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Characteristics of the mixed convection heat transfer of molten salts in horizontal square tubes

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ABSTRACT

Molten salt is an important working fluid in the field of solar energy. However, the mixed convection heat transfer of molten salts has not been investigated. In this study, the performance of the mixed convection heat transfer of molten salt in horizontal square tubes under different side heating conditions is experimentally and numerically examined. The bottom side heating is experimentally studied, and a correlation is fitted on the basis of the experimental data. A good agreement between the correlations and the experimental data is achieved. The experimental results show that the mass flow rate of molten salt and the Reynolds number (*Re*) increase with the increase in the pump frequency. Moreover, the Nusselt number (*Nu*) increases with the increase in *Re*. The maximum enhancement of *Nu* in the mixed convection heat transfer compared with the forced convection heat transfer is approximately 50%. The experimental results and previous simulation results of the mixed convection heat transfer of molten salt with bottom surface heating are also compared. The comparison results also show a good agreement. The two-side heating condition (bottom and lateral side) is numerically examined. The simulation results of the two-side heating show that the vortexes caused by the buoyancy effect change the shape of the mainstream core area and strengthen the performance of heat transfer.

1. Introduction

Solar energy is an important renewable energy and is a key solution to the global energy crisis. The intermittent generation of solar energy limits its application, and the energy storage technology is the current most economical and efficient solution to this problem. Given that heat storage is significantly low cost and more efficient than electricity storage, solar thermal power is increasingly attracting attention (Acharya and Bhattacharjee, 2014; Yilmazoglu, 2016; Lu et al., 2016). Mixed molten salts are important working fluids of heat transfer and heat storage in the solar thermal power engineering because of their high thermal capacity, low melting temperature, and low cost (Zaversky et al., 2013; Garbrecht et al., 2013). Therefore, analyzing the heat transfer of molten salts is the key for optimizing the heat transfer in solar thermal power and improving its efficiency.

The heat transfer of fluid can be divided into forced and mixed convections. If the temperature difference between the working fluids and the surface of the transport tube is small, then the buoyancy effect caused by the density gradient becomes minimal and forced convection dominates the heat transfer. However, a large temperature difference between the surface of the transport tube and the incoming fluid exists in several special heat transfer processes, such as the solar molten salt heat receiver, trough concentrating collector, and heat exchanger. The buoyancy effect in these cases is strong and cannot be ignored. Therefore, the type of heat transfer has been changed to mixed convection, which is a combination of buoyancy effect and forced convection. Given that molten salt presents a large thermal expansion coefficient, its density changes significantly with temperature. The flow and heat transfer of molten salt in practical application under the conditions of inhomogeneous heating is considered mixed convection heat transfer. Thus, analyzing the exact mixed convection of molten salt is important in optimizing the process and achieving the best performance.

The characteristics of the mixed convection heat transfer of different working fluids, such as water, air, refrigerant, and oil,

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have been examined in the past century; however, those for molten salts have not been explored yet. Yang et al. (2010) investigated the mixed convection heat transfer of air in the horizontal non-parallel channel. Their results showed that the temperature gradient changes in the uniformly heated channel. The heat transfer capability in the said channel is stronger than that in the parallel channel because of the instability of the vortex. Koffi et al. (2011) conducted an experiment on the mixed convection heat transfer of water in the rectangular channel and determined that vortices can strengthen the heat transfer. Patil and Vijay Babu (2012) investigated the mixed convection heat transfer of water and ethylene glycol. Their results showed that mixed convection under low flow velocity affects the heat transfer. In addition, the Nusselt number (*Nu*) changes minimally with high Reynolds number (*Re*). Gau et al. (2000) and Mare et al. (2006) used the visualization method to analyze the buoyancy effect in horizontal pipes. Their results showed that the flow and heat transfer of fluid are influenced by the buoyancy effect. Allahyari et al. (2011) explored the mixed convection heat transfer of nanofluids. They found that the increase in nanoparticle diameters significantly strengthens the heat transfer coefficient whereas insignificantly influence the friction coefficient. Furthermore, the secondary flow strengthens with the increase in nanoparticle volume fraction and the Richardson number (*Ri*). This relationship indicates the relative intensity between natural and forced convections. Metais and Eckert (1964) combined their experimental results with literature results to obtain a flow judgment graph and a mixed convection correlation. The mixed convection heat transfer of different types of working fluids has been intensively explored, whereas the mixed convection heat transfer of molten salt has been scarcely examined. The application correlations of molten salt under high temperature are unknown, and experimental data of the mixed convection heat transfer of molten salt are rarely available in literature.

