Experimental Thermal and Fluid Science 55 (2014) 6–11

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Convective heat transfer of molten salt in circular tube with nonuniform heat flux

Shen Xiangyang [a,b], Lu Jianfeng [a,*], Ding Jing [a], Yang Jianping [c]

[a] School of Engineering, Sun Yat-Sen University, Guangzhou 510006, China
[b] College of Mechanical & Electrical Engineering, Zhongkai University of Agriculture and Engineering, Guangzhou 510225, China
[c] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of the Ministry of Education, South China University of Technology, Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 10 November 2013
Received in revised form 9 February 2014
Accepted 9 February 2014
Available online 17 February 2014

Keywords:
Molten salt
Heat convection
Circular tube
Nonuniform heat flux
Heat transfer correlation

ABSTRACT

Convective heat transfer performances of molten salt in circular tube with nonuniform heat flux were experimentally investigated using unilateral copper coating tubes. Various experiments were carried out within the range of Reynolds number 10,000–67,000, Prandtl number 4.5–8, and the heat flux ratio of 1.0, 2.0 and 5.7. The results showed that there existed large wall temperature difference in the tube section with nonuniform heat flux, and associated Nusselt number of molten salt flow increased with Reynolds number and Prantal number. Compared with Sieder–Tate correlation, Nusselt number on the smooth side with lower heat flux was mostly larger, while Nusselt number on coating side with higher heat flux was mostly lower. Experimental heat transfer correlation for molten salt flow in circular tube with nonuniform heat flux was developed by least-squares method, and it very well fit with experimental data and classical correlations. In general, average Nusselt number of molten salt flow in circular tube had little relation with nonuniform heat flux, but Nusselt number difference on different sides increased with the heat flux ratio.

1. Introduction

Molten salt is one of the most useful heat transfer and storage medium in kinds of high temperature industrial engineering as concentrated solar thermal power [1]. Molten salt has many advantages like large thermal capacity, low viscosity, large range of operating temperature, low cost, and so on. The heat storage performances of molten salt have been widely investigated in available literature. Herrmann et al. [2] proposed two-tank molten salt storage for parabolic trough solar power plants. Yang and Garimella [3] conducted thermal analysis on solar thermal energy storage in a molten-salt thermocline.

In order to design molten salt system and improve its performance, the heat transfer of molten salt was further investigated in available literature. Hoffman et al. [4–5] experimentally studied convective heat transfer of mixed molten salts including LiF–NaF–KF and $NaNO_2$–KNO_3–$NaNO_3$, and derived associated experimental heat transfer correlations. Silverman et al. [6] conducted heat transfer measurements on forced convection of two molten-fluoride salts as LiF–BeF_2–ThF_4–UF_4 and EUTECTIC $NaBF_4$–NaF. Wu et al. [7,8] investigated convective heat transfer with molten salt in a circular pipe, and they also studied the heat transfer of molten salt in transversally corrugated tube with three different pinches. Lu et al. [9,10] further measured convective heat transfer performances of molten salt flow in spirally grooved tube and transversely grooved tube under different groove heights, and found that the heat transfer can be enhanced by groove height increase. Besides, Pacheco et al. [11] investigated cold filling in molten-nitrate-salt central receiver solar power plants, and considered the phase change phenomena of molten salt. In general, most heat transfer processes and correlations of molten salt convection in kinds of tube assumed that the heat flux and wall temperature were uniform.

In practical molten salt system as solar thermal power, the convective heat transfer inside the heat receiver was mainly calculated by Sieder–Tate correlation [12], while the molten salt heat transfer was probably nonuniform because of uneven solar flux and receiver structure. According to the receiver structure in solar thermal power tower [13], the heat flux on the two sides of receiver panel should be nonuniform. Lu et al. [14] theoretically investigated the heat transfer of an external receiver pipe under unilateral concentrated solar radiation. Jeter [15] analyzed the nonuniform distribution of concentrated solar radiation in parabolic trough collectors. Cheng et al. [16] numerically simulated parabolic trough solar collector with nonuniform solar flux conditions by coupling FVM

* Corresponding author. Tel.: +86 (20) 39332320; fax: +86 (20) 39332319.
E-mail address: lujfeng@mail.sysu.edu.cn (J. Lu).

http://dx.doi.org/10.1016/j.expthermflusci.2014.02.015
0894-1777/

Nomenclature

c_p	thermal capacity (J kg^{-1} K^{-1})
D	outer tube diameter (m)
d	inner tube diameter (m)
e	coating height (m)
h	heat transfer coefficient (W m^{-2} K^{-1}), wall thickness (m)
L	length (m)
q	heat flux (W m^{-2})
q_v	volumetric flow rate (m^3/s)
R	electric resistance (Ω)
t	temperature (°C)
u	velocity (m/s)
Greek symbols	
ρ	density (kg m^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
μ	viscosity (kg m^{-1} s^{-1})
Subscripts	
av	average
c	coating side
cal	calculation
exp	experiment
in	inlet condition
out	outlet condition
ow	outer wall of the tube
s	smooth side
t	tube
w	inner wall of the tube

and MCRT method. Till now, convective heat transfer of molten salt in tube with nonuniform heat flux should be experimentally investigated in detail.

