International Journal of Heat and Mass Transfer 113 (2017) 456–465

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Convective heat transfer of molten salt in the shell-and-tube heat exchanger with segmental baffles

Bao-Cun Du, Ya-Ling He *, Kun Wang, Han-Hui Zhu

Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

ARTICLE INFO

Article history:
Received 12 December 2016
Received in revised form 19 May 2017
Accepted 20 May 2017
Available online 3 June 2017

Keywords:
Solar energy
Molten salt
Heat exchanger
Segmental baffles
Heat transfer

ABSTRACT

In this paper, a special flow layout with U-shaped tubes applied in the laboratory was designed for testing the heat transfer performances (HTPs) of molten salt in the shell side of a shell-and-tube heat exchanger (STHE). Based on this design, the transitional convective HTPs ($6142 < Re < 9125$) of molten salt with higher temperature (209.41–241.49 °C) in the STHE with segmental baffles (STHE-SBs) were experimentally studied, and the corresponding heat transfer correlations were fitted. Then the validation of the traditional correlation applied in the molten salt STHE-SBs was conducted. Finally, the comparison of heat transfer enhancement in the molten salt STHE-SBs was discussed. The results show that a good agreement with 2% deviations exists between the fitted correlations and the test data. Meanwhile, the traditional Kern correlation, with a 7.1% maximum deviation compared with the test data, is still appropriate to analyze the HTPs of molten salt STHE-SBs. The effects of segmental baffles on the molten salt heat transfer enhancement in lower flow rate region are better than those in higher flow rate region, and the maximum increment of Nusselt number is 26%.

1. Introduction

The concentrating solar power (CSP) technology is one of the significant ways to solve the problem of environment pollution and energy shortage [1–3,30]. In the CSP system, the inorganic molten salt with high specific heat, low viscosity and operation pressure has commonly been adopted as the heat transfer fluid [4–8]. Besides, the molten salt always works in high temperature. For example, the operation temperatures of solar salt (60 wt% $NaNO_3$, 40 wt% KNO_3) and HITEC salt (53 wt% KNO_3, 40 wt% $NaNO_2$, 7 wt% $NaNO_3$) applied in the CSP system are 220–600 °C and 142–550 °C, respectively. Especially, the molten salt with high temperature could also be applied in the nuclear power system [9].

In the solar and nuclear plants, the molten salt shell-and-tube heat exchanger (STHE) is one of the critical units where the water medium could be heated sharply and then transferred into superheated steam with higher pressure and temperature. Thus, the thermal efficiency of plants is influenced significantly by the heat transfer performances (HTPs) of the molten salt STHE. Particularly, the molten salt STHE with segmental baffles (STHE-SBs) is one of the most common heat exchangers, which can improve the HTPs by enhancing the turbulence in the shell side of STHE-SBs. For the molten salt STHE-SBs, there are two special operation characteristics which need to be demonstrated. Firstly, the inlet molten salt could be heated to high temperature by the solar collectors [6,7,10–12] or nuclear reactors [9,13,14], as shown in Table 1. Secondly, the molten salt with low pressure (around the ambient pressure) always flows into the shell side of STHE-SBs.

Specially, the appropriate heat transfer correlations applied in molten salt with high temperature are needed when the STHE-SBs is designed. However, the traditional heat transfer correlations applied in the molten salt STHE-SBs [15] such as the Kern and Donohue equations were fitted based on the test data of water and oil etc. with low temperatures. For example, the Donohue equation was fitted by the experimental data of water and oil fluids around 65 °C [16]. Therefore, it is not clear that whether the traditional heat transfer correlations are appropriate or not in the optimization design of the STHE-SBs with molten salt above 142 °C, such as the solar salt and HITEC salt. Table 2 shows the traditional heat transfer correlations applied in the STHE-SBs.

