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Convective heat transfer of high temperature molten salt in a vertical annular duct with cooled wall

Jianfeng Lu [a,*], Shiquan He [b], Jing Ding [a,*], Jianping Yang [c], Junming Liang [a]

[a] School of Engineering, Sun Yat-Sen University, Guangzhou 510006, China
[b] Academy of Building Energy Efficiency, Guangdong Provincial Key Laboratory of Building Energy Efficiency and Application Technology, Guangzhou University, Guangzhou 510006, China
[c] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of the Ministry of Education, South China University of Technology, Guangzhou 510640, China

HIGHLIGHTS

- Convective heat transfer of molten salt in a vertical annular duct was measured.
- Nusselt number of molten salt in annular duct was higher than that of circular tube.
- Heat transfer correlations for transition and turbulent convection were proposed.
- The correlation included the effects of duct structure and temperature difference.
- The proposed correlations fit with experimental data and classical correlations.

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ABSTRACT

Convective heat transfer performances of high temperature molten salt in a vertical annular duct with cooled wall were experimentally investigated within the range of Reynolds number 3000–16,000, Prandtl number 4.8–7.6, and fluid temperature 300–400 °C, respectively. The results showed that Nusselt number of molten salt flow in annular duct was remarkably higher than that of circular tube, and it increased with Reynolds number and Prandtl number. Because of variable thermal properties and annular configuration, the heat transfer correlation for fully developed turbulent flow was proposed based on Wiegand correlation and Sieder–Tate correlation, while the heat transfer correlation for transition flow was established by Gnielinski equation and Wiegand equation. Based on the experimental data, the modified heat transfer correlations for molten salt flow in annular duct were developed by least-squares method, and the modified correlations for transition and turbulent flow had good agreement with experimental data.

1. Introduction

Heat transfer of forced convection has been widely used in kinds of heat exchanger. Many researchers investigated the transition and turbulent convective heat transfer with different working fluids. Sieder and Tate [1] experimentally measured the heat transfer and pressure drop of liquids in tubes, and derived their important heat transfer correlation. Gnielinski [2] proposed new heat transfer correlations for heat transfer in turbulent pipe due to experimental data by Sieder and Tate. Wiegand [3] investigated the turbulent convection in concentric annular duct and proposed associated heat transfer correlation. Petukhov [4] studied the heat transfer and friction in turbulent pipe flow with variable physical properties. Till now, the forced convection heat transfer with high temperature media should be further investigated.

Molten salts [5,6] are very important heat transfer and storage media at high temperature in solar thermal plants, chemical engineering, nuclear heat source, and so on. In many available literature, the heat storage characteristics of molten salt system [7,8] have been widely studied. However, the convective heat transfer of molten salt as heat transfer fluid was only investigated in a few reports. Hoffman et al. [9,10] experimentally analyzed the heat transfer of mixed molten salts LiF–NaF–KF and

* Corresponding authors. Tel.: +86 20 39332320; fax: +86 20 39332319.
E-mail addresses: lujfeng@mail.sysu.edu.cn (J. Lu), dingjing@mail.sysu.edu.cn (J. Ding).

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Nomenclature

c_p	thermal capacity (J kg^{-1} K^{-1})
d	inner diameter of annular duct (m)
D	outer diameter of annular duct (m)
h	heat transfer coefficient (W m^{-2} K^{-1})
D_h	hydraulic diameter (m)
l	length (m)
P	wetting circumference (m)
q	heat flux (W m^{-2})
q_v	volumetric flow rate (m^3/s)
S	section area (m^2)
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})
σ	uncertainty (−)
Subscripts	
f	fluid
in	inlet condition
out	outlet condition
w	wall

$NaNO_2$–KNO_3–$NaNO_3$, and derived the convective heat transfer coefficients of different molten salts. Silverman et al. [11] conducted heat transfer measurements on the forced convection loop with two molten-fluoride salts: LiF–BeF_2–ThF_4–UF_4 and $NaBF_4$–NaF. Wu et al. [12] considered the turbulent and transition region convective heat transfer with molten salt in a circular pipe. In addition, Lu et al. [13,14] further investigated the transition and turbulent convective heat transfer of molten salt in spirally grooved tube and transversely grooved tube to increase the heat transfer coefficient of molten salt in pipe. In general, molten salt heat transfer in various tubes was investigated in some literature, but molten salt heat transfer outside the tube was seldom reported. In some molten salt steam generator [15] and molten salt heater, molten salt in the annular duct was used to heat the cold medium like water and steam inside the tube, and the heat transfer correlation of molten salt in annular duct was required to design this kinds of heat exchanger.

