International Communications in Heat and Mass Transfer 36 (2009) 912–916

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Turbulent convective heat transfer with molten salt in a circular pipe ☆

Liu Bin, Wu Yu-ting *, Ma Chong-fang, Ye Meng, Guo Hang

Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100022, China

Key Laboratory of Heat Transfer and Energy Conversion, Beijing Municipality, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100022, China

ARTICLE INFO

Available online 30 June 2009

Keywords:
Molten salt
Forced convection
Heat transfer coefficient
Least-squares method

ABSTRACT

In order to understand the heat transfer characteristics of molten salt and testify the validity of the well-known empirical convective heat transfer correlations, an experimental study on turbulent convective heat transfer with molten salt in a circular tube was conducted in this paper. Molten salt circulations were realized and operated in a specially designed system over 1000 h. The flow rates and temperatures of molten salt and mineral oil at the inlet and outlet in the test section were measured and the average forced convective heat transfer coefficients of molten salt were determined by least-squares method. Finally, heat transfer correlations of turbulent flow with molten salt in a circular tube were obtained. Good agreement was observed between the experimental data of molten salt and the existing well-known correlations. The experimental data of molten salt in the present work are consistent with experimental results reported by different references in a wide range of Prandtl numbers from 0.7 to 59.9.

1. Introduction

Turbulent convection heat transfer in pipes exists in heat exchangers of nearly all branches of process industries. Many experimental studies have been made to investigate the turbulent convection heat transfer with different working fluids. One of the earliest equations used for fully developed turbulent flow in a smooth tube is the so-called Dittus–Boelter equation (Dittus and Boelter [1]), given by McAdams [2] as

$$Nu = 0.023Re^{0.8}Pr^{n} \tag{1}$$

where $n=0.4$ and $n=0.3$ for fluid heating and cooling respectively. This equation was based on experimental data covering the Prandtl numbers from 0.7 to 120, Reynolds numbers from 10,000 to 120,000, and $l/d>60$. Another well-known equation was presented by Colburn [3]:

$$StPr^{2/3} = 0.023Re^{-0.2} \quad \text{or} \quad Nu = 0.023Re^{0.8}Pr^{1/3}. \tag{2a, b}$$

Eqs. (1) and (2) are identified with each other except a small difference in the Prandtl exponent. For situations involving a large property variation, the Sieder and Tate [4] equation is recommended:

$$Nu = 0.027Re^{0.8}Pr^{1/3}\left(\frac{\mu_b}{\mu_w}\right)^{0.14}. \tag{3}$$

This equation is applicable for $0.7<\mathrm{Pr}<16{,}700$, $\mathrm{Re}>10{,}000$ and $l/d>60$ (smooth pipes).

The above correlations are relatively simple, but they give maximum errors of $\pm 25\%$ in the range of Prandtl numbers between 0.67 and 100. A more accurate correlation, which is also applicable for rough ducts, has been developed by Petukhov [5]:

$$Nu = \frac{RePr}{X}\left(\frac{f}{8}\right)\left(\frac{\mu_b}{\mu_w}\right)^{n} \quad \text{where } X = 1.07 + 12.7\left(Pr^{1/3}-1\right)\left(\frac{f}{8}\right)^{1/2} \tag{4a, b}$$

and $n=0.11$ for liquid heating with uniform T_w ($T_w>T_b$), $n=0.25$ for liquid cooling with uniform T_w ($T_w<T_b$) and $n=0$ for uniform wall heat flux or gases. Eq. (4) is applicable for fully developed turbulent flow in the range of Reynolds numbers between 10^4 and 5×10^6 and μ_w/μ_b between 0.08 and 40, with 5–6% error for Prandtl numbers between 0.5 and 200 and with 10% error for Prandtl numbers between 0.5 and 2,000. We note that $\mu_w/\mu_b<1$ when a liquid is heated and $\mu_w/\mu_b>1$ when the liquid is cooled. All physical properties, except μ_w, are evaluated at the average bulk temperature. The friction factor f in Eq. (4) can be evaluated by Eq. $f=(1.82\log\mathrm{Re}-1.64)^{-2}$ for smooth tubes or obtained from the Moody chart [6] for both smooth and rough tubes. Among the four heat transfer correlations given above, the Petukhov equation is the most up-to-date correlation that is applicable for both smooth and rough tubes, and it appears to correlate experimental data very well over a wide range of parameters.

Besides the above four correlations for turbulent flow, Hausen [7] developed another correlation based on experimental data collected

☆ Communicated by P. Cheng and W.Q. Tao.

* Corresponding author.
E-mail address: wuyuting@bjut.edu.cn (W. Yu-ting).

