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Research Paper

Convective heat transfer of high temperature molten salt flowing across tube bundles of steam generator in a solar thermal plant

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HIGHLIGHTS

- A novel convective heat transfer experimental system of molten salt is designed and established.
- The Nusselt number of high temperature molten salt flowing across tube bundles is studied.
- The effects of the pressure, temperature and flux on the Nusselt number are analyzed in the shell-and-tube heat exchanger.
- Several modified heat transfer correlations of molten salt in shell-and-tube heat exchanger are fitted.

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ABSTRACT

A high temperature molten salt heat transfer experimental system was established and operated over 1500 h, started up and shut down every day, for research and development of steam generator in a solar thermal plant. Convective heat transfer performances of high temperature molten salt was investigated experimentally when it flowed across tube bundles in a shell-and-tube heat exchanger with Reynolds number ranging from 2129 to 10072 and fluid temperature 400–500 °C. Various experiments were respectively carried out to study the effect of pressure (water range: 14–18 MPa), temperature, flux (water range: 200–400 kg h^{-1}) and phases of the tube side of heat exchanger. The results show that the Nusselt number of molten salt increases when the flux of water and the temperature of molten salt increased respectively with other conditions unchanged. Moreover, the Nusselt number of molten salt slightly decreases when the pressure of water increased. Finally, based on the experimental data and Zhukauskas correlation, several modified Zhukauskas correlations were proposed, and a good agreement was observed with deviations less than ± 16% between the experimental data of molten salt and the empirical correlation.

1. Introduction

Concentrating solar power is a solar electricity generation technology that captures and stores solar energy in the form of heat by using low cost but stable materials. Two of the most important components of concentrated solar power are receiver and heat exchanger. The heat exchanger constitutes of a number of tubes that can transfer heat in fluid cross-flow tube banks that is steam cooled on the tube side. Many researchers have investigated the convective heat transfer behaviors of molten salt and oil in heat exchanger, but the up-to-date power plants often utilize solar salt and water as heat transfer medium in shell-and-tube heat exchanger to improve efficiency.

Up to now, the convective heat transfer behaviors have been widely investigated. For instance, Lu et al. [1] experimentally measured the convective heat transfer coefficients of high temperature molten salt in different transversely grooved tubes. The results showed that the Nusselt number increased with grooved height and Reynolds number. Du et al. [2] conducted heat transfer measurements on the forced convection of molten salt in the shell-and-tube heat exchanger with segmental baffles, and the comparison of heat transfer enhancement in the molten salt STHE-SBs was discussed. Lu et al. [3] studied the convective heat transfer in the laminar-turbulent transition region of molten salt in annular passage. The results showed that Nusselt number of molten salt flowing in annular passage was remarkably larger than that in circular tube, and it increased with Reynolds number and Prandtl number. Chen et al. [4] experimentally analyzed the characteristics of laminar convective heat transfer of molten salt in concentric tube. The results showed that the measured Nusselt number is larger than that has been predicted by pure forced convective heat transfer correlations, and the deviations decrease as Reynolds number increases. Wu et al. [5]

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Nomenclature

A	flow area
C_p	specific heat ($J/kg^{-1}K^{-1}$)
d	equivalent diameter (m^2)
f	friction coefficient
l	length of tubes (m)
h	heat transfer coefficient ($W/m^{-2}K^{-1}$)
K	over heat transfer coefficient ($W/m^{-2}K^{-1}$)
Q	heat transfer capacity (J)
q_v	volume flow rate (m^3/s^{-1})
T	temperature (K)
ΔT_m	log-mean temperature difference (K)
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number

Greek symbols

ρ	fluid density (kg/m^{-3})
λ	thermal conductivity ($W/m^{-1}K^{-1}$)
μ	kinematic viscosity (Pa s)
Φ	heat balance deviation

