Transient Forced Convection Heat Transfer for Helium Gas Flowing Over a Horizontal Plate

Qiusheng LIU**, Makoto SHIBAHARA** and Katsuya FUKUDA**
**Graduate School of Science and Technology, Kobe University,
5-1-1, Fukaeminami, Higashinada, Kobe, Hyogo, Japan
E-mail: qsliu@maritime.kobe-u.ac.jp

Abstract
Transient heat transfer coefficients for helium gas flowing over a horizontal plate (ribbon) were measured under wide experimental conditions. The platinum plate with a thickness of 0.1 mm was used as test heater and heated by electric current. The heat generation rate was exponentially increased with a function of \( Q_0 \exp(t/\tau) \). The gas flow velocities ranged from 4 to 10 m/s, the gas temperatures ranged from 313 to 353 K, and the periods of heat generation rate, \( \tau \), ranged from 50 ms to 17 s. The surface superheat and heat flux increase exponentially as the heat generation rate increases with the exponential function. It was clarified that the heat transfer coefficient approaches the quasi-steady-state one for the period \( \tau \) longer than about 1 s, and it becomes higher for the period shorter than around 1 s. The dependence of transient heat transfer on the gas flowing velocity becomes weaker when the period becomes very shorter. The gas temperature in this study shows little influence on the heat transfer coefficient. An empirical correlation for quasi-steady-state heat transfer was obtained based on the experimental data.

Key words: Transient Heat Transfer, Forced Convection, Helium Gas, Period, Horizontal Plate, HTGR

1. Introduction
Transient forced convection heat transfer accompanying exponentially increasing heat input to a heater is important as a database for safety assessment of the transient heat transfer process in a high temperature gas cooled reactor (HTGR) due to an accident in excess reactivity\(^1\), \(^2\), \(^3\), \(^4\).

Concerning the problem of transient heat transfer with exponentially increasing heat generation rate \( (Q = Q_0 \exp(t/\tau), \) here, \( Q \) is heat generation rate, \( Q_0 \) is initial heat generation rate, \( t \) is time, and \( \tau \) is period of heat generation rate), there are only a few analytical and experimental works as far as the authors know. Soliman et al.\(^5\) analytically obtained a temperature change in plate by taking into account the turbulent boundary layer around the plate. However, the solution of heat transfer coefficient for water is 50% higher than their experimental data. Kataoka et al.\(^6\) conducted the transient experiment of water which flows in parallel to a cylinder, and obtained an empirical correlation for the ratios between the transient heat transfer coefficient and steady state one in term of one nondimensional parameter composed of period, velocity, and heater length. Liu and Fukuda \(^3\), \(^4\), \(^7\) obtained the experimental data and correlation for both parallel flow and cross-flow of helium gas over a horizontal cylinder. However, the experimental data were limited to a...
cylinder for the parallel flow, and limited to a low-Reynolds number region for the cross flow.

The above previous researches have not resulted in a correlation with reliability based on physical model. Moreover, there is almost no experimental research on transient forced convection heat transfer process for helium gas flowing over various shapes of heating elements such as a plate, and there are no detailed knowledge on the effects of the period of heat generation rate, the flow velocity, the gas temperature, and the shape of a test heater on the transient heat transfer for helium gas.

In this research, the forced convection transient heat transfer of helium gas flowing over the horizontal plate was experimentally studied at various periods of heat generation rate added to the heater exponentially. The purposes of this study are to obtain the experimental data of transient heat transfer coefficient at various periods, velocities, and gas temperatures; then to clarify the effects of period, velocity, and temperature on the transient heat transfer.

2. Nomenclature

\[ c_h \text{ specific heat of test heater, J/(KgK)} \]
\[ h \text{ heat transfer coefficient, W/m}^2\text{K} \]
\[ L \text{ effective length of heater, m} \]
\[ Nu \text{ Nusselt number, hL}/\lambda \]
\[ Pr \text{ Prandtl number} \]
\[ Q \text{ heat generation rate per unit volume, W/m}^3 \]
\[ Q_0 \text{ initial heat generation rate per unit volume, W/m}^3 \]
\[ q \text{ heat flux, W/m}^2 \]
\[ Re \text{ Reynolds number}, \text{ UL}/\nu \]
\[ T \text{ temperature, K} \]
\[ \Delta T \text{ temperature difference between wall and gas, K} \]
\[ t \text{ time, s} \]
\[ U \text{ velocity of gas} \]
\[ \delta \text{ heater thickness, m} \]
\[ \rho_h \text{ density of test heater, kg/m}^3 \]
\[ \lambda \text{ thermal conductivity, W/mK} \]
\[ \nu \text{ kinematic viscosity, m}^2/\text{s} \]
\[ \tau \text{ period of heat generation rate, s} \]
\[ \tau^* = \tau U/L \text{, nondimensional parameter} \]

