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Investigations on heat transfer characteristic of molten salt flow in helical annular duct

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HIGHLIGHTS

- A molten salt double tube helical heat exchanger was built.
- Nusselt number of molten salt flow in helical annular duct was experimental obtained.
- The molten salt flow regimes could be distinguished by Darcy friction factor.
- Higher heat transfer enhancement ratio was found with decreasing molten salt temperature.
- Smaller inner–outer-pipe diameter ratio leads to higher heat transfer enhancement ratio.

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ABSTRACT

Molten salt is a preferable heat storage and heat transfer media, which can be employed in the high temperature industrial applications. A novel double tube helical heat exchanger (DTHHE) was developed in State Key Laboratory of Multiphase Flow in Power Engineering (SKLMF) using molten salt as the hot fluid flowing through the outer annular duct, to supply the heat for subcritical and supercritical water. In this work, the heat transfer characteristics of molten salt flow from laminar flow regime to turbulent flow regime were experimentally investigated. Heat transfer enhancement was detected in helical annular duct, and the enhancement ratio was found different from that in helical circular pipe. The heat transfer results were correlated separately in various flow regime, and the divergences between correlated equation and the classical heat transfer correlations of helical circular tube were analysed. The effects of inner tube surface were found pronounced on the flow and heat transfer characteristics. The experimental effort and results will benefit the design and operation of heat exchanger process between molten salt flow and water.

1. Introduction

A variety of fluids was employed in high temperature heat storage and transfer, including water, vapour, air, and mineral oil, before molten salt was considered as more preferable, within the temperature range from 300 °C to 600 °C. Profit from their favourable thermal physical and chemical properties at high temperature, such as large specific heat, low vapour pressure, low corrosive and toxic, chemical stability etc, molten salt was widely used in chemical, metallurgy and nuclear industries as an ideal heat transfer medium. In this work, the molten salt (KNO_3: 53%, $NaNO_2$: 40%, $NaNO_3$: 7%) was used to store solar thermal energy and transfer the absorbed heat to supercritical water for power generation or thermochemical utilization.

Because of many advantages of a helical coiled tube, such as high efficiency in heat transfer, compactness in structure, easy to manufacture, etc., a novel double tube helical heat exchanger using molten salt as a hot heat transfer medium was proposed, which was successfully constructed at the State Key Laboratory of Multiphase Flow in Power Engineering.

The issue of fluid flow and heat transfer in curved pipe was widely concerned. Dean [1] (1928) proposed a dimensionless flow parameter, called Dean number, for assessing the effect of centrifugal force in a curved tube. It was reported that the presence of centrifugal force due to the curvature will lead to a significant radial pressure gradient in the flow core region, and then two symmetrical vortexes (secondary flow) are generated when the Dean number exceeds a critical number.

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$$De = Re(d/D_H)^{1/2} \quad (1)$$

In this work, the thermal equivalent diameter d in annular duct was obtained according to Kays's theory [2]. The calculation equations of d were listed in the Nomenclature. After the pioneer work of Dean [1], many investigations have been conducted regarding flow in curved and helical tubes. The heat transfer and frictional pressure drop characteristics of steady flow in curved tube have been studied by numerous work, both theoretically and experimentally. Seban et al. [3] experimentally investigated the laminar and turbulence flow in curved tube respectively. The entry effect for laminar flow was found significant on heat transfer rate, while it has little impact for turbulent flow. For unsteady flow in curved pipe, Mori et al. [4,5] analysed the flow field in curved tube for fully developed laminar flow, and divided the flow region into the core region and the boundary layer region along the wall. The mechanisms of heat transfer enhancement and additive flow resistance were deduced by theoretically analysis. Guo et al. [6] performed an investigation of the effects of pulsation upon transient convective heat transfer characteristics in a uniformly heated helical coiled tube. The secondary flow mechanism and the effect of interaction between the flow oscillation and secondary flow were analysed. A series of new correlations of the average and local heat transfer coefficients were proposed under steady and oscillatory conditions.

In the previous experiments, water, air or oil were used as a heat transfer medium, which have little temperature-dependent thermal physical properties, thus little deviation was generated when the fluid was postulated as constant thermal property.

