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Research Paper

Convective heat transfer characteristics in the laminar and transition region of molten salt in concentric tube

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HIGHLIGHTS

- Experiment of flow heat transfer for molten salt in concentric tube is carried out.
- Effect of free convection on heat transfer enhancement for laminar flow is studied.
- Free convection can accelerate transition from laminar flow to transition flow.
- Nusselt number of molten salt for laminar flow rises with increasing temperature.
- Heat transfer correlations for laminar and transition convection are proposed.

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ABSTRACT

Convective heat transfer performances of molten salt for laminar and transition flow in concentric tube are experimentally investigated using molten salt as the hot fluid flowing through the inner concentric tube within the range of Reynolds number 300–10,000 and Prandtl number 11–27. Heat transfer coefficients of tube side molten salt are calculated using Wilson plots and the heat transfer characteristics are studied by comparing with the traditional correlations. The results show that the laminar flow heat transfer coefficients of molten salt are higher than that of pure forced flow due to natural convection. In the transition region, the transition point to transition flow is expedited to critical Reynolds number down to 1800–2000 due to the effect of natural convection, which might increase the mean value of Nusselt number in low-Reynolds-number transition regime up to 1.3 times than that value predicted by Modified Petukhov correlation. Finally, based on the model of Churchill and Usagi, an overall correlated equation for all *Re* and *Pr* is proposed to predict the heat transfer characteristics for laminar and transition regimes. The correlated equation shows good agreement with the experiment data and higher accuracy than prior expressions for the restricted ranges of *Re* and *Pr*.

1. Introduction

As a clean energy medium, liquefied molten salt with advantages of large thermal capacity and good chemical stability has become an important working fluid for concentrating solar power and nuclear power engineering as well as newer technologies used these industrial processes [1–3]. Heat transfer of forced convection has been widely used in many kinds of heat exchanger using molten salt as hot heat transfer medium. However, a large number of heat exchangers operate in the so-called transition regime between laminar and turbulent flow due to the design constraints, such as pressure drop. Similarly, the design of compact heat exchangers and optimization of heat transfer systems also usually result in operation in the laminar regime due to the size of the flow passages and the nature of coolant fluids. Therefore, the need for information of the proper design of these devices has motivated several attempts to investigate the convective heat transfer characteristics of molten salt in the laminar and transition region.

Several studies related to forced convection heat transfer characteristics of molten salt in heat exchanger have been published to date [4,5], but every such study deals with the turbulent flow and very little experiment data with laminar flow and transitional flow are available. Hoffman et al. [6] experimentally studied convective heat transfer of molten salts NaF-KF-LiF (11.5-42.0-46.5 mole%,

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Nomenclature

A, *B*, *a*, *b*, *c*	constant
D	diameter (m)
Gr	Grashof number (–)
Gz	Graetz number (–)
K	the overall heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
L	length (m)
Nu	Nusselt number (–)
Pr	Prandtl number (–)
Re	Reynolds number (–)
T	temperature (K)
V	volume flow ($m\ h^{-1}$)
u	velocity ($m\ s^{-1}$)

Greek letters

μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
υ	kinematic viscosity ($m^2\ s^{-1}$)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
ρ	density ($kg\ m^{-3}$)
C_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)

Subscripts

b	bulk (–)
i	inlet or inner parameter
m	exponent of Reynolds number (–)
n	exponent of velocity
o	outlet or oil parameters
s	salt parameters
w	wall (–)

FLiNaK) with 2300 < *Re* < 9500, it was found that the heat transfer performance for FLiNaK can be described by the general heat transfer correlation for ordinary fluids. Cooke et al. [7] obtained forced convective heat transfer performances of molten salts $LiF\text{-}BeF_2\text{-}ThF_2\text{-}UF_4$ and found that experiment data lied below the standard correlations in the turbulent and transition regions but not in the laminar region. Silverman [8] experimentally studied the convective heat transfer characteristics in the laminar region with $LiF\text{-}BeF_2\text{-}ThF_2\text{-}UF_4$ (72-16-12-0.3 mole%) and $NaBF_4\text{-}NaF$ (92-8 mole %), however, there was no conclusion to be drawn at low Reynolds number due to the freezing of the salt. Wu [9] and Lu [10] experimentally studied convective heat transfer characteristics of molten salts $NaNO_2\text{-}KNO_3\text{-}NaNO_3$ in the transitional flow region with 4000 < *Re* < 10,000 but no laminar flow data was reported.