In the present study, Hitec salt (53 wt% KNO_3 + 40 wt% $NaNO_2$ + 7 wt% $NaNO_3$) is selected as the working fluid; this molten salt is low cost and widely used (Nunes et al., 2003; Eck and Hennecke, 2007; Tofield, 1981; Tamme et al., 2004). The salt is used to investigate the characteristics of the mixed convection heat transfer of molten salt; these characteristics are compared with those of the forced convection heat transfer of molten salt obtained in the present authors' previous study (Chen, 2013). The performance of the mixed convection heat transfer of molten salt in horizontal square tubes under different side heating conditions is numerically and experimentally explored. Accordingly, an experimental correlation is fitted. The difference between the mixed and forced convection heat transfer of molten salt is presented, and the strengthening effect of the mixed convection heat transfer is analyzed.

2. Experimental study on the mixed convection heat transfer of molten salt

2.1. Experimental system

The experimental system of the mixed convection heat transfer of molten salt is shown in Fig. 1. The system includes three parts: the molten salt cycle, heat conduction oil cycle, and test section. The high-temperature molten salt, which is extracted from the molten salt tank, flows into the inner tube of an oil–salt heat exchanger. The molten salt flows back into the tank through a pipe line. In the oil–salt heat exchanger, the conducting oil flows from the opposite side first and then flows back into the oil slot after passing through a flow meter. In the test section of the square tube, the bottom surface of the square tube is the heating surface; the buoyancy effect generated during the molten salt flow process forms the mixed convection.

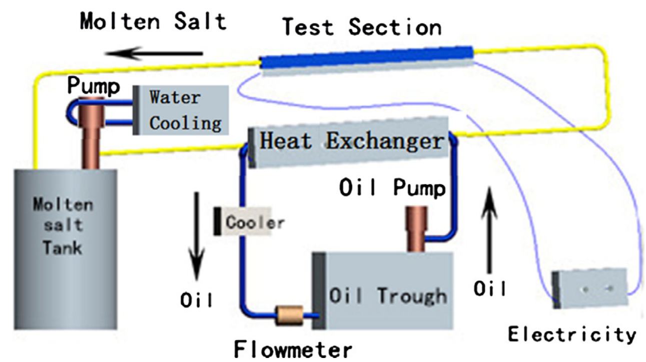

Fig. 1. Schematic of the experimental system of the mixed convection heat transfer of molten salt.

2.1.1. Molten salt cycle

The molten salt cycle includes a molten salt tank, a molten salt pump, circulating pipes, and a cooling water system. The cooling water system is mainly used for cooling the pump of molten salt. The pipe is made of 316 L stainless steel. The molten salt has a freezing temperature of approximately 140 °C. An electric heating system is used with a heat insulation material (i.e., aluminum silicate) to prevent freezing. The electric heating system uses the resistance wire to produce heat.

The molten salt tank is an important part of the experimental system and is shown in Fig. 2. The diameter and height of the tank are 0.7 and 1.2 m, respectively. The tank is used to heat and melt the molten salt and store the thermal energy. A temperature control system is also used to control and switch the heating and cooling with the relay.

The volume of the molten salt tank is 0.4 m^3, and the tank can contain approximately 400 kg molten salt. Hitec salt is selected as the working fluid in the experiment, and its thermal physical properties are as follows:

Fig. 2. Molten salt tank.