Subscripts

f	fluid
i	inner
o	outer
in	inlet
out	outlet
max	maximum
min	minimum
s	molten salt
w	water

investigated the forced convective heat transfer of molten salt in circular tubes. The results showed that all the experimental data in the range of Prandtl number from 1.6 to 59.9 may be well correlated by Gnielinski equation. Hoffman et al. [6,7] obtained the convective heat transfer coefficient of mixed molten salt LiF-NaF-KF and $NaNO_2$-KNO_3-$NaNO_3$. Silverman et al. [8] proposed the heat transfer measurements in a forced convection loop with two molten-fluoride salts. In general, high temperature molten salt in the CSP system was applied to heat the steam, so the convective heat transfer of high temperature molten salt with the high temperature and high pressure steam in shell-and-tube heat exchanger should be further investigated. Ravigururajan and Bergles [9] proposed general heat transfer correlations for single-phase turbulent flow in enhanced tubes. The results proved that the correlations can be successfully applied to a wide range of roughness types and Prandtl number. Vicente et al. [10] investigated the mixed convection heat transfer in corrugated tubes for laminar and transition flow. Huang et al. [11] proposed shape optimization of transversely ridged tube through orthogonal numerical simulation test. Some researchers [12–15] also investigate the flow and heat characteristics of molten salt using CFD simulations. In a word, the convective heat transfer of high temperature molten salt flowing in the tube with the laminar and turbulent motion has been already investigated, but high temperature molten salt flowing across tube bundles was rarely studied.

In the present paper, experimental measurements were conducted to analyze the heat transfer performance of molten salt in shell-and-tube heat exchanger. The binary nitrate salt $NaNO_3$-KNO_3 was used as medium to approach the heat transfer coefficients of shell-and-tube heat exchanger with various Reynolds numbers and at different fluid temperatures. Based on these experimental results and existing correlations, an improved correlation grasping the essence of both natural convection and forced convection is proposed.

2. System description

2.1. Experimental system

In order to study the convective heat transfer behavior of molten salt in shell-and-tube heat exchanger at high temperature, the author independently designed and established a high temperature molten salt heat exchange experimental system, as shown in Fig. 1.

The high temperature molten salt heat exchange experimental system consisted of a high temperature vapor cyclic system (blue and red cycle) and a high temperature molten salt cyclic system (green cycle). The high temperature molten salt cyclic system is made up of a molten salt can (approximately 1.8 m in height and 1.5 m in diameter), a molten salt pump, a flowmeter, a heater and test section. The molten salt was electrically heated up to 300 °C in the molten salt can, in which the molten salt can be kept in fluid state 24 h a day. Then the molten

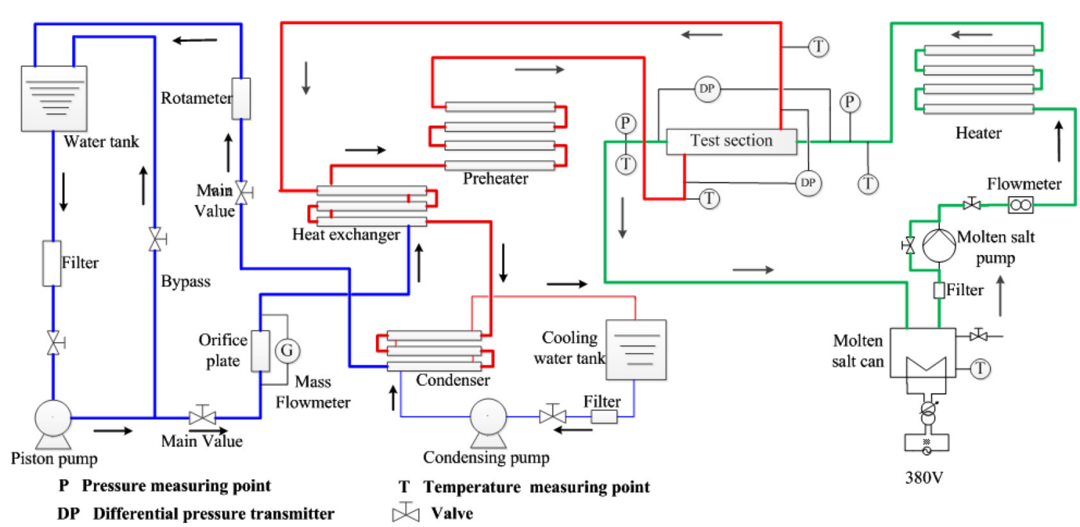

Fig. 1. Experimental system diagram.