Transient Heat Transfer for Forced Convection Flow of Helium Gas*

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The knowledge of forced convection transient heat transfer at various periods of exponential increase of heat input to a heater is important as a database for understanding the transient heat transfer process in a high temperature gas cooled reactor (HTGR) due to an accident in excess reactivity. The transient heat transfer coefficients for forced convection flow of helium gas over a horizontal cylinder were measured using a forced convection test loop. The platinum heater with a diameter of 1.0 mm was heated by electric current with an exponential increase of $Q_0 \exp(t/\tau)$. It was clarified that the heat transfer coefficient approaches the quasi-steady-state one for the period τ over 1 s, and it becomes higher for the period of τ shorter than 1 s. The transient heat transfer shows less dependent on the gas flowing velocity when the period becomes very shorter. Semi-empirical correlations for quasi-steady-state and transient heat transfer were developed based on the experimental data.

Key Words: Transient Heat Transfer, Forced Convection, Nuclear Reactor, HTGR, Helium Gas, Exponentially Increasing Heat Generation, Period

1. Introduction

The high temperature gas cooled nuclear reactor (HTGR) using helium gas can supply heat with high temperature up to about 1 000°C, and enables achievements of high thermal efficiency and high efficiency of heat utilization. The high grade heat supplied from the HTGR is applicable to the manufacture of synthetic gas (such as hydrogen, methanol), steam turbine power generation, etc. in many stages, and the heat can be used at a very high efficiency exceeding 80%^{(1),(2)}. Utilization of HTGR will also be expected to perform a great contribution in the future to the construction of clean secondary energy system using hydrogen^{(1),(2)}. However, some engineering problems, which should be solved, are still left in the development of HTGR, and the accumulation of fundamental research is necessary.

The transient forced convection heat transfer process with exponentially increasing heat input is

important associated with accident analysis for nuclear reactors. The transient heat transfer has not been solved though many analytical solutions and experimental were reported concerning the steady state heat transfer. The following theoretical researches were carried out on transient convection heat transfer when the wall temperature of test heater rises in the shape of a step. In 1960, Siegel⁽³⁾ analyzed the transient heat transfer for laminar flows in parallel plate and tube when the surface temperature of wall varied in step changes. He also obtained analytical solution on the change of heat transfer. Then, Sparrow et al.⁽⁴⁾ and Goodman⁽⁵⁾ analyzed the transient heat transfer for turbulent flow in a tube. In these works, the transient heat transfer was analyzed for step changes in wall temperature; there was no verification by experiment data.

Concerning the problem of transient heat transfer with exponentially increasing heat generation rate ($\dot{Q} = Q_0 \exp(t/\tau)$, here, $\dot{Q}$ is heat generation rate, Q_0 is initial heat generation rate, t is time, and τ is period of heat generation rate), there are only a few analytical and experimental works as far as the authors know. Soliman et al.⁽⁶⁾ analytically obtained a temperature change in plate by taking into account the

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turbulent boundary around the plate. However, the solution of heat transfer coefficient for water is 50% higher than their experimental data. Kataoka et al.⁽⁷⁾ conducted the transient experimental of water which flows in parallel with 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.

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 a heating element with exponentially increasing heat generation rate, and there are no detailed knowledge on the effects of the period of heat generation rate and the flow velocity on the transient heat transfer for helium gas.

In this research, the case where the reactor power rises in the exponential function by the reactivity excess is assumed in the helium-cooled nuclear reactor. The forced convection transient heat transfer of helium gas flowing parallel to the horizontal cylinder heater was experimentally studied at various periods of heat generation rate added to the heater exponentially. The purposes of this study are: first, to obtain the experimental data of transient heat transfer coefficient at various periods and velocities, second, to clarify the effect of period and velocity on the transient heat transfer, third, to derive a correlation based on the experimental data.