Subscripts

\[ st: \text{ quasi-steady state} \]
\[ tr: \text{ transient} \]

3. Experimental Apparatus

3.1 Schematic Diagram of Experiment Apparatus

Experiment apparatus was reported in previous papers\(^{(3),(4)}\). Figure 1 shows the schematic diagram of the experiment apparatus. The experiment apparatus is composed of gas compressor (2), flow meter (5), test section (6), surge tank (3), (8), cooler (7), the heat input control system, and the data measurement and processing system. The vacuum pump was used to degas the loop and test section. The gas was circulated by compressor, and the
fluctuations of gas flowing and pressure due to compressor were removed with the surge tanks. Moreover, the gas inside the loop was heated to the desired temperature level by a preheater, and cooled by a cooler before the gas flows into the compressor. Flowing rate in the test section was measured with the turbine meter, and the pressure was measured with the pressure transducer. The temperature of the turbine meter exit and the temperature near test section heater were measured by K-type thermocouples with a precision of ±1 K. Helium gas with a high purity of 99.9999% was used as the test fluid.

3.2 Test Section and Test Heater

Figure 2 shows a vertical cross-sectional view of test section. The test heater was mounted horizontally along the center part of the circular test channel, which is made of the stainless steel (20 mm in the inside diameter). Platinum plate (ribbon) with a thickness of 0.1 mm, and a width of 4.0 mm was used as the test heater. The test heater was 50 mm in length; the ends of it were connected to two copper plates with the same thickness, then connected to two copper electrodes. Two fine platinum wires (0.05 mm-dia.) were spot welded to the central parts of the plate as potential conductors. The effective length of the heater between the potential taps on which transient heat transfer was measured was 40 mm.

4. Experimental Method and Procedure

The platinum test heater was heated by direct current from a power source. The heat generation rates of the heater were controlled and measured by a heat input control system (8). The average temperature of test heater was measured by resistance thermometry using a
double bridge circuit including the test heater as a branch\(^9\). The test heater was annealed and its electrical resistance versus temperature relation was calibrated in water, and washed with a trichloroethylene liquid before using it in the experiment\(^8\),\(^9\). The heat flux of the heater is calculated by the following equation.

\[
q = \frac{\delta}{2} (Q - \rho_a c_h \frac{dT}{dt})
\]  

(1)

Where, \(\rho_a\), \(c_h\), and \(\delta\) are the density, specific heat, and thickness of the test heater, respectively. \(Q\) (W/m\(^3\)) is the internal heat generation rate (measurement value), \(T_a\) (K) is the average temperature of test heater (measurement value), \(q\) (W/m\(^2\)) is the heat flux on surface of test heater (calculated value).

Using the measured average temperature of the test heater, the test heater surface temperature was calculated from heat conduction equation of the plate by assuming the surface temperature around the test heater to be uniform.

When the experimental data were processed, the physical properties of the fluid were calculated based on the film temperature, which was the average temperature of the test heater surface temperature and the flowing gas temperature.

The experiments were carried out according to the following procedure. The helium gas was first filled to the test loop after the test loop was degassed by a vacuum pump. The working fluid was circulated by driving compressor. Flowing rate was sequentially lowered from maximum stream flow in stages. The regulation of the flowing rate was carried out by using the by-pass valves of the test section and the by-pass valve of the compressor. After the pressure was confirmed to be stable at each flow velocity in the loop, the electric current was supplied to the test heater, and the heat generation rate was raised exponentially, then the test heater surface temperature and the heat flux accompanying the passage of the time were measured.

The uncertainties of the measurements of the heat generation rate, the heat flux of the test heater, and the heater surface temperature are estimated to be \(\pm 1\%\), \(\pm 2\%\) , and \(\pm 1\) K, respectively\(^8\).