Heat transfer correlations currently used to study the thermal design of heat exchangers for molten salt are the classic correlation used to predict the traditional medium accurately, such as the correlations proposed by Sieder and Tate [11], Hausen [12] and Gnielinski [13]. However, all such correlations are based either on water, oil or gasoline, very little equation is obtained according to experiment data with molten salt, especially for laminar and transition region. Furthermore, all the existing correlations are based on the uniform heat flux or constant wall temperature boundary condition rather than the variable heat flux or temperature condition that are is practical and usually encountered in the heat exchanger regime.

In this paper, Heat Transfer Salt (HTS) $KNO_3\text{-}NaNO_2\text{-}NaNO_3$ (53-40-7 mole%) is used as heat transfer medium and a series of heat exchanger experiments are designed. The objectives of the present work are to investigate the heat transfer behavior of molten slat in laminar flow and transitional flow regime by considering the temperature and natural convection effects as well as being compared with traditional correlations, then to create an accurate correlation for the predictions of heat transfer coefficients with Reynolds numbers range from 300 to 10,000. These results will also provide the reliable evidence and favorable guidance for the design of concentric tube heat exchanger of molten salt in the laminar and transition region.

2. Experiments

2.1. Experimental system and method

Experimental system used to investigate the heat transfer characteristics of molten salt is built at Shanghai Institute of Applied Physics, Chinese Academy of Sciences (SINAP, CAS). The experimental set-up is shown schematically in Fig. 1. The system basically includes two closed flow loops (hot HTS loop and cold oil loop) and one test section. The HTS loop consists of a molten salt tank, molten salt electric heater with a maximum power of 120 kW, a molten salt pump, mixing chamber, test section and molten salt flow-meter. HTS is pumped from the molten salt tank to the molten salt electric heater, where the HTS is heated up to an exit temperature as experiment requires. Then molten salt leaves the heater and exchanges heat in the test section with cold oil, and finally returns to the molten salt heater. The oil loop is capable of operating at high temperature up to 443 K and consists of an oil trough, centrifugal pump, oil flow-meter, and air cooler (to remove heat that is exchanged to the oil from HTS and keep the oil temperature constant). The inlet and outlet temperature of HTS and oil are adjusted directly at the mixing chamber located on the ends of test section. The flow of HTS and oil is measured by flow-meter.

The test section is a concentric tube heat exchanger operated under countercurrent-flow conditions where hot HTS flows in the

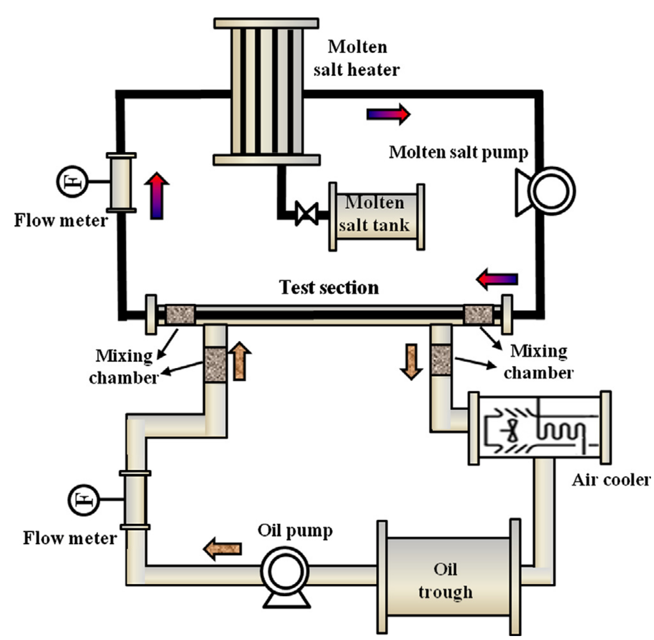

Fig. 1. Schematic diagram of the experimental set-up.