0735-1933/$ – see front matter
doi:10.1016/j.icheatmasstransfer.2009.06.003

Nomenclature

A	heat transfer area, (m^2)
C, c	constant
c_p	specific heat, (kJ/(kg K))
d	diameter, (m)
f	friction factor
h	heat transfer coefficient, (W/(m^2 K))
k	thermal conductivity, (W/(m K))
l	length, (m)
m	mass flow rate, (kg/s)
Nu	Nusselt number (hl/k)
Pr	Prandtl number (υ/a)
Q	heat transfer capacity, (W)
Re	Reynolds number ($\nu l/\upsilon$)
St	Stanton number ($h/\rho\nu c_p$)
T	temperature, (K)
ΔT	logarithmic mean temperature difference, (K)
v	velocity, (m/s)
U	overall heat transfer coefficient, (W/(m^2 K))

Greek symbols

α	thermal diffusivity of molten salt, (m^2/s)
λ	thermal conductivity, (W/(m K))
μ	dynamic viscosity, (Pa s)
υ	kinematic viscosity, (m^2/s)
ρ	density, (kg/m^3)

Subscripts

b	bulk parameters
i	inlet parameters
j	the fitting number
o	outlet or oil parameters
w	wall

Superscripts

m	exponent of Prandtl number
n	exponent of Reynolds number

by Sieder and Tate [4]. This correlation is valid both for fully developed turbulent flow and transition flow of different liquids (water, oil, gasoline, kerosene and acetone). The equation can be written as:

$$Nu = 0.037\left(Re^{0.75} - 180\right)Pr^{0.42}\left[1 + (d/l)^{2/3}\right](\mu_b/\mu_w)^{0.14}. \tag{5}$$

The above correlations cover a wide range of Reynolds numbers from 2300 to10^6 and Prandtl numbers from 0.6 to 1,000.

Gnielinski [8] developed a new correlation based on experimental data from open literature in 1976:

$$\text{For liquids}: \quad Nu = 0.012\left(Re^{0.87} - 280\right)Pr^{0.4}\left[1 + \left(\frac{d}{l}\right)^{2/3}\right]\left(\frac{Pr_f}{Pr_w}\right)^{0.11} \tag{6}$$

which covers $2300<Re<10^6$ and $0.6<Pr<10^5$.

All the above correlations have been widely verified by a lot of experimental data of different working fluids. However, the validity of the correlations has not been verified with the experimental data of molten salt. To the best knowledge of the present authors, the experimental data of convective heat transfer coefficients with molten salt have never been reported in open literature. Proper heat transfer data with molten salt may be obtained only from the report about Solar Two project. Three data points of overall heat transfer coefficients from nitrate molten salts to water/steam were presented in the reference [9].

On the other hand, more and more attraction in engineering practice was drawn on the heat transfer and thermal storage with molten salt due to the recent rapid development of solar thermal electricity. The present work provides the experimental data of turbulent molten salt flow in a circular tube. These experimental results fill the gap of heat transfer database with molten salts. Comparison was made between the present experimental data and widely recognized heat transfer empirical correlations. The validity of the heat transfer correlations was testified by the present data of molten salt.

2. Experimental apparatus and working fluids

The schematic diagram of experimental system is shown in Fig. 1. A specially designed test section consists of two stainless steel concentric tubes in which a high temperature molten salt stream flowing inside the inner tube is cooled by a low temperature mineral oil stream flowing in the outer tube. The diameter of the outer tube is 34 mm while the inner tube is 20 mm. The tubes are 1,000 mm long and 2 mm thick. The outer tube surface was wrapped with insulation to minimize heat loss to the surroundings. The system contains molten salt circulation and mineral oil circulation. The main parts of the two cycles are molten salt tank, high temperature molten salt pump, concentric tube test section, super constant temperature oil trough, oil cooler and oil pump. The whole experimental system is 14.5 m in length, 4 m in height and has 400 kg molten salt in it.

Before molten salt was pumped from the storage tank to the pipeline, it was very necessary to warm up the whole molten salt flow loop. The molten salt of storage tank was heated using an electric heater. Reaching a prescribed temperature, molten salt pump started to circulate the molten salt in the cycle. Two mass flow meters were installed to measure the flow rates of the molten salt stream and the mineral oil stream. Four mixed chambers were designed and installed at the inlet and outlet of the test section. The inlet and outlet temperatures of the molten salt and mineral oil were measured using PT100 thermocouples with accuracy of 0.2 °C. To obtain the different flow rates of molten salt, a frequency converter was installed to control the molten salt pump. All the fluid properties were assessed at the mean temperature of the fluids (average of inlet and outlet temperatures). The overall heat transfer coefficient from molten salt to mineral oil in the test section can be obtained by measuring the temperature of four points (oil inlet, oil outlet, molten salt inlet and molten salt outlet) and the heat loss of test tube.

Molten salt ($LiNO_3$) was chosen as the working fluid in our experimental investigation, because $LiNO_3$ has the lower melting temperature (254 °C) and higher boiling temperature (601 °C). It has a

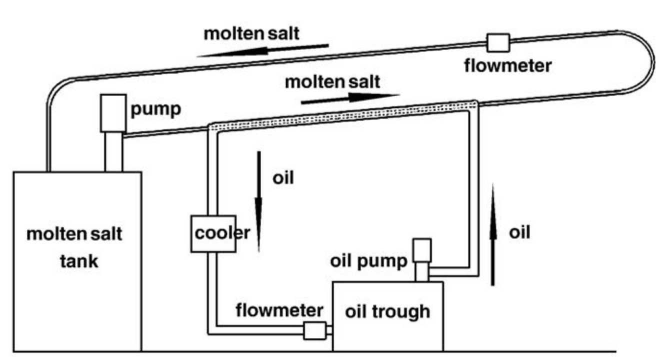

Fig. 1. Experimental system for forced convection heat transfer with molten salt.