5. Experimental Result and Discussion

5.1 Experiment Conditions

The transient heat transfer experimental data were measured for the periods of heat generation rate ranged from 50 ms to 17 s and for the helium gas temperatures ranged from 313 to 353 K under a system pressure of around 500 kPa. The flow velocities ranged from 4 to 10 m/s, and the corresponding Reynolds numbers ranged from \(3.5 \times 10^3\) to \(9.5 \times 10^3\). The heat generation rate was raised with exponential function, \(Q = Q_0 \exp(t/\tau)\). Where, \(Q\) (w/m\(^3\)) is heat generation rate, \(Q_0\) (w/m\(^3\)) is initial heat generation rate, \(t\) (s) is time, and \(\tau\) (s) is period of heat generation rate. A smaller or shorter period means a higher increasing rate of heat generation.

5.2 Experimental Data of Transient Heat Transfer at Various Periods and Velocities

Figure 3 shows typical experimental data of the time-dependence of heat generation rate, \(Q\), surface superheat, \(\Delta T\), and heat flux, \(q\), at the heat generation rate increasing periods of (a) 8.68 s, (b) 735 ms, (c) 445 ms, and (d) 92 ms at flow velocity of 10 m/s (Reynolds number 9.5 \(\times 10^3\)) and gas temperature of 313 K. It is understood that the surface superheat and heat flux at each period increases exponentially as the heat generation rate increases exponentially. Heat transfer coefficient, \(h\), is defined as shown in the next
\[ h = \frac{q}{\Delta T} \]  

Figure 4 shows heat transfer coefficients versus times at periods of 92 ms and 8.7 s for gas temperatures of (a) 313 K, (b) 333 K, and (c) 353 K. The heat transfer coefficients approach constant values from higher initial values when the time passes over a certain time of about 4 to 5 times of the period \((t/\tau > 4-5)\). It was confirmed that the heat transfer coefficients approach asymptotic values similarly at all periods, velocities, and gas temperatures. These asymptotic values will be used as the transient heat transfer coefficients. The reproducibility of the measurement of the heat transfer coefficient was within \(\pm 1.5\%\) for twice measurements at the same experimental condition.
Fig. 3 The relation of $\dot{Q}$, $q$, $\Delta T$ with $t/\tau$ at the periods of (a) 8.68 s, (b) 735 ms, (c) 445 ms, and (d) 92 ms for the temperature of 313 K.
Fig. 4 Heat transfer coefficients with the increase of time at periods of 92 ms and 8.7 s for gas temperatures of (a) 313 K, (b) 333 K, and (c) 353 K.

Figure 5 shows the relation between the heat transfer coefficients and the periods of heat generation rate at a gas temperature of 333 K. The heat transfer coefficient, $h$, becomes to approach asymptotic value at every velocity when $\tau$ is longer than about 1 s. The heat
transfer process in this region transmits heat as well as usual convective heat transfer through the thermal boundary layer influenced by the flow of helium gas. It is called the quasi-steady-state heat transfer here. On the other hand, when the period \( \tau \) is shorter than about 1 s, \( h \) increases as \( \tau \) shortens. This shows that the heat transfer process is in the unsteady state. In the case of extremely shorter period (\( \tau < 100 \) ms), the conductive heat transfer near the heater comes to govern the heat transfer process, and the heat transfer coefficient increases greatly with shorter period in this region. It was clarified that the heat transfer phenomenon was divided into a quasi-steady-state heat transfer and a transient heat transfer on the boundary of around 1 s. The coefficient of heat transfer increases with the flow velocity as shown in the Fig.5.

Figure 6 shows the transient heat transfer coefficients at various temperatures at a definite velocity of 10 m/s. The heat transfer coefficient at 353 K is 4% to 6% higher than that at 313 K. It is considered that the gas temperature in the range of this study shows little influence on the heat transfer coefficient. However, at high temperature condition such as normal operation temperature of HTGR, the temperature is as high as 1000 K, the effect of temperature on heat transfer coefficient might become large because of the changes in the thermal physical properties. This needs further investigation.

5.3 Nusselt Numbers for Quasi-Steady-State and Transient (Unsteady State) Heat Transfer at Various Velocities and Periods

Figure 7 shows the relation between the Nusselt numbers and the Reynolds numbers for the periods ranging from 1.762 s to 17.29 s at gas temperatures of (a) 333 K, and (b) 353 K on \( Nu_\alpha \) versus \( Re \) graphs. As shown in the figures, for the periods longer than about 1 s, the Nusselt numbers are not influenced by the period, but increase with flow velocity.