Fig. 1 shows the thermal physical properties of ternary nitrate molten salt (KNO_3:$NaNO_3$:$NaNO_2$ = 53:7:40). When the molten salt is heated beyond the melting point, solid-to-liquid phase change occurred. Then molten salt becomes oil like fluid with high viscosity at low temperature region (150 °C–300 °C). The molten salt had a high Prandtl number ($Pr > 7$) and poor fluidity, which means that the thickness of the velocity boundary layer was much bigger than the thermal boundary layer, thus secondary flow in curved tube was very effective for enhancing the heat transfer process. With the increasing temperature, the viscosity and Prandtl number decrease, and the molten salt transforms into water-like liquid. The Prandtl number of the molten salt in high temperature region (300 °C–500 °C) is close to that of ordinary condition water: around the number of 7. The molten salt at the temperature of 300 °C–500 °C has favourable fluidity and thin velocity boundary layer. The ratio of the molten salt's velocity thermal boundary layer to thermal boundary layer is similar to that of ordinary condition water. Since the thermal physical properties of molten salt were more complex and sensitive to the temperature, the variations of thermal properties have to be considered for investigating the heat transfer characteristics.

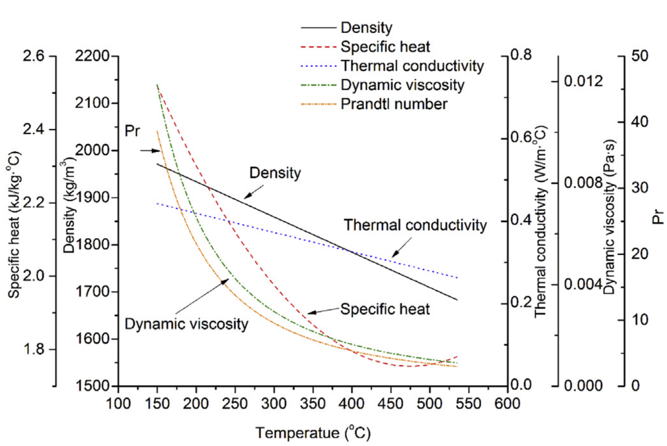

Fig. 1. Thermal physical properties of ternary nitrate molten salt.

The flow patterns in curved annular pipe are significantly different from those in a curved circular pipe because of the presence of the inner-wall boundary. Karahalios [7] proposed that secondary flow took the form of two pairs of vortices in the annular cross-section, which resulted in differences on heat transfer coefficient and frictional pressure drop. Evolution of the secondary flow and the effect of radius ratio on the flow patterns were discussed by Choi et al. [8]. The heat transfer correlations for laminar and transition flow were suggested in curved annular duct. Garimella et al. [9] studied the force convective heat transfer in coiled annular ducts. Hot and cold water were used as heat transfer fluids. The results revealed that the obtained heat transfer coefficients in the coiled annular duct were higher than those in a straight annular duct, especially in the laminar region. Xin et al. [10] investigated the pressure drop of single-phase and two-phase air–water flow in helical annular pipes. A friction factor correlation for single-phase flow in laminar, transition and turbulent flow regime was proposed. Kang et al. [11] studied the condensation heat transfer and pressure drop characteristics of refrigerant HFC-134a flowing in a helical coiled tube. The results showed that the tube-side heat transfer coefficients of the refrigerant decreased as shell-side water Reynolds number increased. Rennie et al. [12] experimentally reported the heat transfer characteristics in a coil-in-coil heat exchanger. The results showed that the flow in the inner tube with high inner-to-outer-pipe ratio was the limiting factor for the overall heat transfer coefficient. The effects of cooling wall temperature on the heat transfer coefficients were investigated. Correlations derived from the measurement data were proposed and compared with that of horizontal straight pipe.

However, to the author's best knowledge, few studies have been done for heat transfer and pressure drop characteristics in annular helical coiled duct, especially regarding property-variable molten salt. This work was primarily focus on the heat transfer and frictional pressure drop characteristics of molten salt fluid in the DTHHE. The characteristics of heat transfer and friction factor induced by secondary flow in curved annular duct were analysed. The correlations for average molten salt heat transfer coefficients were obtained within the laminar region to turbulent region. The present investigations will be helpful to the design and safe operation of molten salt heat exchanger.

2. Experimental system and method

2.1. Molten salt circulation system and test section

A novel system of molten salt heat transfer and a double-tube helical heat exchanger (DTHHE) were built at the State Key Laboratory of Multiphase Flow in Power Engineering (SKLMFPE) to study the molten salt heat transfer behaviours in a helical annular duct.

As shown in Fig. 2, the system consists of: i) a molten salt hot loop, ii) a water cold loop, and iii) a double tube helical heat exchanger (DTHHE). The molten salt hot loop was mainly composed of three components. A molten salt vessel with capacity of 300 L was constructed for heat the solid molten salt to liquid and storage the liquid molten salt. A submersible axial-pump with flow rate of 200–2000 L/h was developed for delivering molten salt fluid. An electrical preheater was used for handling the molten salt flow temperature at a desired value before it entered the heat transfer test section. The preheater was regulated by an automatic PID regulator. The mass flow rate of molten salt was measured by a