Besides, although many studies on the HTPs of molten salt have been conducted, most of researches mainly focus on the analysis in the single tube, the annual tube and the STHE. For the single tube, the forced convective HTPs of LiNaK salt (46.5 wt% LiF, 11.5 wt% NaF, 42 wt% KF) have been experimentally carried out by Hoffman et al. [17], and the corresponding heat transfer correlations were fitted. Liu et al. [18] experimentally analyzed the turbulence con-

* Corresponding author.
E-mail address: yalinghe@mail.xjtu.edu.cn (Y.-L. He).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.05.075

Nomenclature

A_c	maximum flow area of shell (m^2)
A_s	heat transfer area of shell (m^2)
B	pitch of segmental baffles
c_p	specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
c_t	factor
d	diameter of tubes (m)
d_e	equivalent diameter of tubes (m)
D	diameter of shell (m)
D_e	equivalent diameter of shell (m)
f	friction coefficient
h	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
k	conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
K	overall heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
L	length of tubes (m)
N_b	number of segmental baffles
N_t	number of tubes
Nu	Nusselt number
Pr	Prandtl number
q_v	volume flow rate ($m^3 \cdot s^{-1}$)
Q	heat transfer capacity (W)
Re	Reynolds number
s	pitch of tubes (m)
T	temperature (K)
ΔT	temperature difference (K)
ΔT_m	log-mean temperature difference (K)
u	flow rate ($m \cdot s^{-1}$)

Abbreviations

SPRT	standard platinum resistance thermocouple
STHE	shell-and-tube heat exchanger
STHE-SBs	shell-and-tube heat exchanger with segmental baffles

Greek symbols

μ	viscosity ($Pa \cdot s$)
ρ	density ($kg \cdot m^{-3}$)
Φ	heat balance deviation
σ	error

Superscripts

ave	average
corr	correction
f	fluid
i	inner
in	inlet
o	outer
out	outlet
max	maximum
min	minimum
s	shell side
t	tube side
w	wall

Table 1
Operation temperatures of molten salt in the heat exchangers of solar and nuclear power plants.

Applications	Items	Projects	Countries	Years	Temperatures of molten salt (°C)
Solar plants	Tower	Delhi	China	2016	568
		Crescent Dunes	US	2015	550
		Gemasolar	Spain	2011	565
		Solar Two	US	1996	565
		MSEE	US	1984	566
		THEMIS	France	1984	450
	Parabolic Trough	Aksay	China	2016	550
		Archimedes	Italy	2010	550
		Andasol	Spain	2009	390
	Linear Fresnel	Areva	US	2014	550
Nuclear plants	Molten salt reactor	MOSART	Russia	2014	715
		TMSR	China	2013	650
		FHR	US	2012	1000
		MSFR	France	1997	650
		MSR	US	1976	705
		MSRE	US	1963	705
		ARE	US	1954	815

Table 2
Traditional heat transfer correlations applied in STHE-SBs.

Items	Equations	Range	Years
Kern method [15]	$Nu = 0.5Re^{0.507}Pr^{1/3}(\mu/\mu_w)^{0.14}$	$10 < Re < 2000$	1950
	$Nu = 0.36Re^{0.55}Pr^{1/3}(\mu/\mu_w)^{0.14}$	$Re > 2000$	
Donohue method [16]	$Nu = 0.23Re^{0.6}Pr^{1/3}(\mu/\mu_w)^{0.14}$	$20,000 < Re < 30,000$	1949
Bell-Delaware method [15]	$h = j_H \cdot G_s \cdot c_p(\mu/\mu_w)^{0.14}Pr^{-2/3} \cdot J_c \cdot J_e \cdot J_b \cdot J_s \cdot J_r$	–	1947

vective HTPs of $LiNO_3$ salt in a single tube, and the experimental correlation was obtained. Shen et al. [19] also analyzed the heat transfer characteristics of HITEC salt in a single tube with non-uniform heat flux on the tube walls, and the corresponding correlation with heat flux was fitted. The heat transfer and friction characteristics of LiNaK salt were numerically investigated in the smooth tube [20]. Meanwhile, the heat transfer enhancement of spiral ridges and transversally corrugated structures applied in