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Investigation on heat transfer characteristics of molten salt in a shell-and-tube heat exchanger

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ABSTRACT

In order to study the heat transfer characteristics (HTCs) of molten salt outside the tube bundle in a shell-and-tube heat exchanger (STHE) without baffle plates, the HTCs of molten salt (204.06 °C~236.91 °C) are experimentally and numerically investigated in this paper. Firstly, the HTCs of molten salt ($3514 < Re < 5482$) is experimentally studied based on the test platform with HITEC salt and oil. Then the empirical heat transfer equations of molten salt applied in the shell side of STHE are fitted. Finally, the comparison between the experimental and numerical results is conducted. The results show that the fitted equations agree well with the experimental data and the fitted deviations are only 8%. The error is about 11% between the simulation and experiment results which indicates that the HTCs of molten salt STHE would be predicted well using the simulation method. The numerical results also show that there exist flow dead zones in the STHE which could weaken the molten salt HTCs.

1. Introduction

The development and utilization of renewable energy (solar energy, wind energy, tidal power, etc.) are urgently needed because of the serious energy and environment problems [1, 2]. The concentrating solar power (CSP) technology [3–6] is one of the effective ways to solve this issue, and many solar power plants (including tower system [6–12], parabolic trough system [13], linear Fresnel system [14, 15] and dish system [16]) have been built. Particularly, taking the solar tower power system with broad applications as an example, the molten salt has always been simultaneously used as heat transfer and storage medium. Due to the advantages of simple structures and low cost in the tower system, molten salt has the prospect of widely commercial applications [17–21]. Fig. 1 exhibits the diagram of molten salt CSP tower system. It contains solar collection subsystem, thermal storage and heat transfer subsystem, and thermoelectric conversion subsystem. It is worth note that the molten salt steam generator is one of the key components in the thermal storage and heat transfer subsystem, through which the heat can be effectively transferred into the next subsystem.

The researches on the heat transfer characteristics (HTCs) of molten salt mainly focus on the structure of smooth tube, enhanced tube, outside annular tube and shell-and-tube heat exchanger (STHE) with uniform or non-uniform heat flux distribution. For the smooth tube, Wu et al. [22] tested the heat transfer coefficients of $LiNO_3$ and HITEC ($NaNO_3$–KNO_3–$NaNO_2$ eutectic) in smooth pipe, and the corresponding experimental equations in the turbulence regions were fitted. Sun et al. [23] obtained the heat transfer data of HITEC salt in the laminar region and the experimental correlation was fitted. Yang et al. [24] experimentally studied the HTCs of molten salt in a smooth tube with high flux. Meanwhile, the investigation of molten salt in smooth tube with non-uniform heat flux was also carried out by Shen et al. [25]. For the enhanced tubes, Yang et al. [26] and Chen et al. [27] studied the convective heat transfer of HITEC salt in the spiral grooved tube and transversally corrugated tubes, respectively. And the experimental research of molten salt outside annular tube was also carried out in Ref. [28]. Furthermore, based on the experimental platform of HITEC salt and oil, He and Zheng et al. [29] studied the turbulent HTCs of molten salt in a shell-and-tube heat exchanger (STHE). The experimental study was also conducted on the HTCs of molten salt in laminar region outside the tube bundle of STHE, and the corresponding correlation was obtained [30]. The detailed studies of molten salt heat transfer performances are shown in Table 1.

It can be found that the current investigations of molten salt HTCs are mainly focus on the simple structures. Although some experimental researches of molten salt HTCs outside the tube bundle in complex STHE have been carried out, the corresponding heat transfer performances are only tested in the laminar region. Therefore, the HTCs of molten salt in the transition region outside the tube bundle in complex

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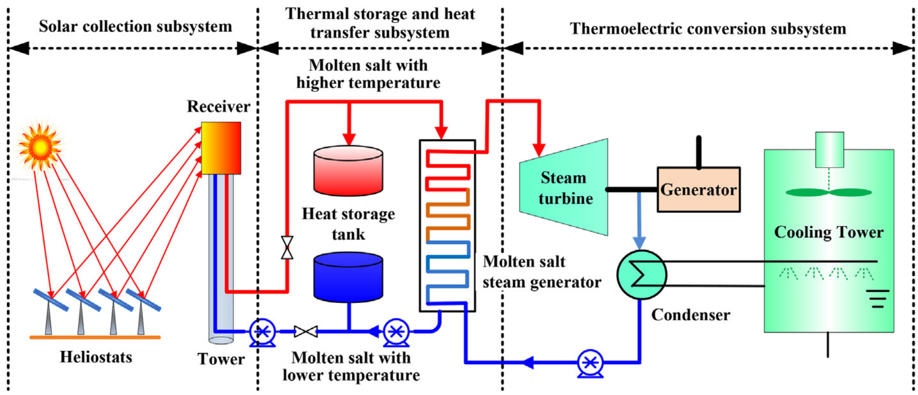

Fig. 1. Diagram of molten salt CSP tower system.