In this paper, experimental measurements and analyses were used to study the heat transfer characteristics of mixed nitrate in circular tube with nonuniform heat flux. The nonuniform heat flux was performed by copper coating on one side of the tube surface for smaller electric resistance, and then the heat transfer performances of molten salt in circular tube were considered with various coating heights and operating conditions. Based on the experimental data and classical correlations, experimental heat transfer correlation will be further developed.

2. Experimental system

2.1. General description

The experimental system mainly included molten salt tank, pump, molten salt furnace, the testing tube, electric power, acquisition system, and molten salt pipeline, as illustrated in Fig. 1. Before experiments, molten salt in the tank should be melted and heated to a prescribed temperature using electric heaters, and the whole molten salt pipeline will be warmed up to above 180 °C. In this article, molten salt was first heated to 290–450 °C in the tank, and then was pumped into the testing tube. The testing tube was directly heated by electric power with voltage of 5–15 V and maximum power of 40 kW, and its surface was insulated to minimize heat loss to the surroundings. The molten salt valves and by-pass channel were used to obtain different flow velocities.

The mixed nitrate (KNO_3–$NaNO_2$–$NaNO_3$) was used as heat transfer medium, and it had a large operating temperature range (200–550 °C) and good thermal stability. The thermal properties of molten salt were experimentally correlated as [9]: ρ = 2085–0.74t kg m^{-3}, c_p = 1549–0.15t J kg^{-1} K^{-1}, λ = 0.697–0.000461t W m^{-1} K^{-1}, and μ = 31.59–0.1948t + 0.000425t^2 – 0.0000003133t^3 g m^{-1} s^{-1}, where t meant the degree Celsius of molten salt.

The unilateral copper coating tube was made of 316L stainless steel, and it was 1.30 m in length, 16 mm and 20 mm in inner and outer diameters, as illustrated in Fig. 2a. The copper coating was electrically plated on one side of the tube surface, and the heat flux on the side with copper coating will be larger for smaller electric resistance. The construction parameters of the testing tube are presented in Fig. 2b, and the detailed parameters are listed in Table 1. The uncertainties of tube length, diameter and coating thickness were respectively 1 mm, 0.1 mm, 0.01 mm.

The temperatures of molten salt and wall were measured using K-type thermocouples with uncertainty of 0.5 K. Two thermocouples were used to measure the inlet and outlet temperature of molten salt. As illustrated in Fig. 2b, two thermocouples were used to measure the wall temperature in one section of the testing tube, and there were totally six thermocouples located in three sections with 0.20 m, 0.65 m, and 1.10 m from the inlet. The flow rate was measured by LG flowmeter with the range of 0–3.5 m^3/h and uncertainty of 2.5%. The current of the testing tube was directly measured by the electric power, while the voltage was measured by universal meter, and the uncertainties of current and voltage were respectively 0.5% and 0.1%.

2.2. Data analyses

The bulk temperature of molten salt flow was calculated as:

$$t_f = \frac{t_{out} + t_{in}}{2} \quad (1)$$

In this article, molten salt properties were calculated at the temperature t_f.

The average heat flux of the testing tube can be calculated as [9]:

$$q_{av} = \frac{\rho c_p (t_{out} - t_{in}) q_v}{2\pi dl} = \frac{\xi \cdot I \cdot U}{2\pi dl} \quad (2)$$

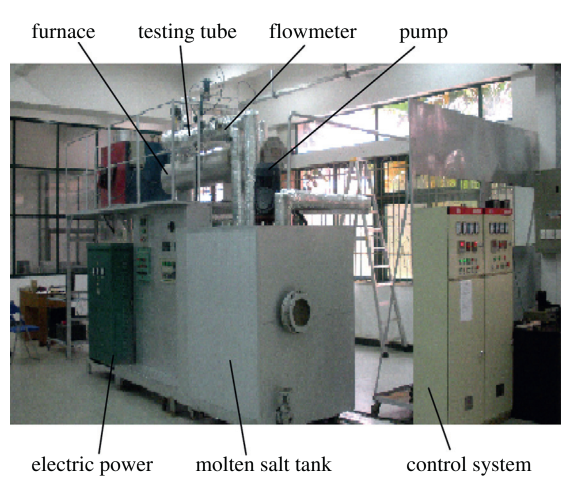

Fig. 1. Experimental system.