The data can be correlated by the following empirical equation by the method of least squares. It was shown by the dashed lines to compare with the experimental data.

\[
Nu_\alpha = 1.24 Re^{0.5} Pr^{1/3}
\]  

(3)

Where, \( Nu = hL/\lambda \), \( Re = UL/\nu \), \( h \) (W/m\(^2\)K) is heat transfer coefficient, \( L \) (m) is effective length of the heater, \( \lambda \) (W/mK) is thermal conductivity of helium gas, \( U \) (m/s) is flow velocity, and \( \nu \) (m\(^2\)/s) is kinematic coefficient of viscosity of helium gas. The Prandtl number \( Pr \) is about 0.68 in the range of this experiment. The values calculated by the correlation\(^{(10)}\), Eq.(4), for an infinite flat plate at the case of uniform heat flux are shown in

![Fig.6 Heat transfer coefficients at various gas temperatures.](image-url)
the Fig. 7(a) for comparison. They are 35% lower than the values given by Eq.(3). The plate used in this experimental has a finite width of 4 mm, and the correlation given by Eq.(4) was obtained based on an analytical solution on the infinite plate. It is considered the disagreement between Eq.(3) and Eq.(4) arises from the difference in the width of plate.

\[
\text{Nu}_\text{a} = 0.916 \text{Re}^{0.5} \text{Pr}^{1/3}
\]  

(4)

On the other hand, as shown in Fig.8 for the periods under about 1 s, the Nusselt numbers are affected both by the period and the flow velocity. They approach asymptotic values in the quasi-steady-state heat transfer for the periods longer than about 1 s (dashed lines, Eq.(3)). The effect of flow velocity becomes weak for shorter periods by decreasing the gradient of the data in the graphs. The solid lines are the values by correlations for each period if they are correlated by the method of least squares.

As mentioned in the Introduction, Liu et al.\(^{(4)}\) carried out an experiment on the transient heat transfer of helium gas flowing across a horizontal cylinder at low Reynolds number region, and obtained an empirical correlation of the ratio of transient Nusselt number to the
Fig. 8 Transient heat transfer at various periods and Reynolds numbers for the gas temperatures of (a) 313 K, (b) 333 K, and (c) 353 K.
quasi-steady-state Nusselt number using a dimensionless period of \( \tau^* \) \((\tau^* = \tau U/L, U \text{ is flow velocity, and } L \text{ is characteristic length})\). It is considered that the present experimental data can be also correlated using the dimensionless period, \( \tau U/L \).

Figure 9 shows the ratios of transient Nusselt number, \( \text{Nu}_t \), to quasi-steady-state Nusselt number, \( \text{Nu}_q \), with the dimensionless period, \( \tau U/L \), at various periods, velocities and gas temperatures. It can be seen from Fig.9, the ratios of \( \text{Nu}_t \) to \( \text{Nu}_q \) decrease to unity as the nondimensional period increases. The transient heat transfer approaches quasi-steady-state one for the nondimensional period larger than about 300. The heat transfer shifts to the quasi-steady-state heat transfer for longer period and shifts to the transient heat transfer for shorter period at the same flow velocity. The transient heat transfer approaches the quasi-steady-state one for higher flow velocity at the same period.

6. Conclusions

The forced convection transient heat transfer coefficients for helium gas flowing over a horizontal plate (ribbon) were measured using an exponentially increasing heat input. It was clarified that the heat transfer coefficient approaches the quasi-steady-state one for the period over about 1 s, and it becomes higher for the period of shorter than about 1 s. The conductive heat transfer becomes predominant for the period less than about 1 s, though the transient heat transfer is influenced by both convection and the conductive heat transfer in the quasi-steady-state heat transfer region for the period larger than about 1 s. The gas
temperature in this study shows little influence on the heat transfer coefficient. The ratios of transient Nusselt number, $N_{ut}$, to quasi-steady-state Nusselt number, $N_{ust}$, at various periods, flow velocities, and gas temperatures were obtained. The heat transfer shifts to the quasi-steady-state heat transfer for longer periods and shifts to the transient heat transfer for shorter periods at the same flow velocity. It also approaches the quasi-steady-state one for higher flow velocity at the same period. The correlation of quasi-steady-state heat transfer for the plate is obtained based on the experimental data.

References