Table 1
Studies on heat transfer performances of molten salt.

Item	Distribution of heat flux	Fluid	Research contents or results	Range of *Re*	Author	Year
Smooth tube	Uniform	$LiNO_3$	$Nu = 0.0242Re^{0.807}Pr^{0.331}, Nu = 0.02948Re^{0.787}{Pr_f}^{1/3}(\mu_f/\mu_w)^{0.14}$	$17{,}000 < Re < 45{,}000$	Liu [32]	2009
	Non-uniform	HITEC	Sieder-Tate equation is not suitable for the pipe with higher heat flux	$Re > 10{,}000$	Yang [24]	2009
	Uniform	$LiNO_3$/HITEC	$Nu = 0.02948Re^{0.787}Pr^{1/3}$	$Re > 10{,}000$	Wu [22]	2012
	Non-uniform	HITEC	$Nu = 0.0205Re^{0.82}{Pr_f}^{0.34}(\mu_f/\mu_w)^{0.14}(flux_{av}/flux_c)^{0.03}$	$10{,}000 < Re < 67{,}000$	Shen [25]	2014
	Uniform	HITEC	$Nu = 0.71(Re \cdot Pr_f \cdot d/l)^{0.45}(\mu_f/\mu_w)^{0.14}$	$Re < 2300$	Sun [23]	2015
Enhanced tube	Uniform	HITEC	Heat transfer property of spiral grooved tube is better than smooth pipe	$400 < Re < 1200$	Yang [26]	2010
	Uniform	HITEC	$Nu = 0.07334Re^{0.8}{Pr_f}^{1/3}(\mu_f/\mu_w)^{0.14}(1 + 2e/d_o)^{-11.45}$	$Re > 10{,}000$	Chen [27]	2013
Annular tube	Uniform	HITEC	$Nu = 0.0206(Re^{0.873} - 280){Pr_f}^{0.4}[1 + (D_e/l)^{2/3}](D_i/d_o)^{0.45}(Pr_f/Pr_w)^{0.11}$	$3000 < Re < 16{,}000$	Lu [28]	2014
STHE	Uniform	HITEC	$Nu = 1.61(Re \cdot Pr_f \cdot De/l)^{0.63}(\mu_f/\mu_w)^{0.32}$	$400 < Re < 2300$	He [30]	2014
	Uniform	HITEC	$Nu = 0.0382Re^{0.8}, Nu = 0.0206Re^{0.8}Pr^{0.3}$	$Re > 10{,}000$	He [29]	2016

STHE without baffle plates are investigated in this paper, and the empirical heat transfer equations applied in molten salt STHE are fitted based on the experimental data. Finally, the simulated study on convective heat transfer in STHE is conducted, and the comparison between the experimental and numerical results is carried out.

2. Experimental method

2.1. Shell-and-tube heat exchanger and working mediums

The test unit is a STHE without baffle plates, as shown in Fig. 2. The arrangement of tube bundle is set as regular triangles presented in Fig. 3. In order to make sure that the inlet and outlet temperature measured by thermocouples from thermometer hole are uniform, the mixing chambers with perforated plates are installed at the inlet and outlet positions of heat exchanger. Then the temperature of fluid can be uniformly mixed after flowing through the perforated plates, as shown in Fig. 4. The diagram of STHE can be found in Fig. 5. Table 2 shows the size of STHE.

The molten salt is HITEC [31] (53%wt KNO_3, 40%wt $NaNO_2$, 7%wt $NaNO_3$), its melting temperature is 142 °C. The type of oil is YD325 and the material of heat exchanger is 316 L stainless steel.

Table 3 shows the physical properties of heat exchanger and working mediums.

Fig. 2. The STHE.

Fig. 3. Regular triangle arrangement of tube bundle.

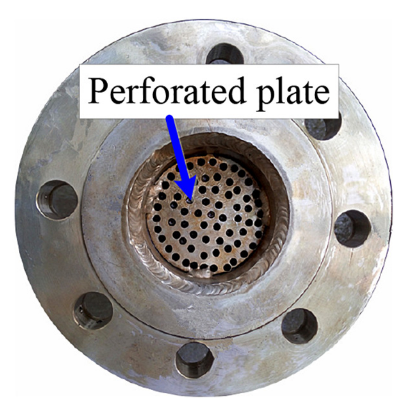

Fig. 4. Perforated plate.