2. Experimental Apparatus

2.1 Schematic diagram of experiment apparatus

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

1. Gas cylinder 2. Compressor 3. Delivery surge tank 4. Filter 5. Turbine flow meter 6. Test section 7. Cooler 8. Suction surge tank 9. Vacuum pump 10. Thermocouple 11. Pressure indicator

Fig. 1 Schematic diagram of experimental apparatus

used to degas the loop and test section. The gas circulates by compressor, and the fluctuations of gas flowing and pressure due to compressor are removed with the surge tank. Moreover, the gas temperature inside the loop was cooled with the cooler, and the gas temperature was kept constant. 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 chromel-alumel thermocouples with a precision of ± 1 K.

2.2 Test section and test heater

Figure 2 shows a vertical cross-sectional view of test section. The test section was mounted horizontally along the center part of the circular test channel, which is made of the stainless steel (10.7 mm in the inside diameter). Platinum cylinder with the diameter of 1.0 mm was used as the test heater. The test heater was 109.4 mm in length; it was connected to the copper electrode by which the support combined. 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.

2.3 Heat input control system

The heat input control system is almost the same as that used by Sakurai et al.⁽⁸⁾ The amplifier gain of each circuit in the heat input system and the shape of waves of the input heat generation rate and the current interception for upper limited temperatures can be set with the personal computer through the analog to digital (A/D) converter. Changeable low-voltage power supply is used as the power supply for heating. Heat generation rates of the test heater are calculated by the analogue computer, they are compared with a corresponding reference signal to the demand heat generation rate. The voltages of these signals are amplified, and the signal of heat generation rate is fed back to the amplifier to minimize the difference with the reference signal. Moreover, the temperature of the test heater is calculated by the analogue computer, when the temperature and heat generation rate of the test heater reaches the values set before, the current of the power supply is instantaneously intercepted.

Fig. 2 Test section

Fig. 3 Double-bridge circuit for the data measurement

2.4 Measurement and data processing system

Figure 3 shows the double bridge circuit used for the measurement. It is involved in the heat input control system. The test heater is a branch of the double bridge circuit. Electric equilibrium was taken at the temperature of the fluid at each experiment before the experiment beginning. When the experiment starts, the electric current, I , flows through the test heater, and the temperature of the test section rises, then the double bridge circuit becomes non-equilibrium. The output voltages of the bridge, V_T , together with the voltage of drops across the potential taps of the heater, V_R , across the standard resistance, V_I , and gas temperature signal from the thermocouple at test section, V_L , are amplified and passed to the analog-to-digital converter of a digital computer. The data was processed by the computer. The A/D converter is 12 bit A/D (synchronization 20 μ s/4CH of sampling simultaneously, 5 μ s of conversion time for one channel).

The resistance of the test heater under the measurement is given by the next equation.

$$R_x = \frac{R_1 R_3 + V_T (R_3 + R_2) / I}{R_2} \quad (1)$$

The average temperature of the test heater is calculated from the previously calibrated resistance-temperature relation. The heat generation rate of the test heater is given by the next expression.

$$\dot{Q} = \left(V_R \frac{V_I}{R_s} \right) / V \quad (2)$$

The heat flux is calculated by the following equation.

$$q = \frac{D}{4} \dot{Q} - \rho_h c_h \frac{D}{4} \frac{dT_a}{dt} \quad (3)$$

Here, ρ_h , c_h , D , and T_a are the density, specific heat, diameter, and the average temperature of the test heater, respectively. The test heater surface temperature can be calculated from unsteady heat conduction equation of the next expression by assuming the surface temperature of the test heater to be the same.

For the cylindrical test heater,

$$\frac{\partial T}{\partial t} = a \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) + \frac{\dot{Q}}{\rho c} \quad (4)$$

Boundary conditions are as follows,

$$\begin{aligned} \frac{\partial T}{\partial r} \Big|_{r=0} &= 0, \quad -\lambda \frac{\partial T}{\partial r} \Big|_{r=R} = q \\ T_a &= \frac{\int_0^R T(2\pi r) dr}{\int_0^R (2\pi r) dr} = \frac{2}{R^2} \int_0^R T r dr \end{aligned} \quad (5)$$

Here

$\dot{Q}$: Internal heat generation rate (measurement value) (W/m³)

T_a : Average temperature of test heater (measurement value) (K)

q : Heat flux on surface of test heater (measurement value) (W/m²)

V : The volume of the test heater (m³)

a : Thermal diffusivity (m²/s)

λ : Thermal conductivity (W/mK)

When the experimental data were processed, the physical properties of the fluid were calculated based on the following film temperature, which was used as a temperature of the representative.

$$T_f = \frac{T_s + T_g}{2} \quad (6)$$

Here, T_s and T_g are the test heater surface temperature, and the flowing gas temperatures respectively.

