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Research Paper

Convective heat transfer characteristics in the turbulent region of molten salt in concentric tube

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ABSTRACT

In order to better understand the heat transfer behavior and characteristics of molten salt in heat exchanger, the convective heat transfer characteristics of molten salt in salt-to-oil concentric tube are studied. Overall heat transfer coefficients of the heat exchanger are calculated using Wilson plots. Heat transfer coefficients of tube side molten salt with the range of Reynolds number from 10,000 to 50,000 and the Prandtl number from 11 to 27 are evaluated invoking the calculated overall heat transfer coefficients. The effects of velocity and temperature on the convective heat transfer in the turbulent region of molten salt are studied by comparing with the traditional correlations. The results show that the heat transfer characteristics of molten salt are in line with the empirical heat transfer correlation; however, Dittus–Boelter, Gnielinski, Sieder–Tate and Hausen correlations all give a larger deviation for the experimental data. Finally, based on the experimental data and Sieder–Tate correlation, a modified heat transfer correlation is proposed and good agreement is observed between the experimental data and the modified correlation. The results will also provide an important reference for the design of the heat exchangers in the Thorium-based Molten Salt Reactor.

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1. Introduction

With advantages of large thermal capacity, good chemical stability, low corrosion, as a heat transfer media or secondary coolants, molten salt have recently been widely applied in kinds of high temperature industrial engineering as concentrating solar power [1–3], nuclear power engineering, high temperature hydrogen production [4–7], and so on. The heat transfer characteristics of molten salt in heat exchanger play important roles to design heat exchange system and improving its performance. However, the heat transfer behavior in heat exchangers is different from that in circular tubes, because the boundary condition of heat transfer in heat exchanger is neither constant heat flux nor constant wall temperature. Therefore, it is necessary to investigate heat transfer process and characteristics of molten salt in heat exchangers comprehensively.

The convective heat transfer characteristics of molten salt have been experimentally investigated in some available literatures. Grele and Gedeon [8] made an experimental investigation of forced convective heat transfer characteristics of NaF–KF–LiF (11.5–42.0–46.5 mol %, FLiNaK) flowing through an electrically heated Inconel X test section with the Reynolds number from 2000 to 20,000 and assessed the average heat transfer coefficients; the results show that the average heat transfer coefficients for FLiNaK were about 40 percent of the values calculated from the McAdams correlation. Hoffman and Jones [9] and Cooke and Cox [10] experimentally studied convective heat transfer of mixed molten salts FLiNaK with the Reynolds number from 2300 to 9500 through a smooth tube with a uniform heat flux and corrected convective heat transfer coefficients. It was found that forced convective heat transfer with FLiNaK can be represented by the general correlation for heat transfer with ordinary fluids. Silverman et al. [11] obtained forced convective heat transfer performances of molten salts $LiF–BeF_2–ThF_2–UF_4$ and $NaBF_4$–NaF and found that the experimental data have satisfactory agreement with the empirical Sieder–Tate correlation in the fully developed turbulent region at Reynolds above 15,000. Ignat'ev et al. [12] have published very limited experimental data about heat transfer of fluoride salts in tubes and these data are not sufficient to give an idea of the general laws governing the heat transfer. Toda et al. [13] and Chiba et al. [14] investigated heat transfer performance of molten salt $KNO_3–NaNO_2–NaNO_3$ flowing in a sphere-packed pipe and circular pipe through a direct electrical heating method and found that heat transfer characteristics of molten salt in a circular pipe were in good accordance with some empirical correlations. Lu et al. [15] experimentally investigated

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the convective heat transfer of molten salt in annular passage within the range of Reynolds number 4000–10,000 and proposed the modified Gnielinski correlation with annular configuration effect. Vriesema [16], Liu et al. [17] and Wu et al. [18] experimentally studied a salt-to-air heat exchanger and salt-to-oil concentric tube heat exchanger respectively and established empirical correlations for heat transfer of molten salt.

It can be seen from the above literature reviews that most studies mainly focus on the heat transfer of molten salts flowing in a circular tube with the conventional boundary conditions of constant wall temperature or constant heat flux and very limited description of the convective heat transfer used in molten salt heat exchangers are reported. Some aspects of heat transfer behaviors and characteristics of molten salt with high Prandtl number, such as the effects of velocity and temperature on the convective heat transfer characteristics in the turbulent region of molten salt and heat transfer law in molten salt heat exchanger, remain poorly understood.

