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Convective heat transfer in the laminar–turbulent transition region with molten salt in a circular tube

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A B S T R A C T

In order to understand the heat transfer characteristics of molten salt and testify the validity of the well-known empirical convective heat transfer correlations, experimental study on transition convective heat transfer with molten salt in a circular tube was conducted. Molten salt circulations were realized and operated in a specially designed system over 1000 h. The average forced convective heat transfer coefficients of molten salt were determined by least-squares method based on the measured data of flow rates and temperatures. Finally, a heat transfer correlation of transition flow with molten salt in a circular tube was obtained and good agreement was observed between the experimental data of molten salt and the well-known correlations presented by Hausen and Gnielinski, respectively.

1. Introduction

Below Reynolds numbers of about 2000 the heat transfer results will be laminar, and above 10,000 the results will normally be fully developed turbulent. In between, the results will be in transition. Heat transfer results are uncertain in the transition region because of the large number of parameters which determine when and how the transition occurs.

Many experimental studies have been made to investigate the transition convection heat transfer with different working fluids. Hausen [1] developed a correlation based on experimental data collected by Sieder and Tate [2] in 1959. 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:

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

The above correlation covers a wide range of Reynolds number from 2300 to 10^6 and Prandtl number from 0.6 to 1000.

Gnielinski [3] developed a new correlation based on experimental data from open literature in 1976:

For liquids :

$$Nu = 0.012(\mathrm{Re}^{0.87} - 280)\mathrm{Pr}^{0.4}\left[1 + \left(\frac{d}{l}\right)^{2/3}\right]\left(\frac{\mathrm{Pr}_f}{\mathrm{Pr}_w}\right)^{0.11} \tag{2}$$

This equation covers 2,300 < Re < 10^6 and 0.6 < Pr < 10^5.

Hausen correlation and Gnielinski correlation have been widely testified 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 was little in open literature. Oak Ridge National Laboratory had made a continuing investigation into the heat transfer characteristics of molten salts from 1952 to 1960 and obtained the convective heat transfer coefficients with LiF–NaF–KF [4] and $NaNO_3$–KNO_3–$NaNO_2$ eutectic mixture [5].

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. Sponsored by Ministry of Sciences & Technology and National Natural Science Foundation of China, scientific research of thermal fluid science with molten salt has been conducted since 2003 at the Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Ministry of Education in Beijing University of Technology. The goal of the research is to characterize the convective heat transfer of molten salt with or without phase change. Investigation was also made for the preparation of molten salts mixture and determination of thermal physical properties. First paper on turbulent heat transfer coefficients in duct with molten salts had been accepted by International Communication in Heat and Mass Transfer. As the second formal scientific report, the present work provides the experimental data of transition convective heat transfer with molten salt in a circular tube. Comparison was made between the present experimental data and widely recognized heat transfer empirical correlations. The validity of the heat transfer correlations were testified by the present data of molten salt. It

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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, vl/υ
T	temperature, K
$\triangle T$	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

is hoped that the research project can provide useful information both in academic and technological aspects.

2. Experimental apparatus and working fluids

The schematic diagram and picture of experimental system are shown in Figs. 1 and 2, respectively. 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 1000 mm long and 2 mm thick. The outer tube surface was wrapped with insulation to minimize heat loss to 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 has 14.5 m in length, 4 m in height and 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 to a prescribed temperature, molten salt pump was 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 rate of molten salt, a frequency converter was installed to control the molten salt pump. All the fluids 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

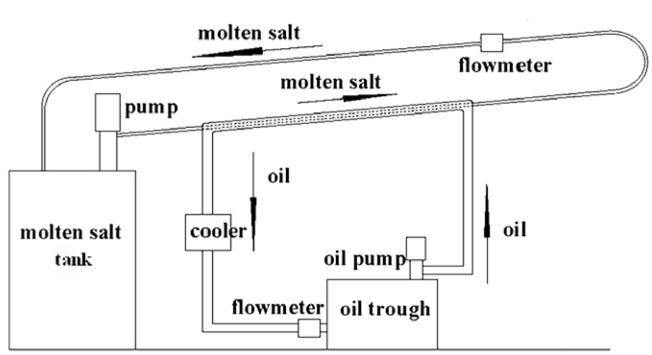

Fig. 1. Experimental system configuration schematic for forced convection heat transfer with molten salt.

Fig. 2. Experimental system picture for forced convection heat transfer with molten salt.