3. Experiment Method

The experiments were carried out according to the following procedure. As a preliminary experiment, the relation between electric resistance of the test heater and the temperature was first measured in the thermostat using a precise double bridge, and the result was expressed by the following relation.

$$R = R_0(1 + \alpha T + \beta T^2) \quad (7)$$

Here, T is the averaged temperature, °C, R is the measured resistance at temperature of T_a , $m\Omega$, α and β are temperature coefficients which are 3.98×10^{-3} , 5.88×10^{-7} for high purity platinum respectively. In this experiment, the next expression was obtained from the measurement result.

$$R = 14.52(1 + 3.771915 \times 10^{-3} T - 0.5880 \times 10^{-6} T^2) \quad (8)$$

Next, the test heater was installed in the test section. The helium gas was filled to the test loop after the test loop was degassed by a vacuum pump. The working fluid was circulated by driving compressor. Flowing

Table 1 Experimental conditions

Fluid	Helium gas
Pressure	500 kPa
Fluid temperature	25 °C
Test heater diameter	1.0 mm
Heat generation period (τ)	50 ms–20 s
Velocity	3.0 m/s–38.8 m/s
Reynolds number	1.3×10^4 – 1.7×10^5

rate is 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.

4. Experiment Result and Discussion

4.1 Experiment conditions

The experimental conditions are shown in Table 1. The heat generation rate was raised with exponential function ($\dot{Q} = Q_0 \exp(t/\tau)$). Here, $\dot{Q}$: heat generation rate, W/m^3 , Q_0 : initial heat generation rate, W/m^3 , t : time, s, and τ : period of heat generation rate, s.

4.2 Time-dependence of heat generation rate, surface superheat, and heat flux

Figures 4 and 5 show the time-dependence of heat generation rate, surface superheat, and heat flux at the heat generation rate rising periods of 420 ms and 1.6 s respectively under flow velocity of 38.8 m/s (Reynolds number 1.66×10^5). It is understood that surface superheat and heat flux increase exponentially as the heat generation rate increases with the exponential function.

4.3 Heat transfer coefficient in the transient heat transfer process

Heat transfer coefficient of h is defined as shown in the next equation.

$$h = q / \Delta T \quad (9)$$

Figure 6 shows heat transfer coefficients versus time under a pressure of 500 kPa with flow velocity of 38.8 m/s at the periods of 1.6 s and 420 ms. The heat transfer coefficient approach constant values from a high initial value when the time passes over a certain

Fig. 4 The relation of, $\dot{Q}$, q , ΔT with t/τ at the period of 420 ms

Fig. 5 The relation of, $\dot{Q}$, q , ΔT with t/τ at the period of 1.6 s

Fig. 6 Heat transfer coefficient with the increase of time

time. It was understood that the heat transfer coefficients approach asymptotic values similarly at all periods. These asymptotic values will be used as the transient heat transfer coefficients.

4.4 Relation between heat transfer coefficient and the period of heat generation rate

Figure 7 shows the relation between the heat transfer coefficient and the period of heat generation rate at a surface superheat of 150°C. The heat transfer coefficient becomes constant when the period τ is

Fig. 7 Heat transfer coefficients at various periods

Fig. 8 Quasi-steady-state heat transfer at various Reynolds numbers

longer than 1 s, and the heat transfer process is almost in the quasi-steady-state in this area. On the other hand, The heat transfer coefficient increases when τ becomes shorter than 1 s. This shows that the heat transfer process is in the unsteady state, and the heat transfer in this area has received greatly the influence of the temperature gradient within temperature boundary. It is understood that the coefficient of heat transfer increases with flow velocity as shown in the figure.