The Thorium-based Molten Salt Reactor (TMSR) nuclear system project launched by the Chinese Academy of Sciences (CAS) [19,20] used molten salt $LiF–BeF_2$ (66–34 mol %, FLiBe) as the primary coolant [21]. However, due to the high melting point and toxic beryllium of FLiBe, Heat Transfer Salt (HTS) $KNO_3–NaNO_2–NaNO_3$ (53–40–7 mol %) with similar Prandtl number was employed as the substitute to evaluate the heat transfer characteristics of FLiBe. In this paper, a more practical salt-to-oil concentric tube heat exchanger was designed and a series of heat exchanger experiments were conducted to study heat transfer characteristics of HTS in heat exchanger. The effects of different flow rates and temperatures on the convective heat transfer characteristics in the turbulent region of HTS were deeply studied. In particular, based on the experimental data and classical correlations, a developed heat transfer correlation within the range of Reynolds number 10,000–50,000 and Prandtl number 11–27 derived from molten salt heat exchanger special boundary conditions was established. These results will also provide the reliable evidence and favorable guidance for the design of the molten salt heat exchanger in TMSR.

2. Experiments

2.1. Experimental system and method

The HTS loop used to investigate the heat transfer characteristics of molten salt was built at Shanghai Institute of Applied Physics, Chinese Academy of Sciences (SINAP, CAS). The schematic diagram of HTS loop is shown in Fig. 1. The experimental system contains molten salt circulation loop and oil circulation loop and mainly includes molten salt tank, pump, heater, test section, oil tank, oil pump, air cooler, pipelines and gas system. The gas system is mainly used to keep the experiment under safe and stable conditions. All components of the HTS loop and all pipes are wrapped with insulation to minimize heat loss to the surroundings and heated up above HTS melting temperature before circulating HTS. The photos of experimental setup and test section are shown in Fig. 2.

The test section mainly consists of entrance region and heat transfer region. The heat transfer region is a concentric tube heat exchanger and the high temperature molten salt will flow through the inner tube while the low temperature oil will flow through the outer tube as flow directions are shown in the Fig. 1 with arrows. The tubes are 1200 mm long and 2.5 mm thick, and the diameter of the outer tube is 39 mm while the inner tube is 20 mm. The length of the entrance region is about 700 mm, which is almost 35 times the diameter of the inner tube, which made the velocity distribution of HTS be fully developed before entering the heat transfer region. In order to measure the bulk temperature accurately, four mixing chambers are designed and installed at the inlet and outlet of the test section.

In the experiment, the temperature of HTS from 473 K to 573 K is obtained by controlling the electric heater, and the velocity of HTS from 0.89 m s^{-1} to 5.08 m s^{-1} are obtained by controlling the pump

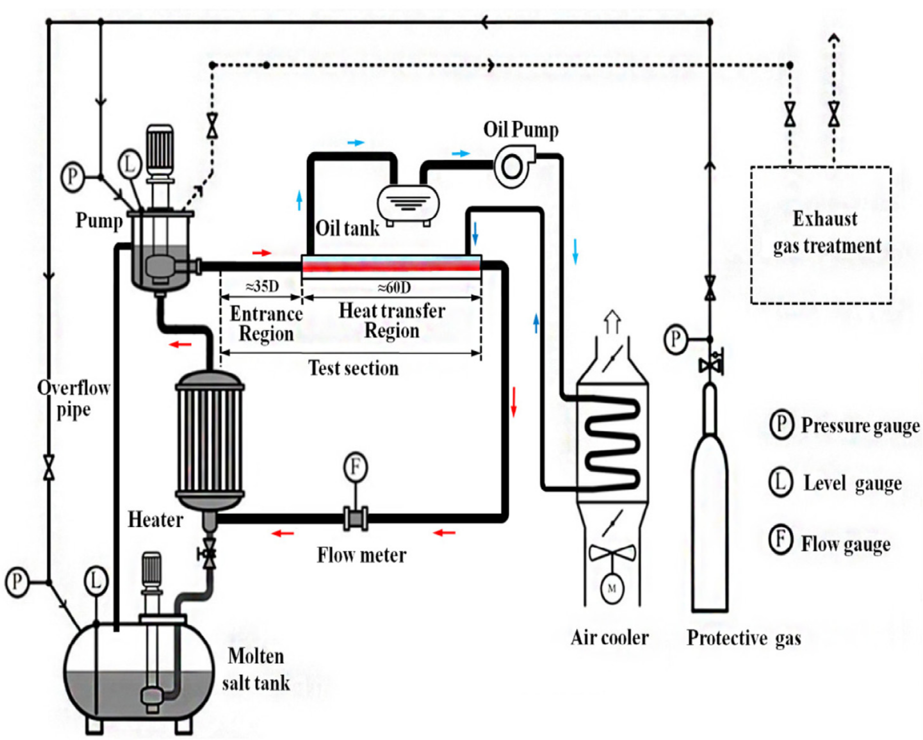

Fig. 1. Schematic diagram of HTS loop at SINAP, CAS.

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