In the present paper, experimental measurements and analyses were conducted to study the heat transfer of molten salt in annular duct. The ternary molten salt $NaNO_2$–KNO_3–$NaNO_3$ was used as working medium to investigate the heat transfer coefficients of annular duct with different operating temperatures and flow velocities. Based on the experimental data and classical correlations of Wiegand correlation, Sieder–Tate correlation and Gnielinski equation, the modified correlations of transition and turbulent heat convection will be developed.

2. Experimental system and data analyses

2.1. System description

Fig. 1 illustrated the experimental facility including the testing unit, molten salt tank, molten salt pump, furnace, acquisition system and molten salt flow loop. The molten salt in the tank can be heated to 500 °C using eight electric heaters, and it can be reheated to 550 °C in the furnace. Before experiments, molten salt should be melted and heated to a prescribed temperature, and the whole molten salt flow loop should be warmed up to above 180 °C. After that, molten salt can be pumped through the flow meter into the testing section. The testing unit was a double pipe heat exchanger with the inner tube and annular duct. In the testing unit, high temperature molten salt flowed from the bottom to top, and water preheated by the heater in the water tank was pumped into the inner tube from the bottom. In the present experimental system, the molten salt flows in a circulation loop, while the water flows in an open loop.

Fig. 2 further illustrates the structure of the testing unit. The length of the whole double pipe exchanger was 1300 mm, and the outer tube had a diameter of 57 mm and wall thickness of 2 mm, while the inner one had a diameter of 19 mm and wall thickness of 2 mm. In order to reduce the entrance effect and outflow effect, the testing section only had the length of 750 mm, and six sections with equidistance of 150 mm were chosen along the flow direction. In every section, four K-type thermocouples were used to measure the temperatures of inner tube wall and bulk molten salt. In present article, the water/steam inside the tube was used as cooling media, and the molten salt heat transfer in the annular duct was studied in detail. Meanwhile, the double pipe exchanger was insulated to minimize heat loss. In this experiment, molten salt valves and bypass channel were used to obtain the different molten salt flow rates, and the inlet molten salt temperature was adjusted by temperature controller in the tank. The cooling boundary conditions of molten salt flow were affected by the inlet conditions of water. As the water flow rate increased or inlet water temperature decreased, the convective heat flux of molten salt increased with heat transfer temperature difference rising, while Nusselt number slightly decreased with the wall temperature and Pr/Pr_w dropping.

The mixed nitrate molten salt (KNO_3–$NaNO_2$–$NaNO_3$) as the heat transfer medium had a wide operating temperature region (200°C–550 °C) and good thermal stability. The thermal properties of molten salt were correlated from experiments as [14]:

$$\rho\left(\text{kg m}^{-3}\right) = 2085 - 0.74T(°\text{C}) \tag{1a}$$

$$c_p\left(\text{J kg}^{-1}\ \text{K}^{-1}\right) = 1549 - 0.15T(°\text{C}) \tag{1b}$$

$$\lambda\left(\text{W m}^{-1}\ \text{K}^{-1}\right) = 0.649 - 0.00046T(°\text{C}) \tag{1c}$$

$$\mu\left(\text{gm}^{-1}\ \text{s}^{-1}\right) = 31.59 - 0.1948T(°\text{C}) + 0.000425T(°\text{C})^2 - 0.0000003133T(°\text{C})^3 \tag{1d}$$

$$Pr = \mu c_p/\lambda \tag{1e}$$

2.2. Data analyses

The section area and hydraulic diameter of annular duct can be calculated as:

$$S = \frac{\pi}{4}\left(D^2 - d^2\right) \tag{2a}$$

$$D_h = \frac{4S}{P} = D - d \tag{2b}$$

where D, d mean the outer and inner diameter of annular duct, and $P = \pi(D + d)$ mean wetting circumference.