4.5 Quasi-steady-state heat transfer

Figure 8 shows the relation between the Nusselt number and the Reynolds number for the periods ranging from 1.0 s to 20.0 s. They are shown on $Nu_f / Pr_f^{0.4}$ versus Re_f graph. The number of Pr_f is about 0.68 in the range of this experiment. The Nusselt number is not influenced by the period, and increases with flow velocity. The following empirical equation was obtained by the method of least squares. It was shown by the solid line in figure to compare with the experimental data.

Fig. 9 Transient heat transfer at various periods and Reynolds numbers

$$Nu_{st} = 3.0 Re_f^{0.5} Pr_f^{0.4} \quad (10)$$

$$\text{Here, } Nu_{st} = \frac{hl}{\lambda}, \quad Re_f = \frac{Ul}{\nu}$$

h (W/m²K) : heat transfer coefficient

l (m) : length of heater

λ (W/mK) : thermal conductivity of fluid

U (m/s) : flow velocity

ν (m²/s) : kinematic coefficient of viscosity of fluid

4.6 Transient (unsteady) heat transfer

Figure 9 shows the relation between the Nusselt number and the Reynolds number in the transient heat transfer. The short dashes line shows the data at the periods more than 1 s for the comparison. The Nusselt number is affected both by the period and flow velocity. It is asymptotic in the quasi-steady-state heat transfer for the periods longer than 1 s. The effect of flow velocity becomes weak for smaller periods by the decreasing of gradient of the data.

The following empirical formula can be obtained based on the experimental data.

$$Nu_{tr} = a Re_f^b Pr_f^{0.4} \quad (11)$$

Here, parameter a and b can be obtained as functions of τ .

4.7 Relation between Nu_{tr}/Nu_{st} and period

Figure 10 shows the ratio of transient Nu_{tr} and quasi-steady-state Nu_{st} at various periods with the flow velocity as a parameter. The transient heat transfer approaches the quasi-steady-state one for higher flow velocity at the same period. 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. The following empirical equation was obtained based on the experimental data. It was shown in the solid line in figure.

Fig. 10 Transient heat transfer and its correlation

Fig. 11 Transient heat transfer and its correlation correlated by dimensionless parameter $\tau U/l$

$$Nu_{tr} = Nu_{st} \{1 + 0.04 \tau^{-1.25}\} \quad (12)$$

As cited in the introduction, Kataoka et al.⁽⁷⁾ carried out an experiment on the transient heat transfer of water, and obtained an empirical correlation of the ratio of transient Nusselt number to the quasi-steady-state Nusselt number using a dimensionless parameter of $\tau U/l$. Where, τ is period, U is flow velocity, and l is characteristic length.

Our experimental data can be also correlated using the dimensional period, $\tau U/l$, as shown in Fig. 11, and we obtained the following correlation. It can be seen from Fig. 11, the ratios of Nu_{tr} to Nu_{st} decrease to unity as the nondimensional parameter, $\tau U/l$, increases. The transient heat transfer approaches quasi-steady-state one for the nondimensional parameter larger than about 300.

$$Nu_{tr} = Nu_{st} \{1 + 6.5(\tau U/l)^{-0.8}\} \quad (13)$$

5. Conclusions

The transient heat transfer coefficients for forced convection flow of helium gas over a horizontal cylinder were measured using a forced convection test loop. The platinum heater with a diameter of 1.0 mm was heated by electric current with an exponential increase of $Q_0 \exp(t/\tau)$. It was clarified that the heat transfer coefficient approaches the quasi-steady-state one for the period τ over 1 s, and it becomes higher for the period of τ shorter than 1 s. The transient heat transfer shows less dependent on the gas flowing velocity when the period becomes very smaller. Semi-empirical correlations for quasi-steady-state and transient heat transfer were developed based on the experimental data.

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