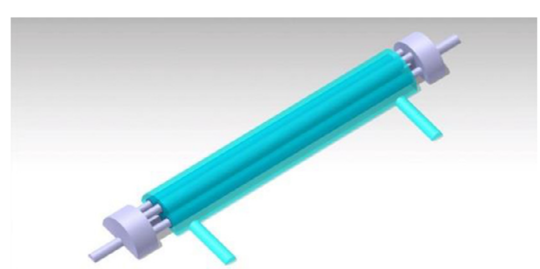

Fig. 2. Symmetry model of the heat exchanger.

Table 1
Properties of LBE at 400 °C.

Parameters of LBE at 400 °C	Value
Density (kg/m^3)	10194.8
Kinematic viscosity (m^2/s)	1.486×10^{-7}
Thermal Conductivity (W/mK)	13.121
Specific heat (J/kgK)	142.94
Prandtl number	0.0221
Thermal expansion coefficient (1/K)	1.27×10^{-4}