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Transient Heat Transfer for Forced Convection Flow of Helium Gas over a Horizontal Plate

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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 290 to 353 K, and the periods of heat generation rate, τ, 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 τ longer than about 1 s, and it becomes higher for the period shorter than around 1 s. Empirical correlation for transient heat transfer was also obtained based on the experimental data.

1. Introduction

The Advanced High Temperature Reactors (AHTR) are novel reactors that use helium gas or clean liquid fluoride salts as primary coolants for conventional graphite matrix, coated particle fuels [1]. The AHTR enables the achievements of high thermal efficiency and high performance of heat utilization because they can supply heat with a high temperature of about 1000 ^{o}C. Utilization of AHTR is expected as a clean energy supply source to produce hydrogen gas which is not accompanied by the exhaust of carbon dioxide. However, some engineering problems such as thermal hydraulic problems have not been solved in the development of AHTRs. In this research, we focused on a transient heat transfer problem.

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 [2], [3], [4], [5].

The transient heat transfer has not been solved though many analytical solutions and experiments were reported concerning the steady state heat transfer. 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 (a time needed for $\dot{Q}$ to increase e-fold)), 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 turbulent boundary around the plate. However, the solution for the heat transfer coefficient in water is 50% higher than their experimental data. Kataoka et al. [7] conducted a transient experiment with water which flows along 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] 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.

The present research concerns the operational case when the power of a helium-cooled nuclear reactor increases exponentially due to reactivity excess. 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. Experimental Apparatus and Method

2.1 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 temperature 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 uncertainty for the measurement of flow rate is $\pm 0.3\%$. 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.

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.

2.2 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]. This system is the same with that of Sakurai [9]. The heat generation rate and the temperature of test heater were calculated and then the heat generation rate was simultaneously controlled. The validity of this system was verified [8, 3, 10].

The average temperature of test heater was measured by resistance thermometry using a double bridge circuit including the test heater as a branch [8, 3, 10]. 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. The average temperature of the test heater was calculated from the previously calibrated resistance-temperature relation. In data processing, a personal computer was used. The unbalanced voltage of the double bridge circuit including the heater, and the voltage differences between the potential taps of the heater and across the standard resistance were fed to the personal computer through an analog-to-digital (A/D) converter[8]. The fastest sampling speed of the A/D converter was 5 μs/channel. All these calculations were carried out by the personal computer.

The heat flux of the heater is calculated by the following equation.

$$q = \frac{\delta}{2}(\dot{Q} - \rho_h c_h \frac{dT_a}{dt}) \quad (1)$$

Where, ρ_h, c_h, and δ are the density, specific heat, and thickness of the test heater, respectively. $\dot{Q}$ (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 following film temperature, which was used as a reference temperature.

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

Where, T_s and T_l are the test heater surface temperature, and the flowing gas temperature, respectively.

The uncertainties of the measurement of the heat generation rate, the heat flux of the test heater, and the heater surface temperature are estimated to be ±1%, ±2%, and ±1 K, respectively [8, 3, 10]. And the uncertainty for the obtained heat transfer coefficients is estimated to be ±2.5%.

The experiments were carried out according to the following procedure. The helium gas was first filled to the test loop after being 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.

3. Experimental Results and Discussion

3.1 Experimental Data of Heat Generation Rate, Surface Superheat, Heat Flux, and Transient Heat Transfer Coefficient

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 290 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 3.5×10^3 to 9.5×10^3. The heat generation rate was raised with exponential function, $\dot{Q} = Q_0 \exp(t/\tau)$. Where, $\dot{Q}$ is heat generation rate, w/m^3, Q_0 is initial heat generation rate, w/m^3, t is time, s, and τ is period of heat generation rate, s. A smaller or shorter period means a higher increasing rate of heat generation.

Figure 3 shows typical experimental data of the time-dependence of heat generation rate, $\dot{Q}$, surface superheat, ΔT, and heat flux, q, at the heat generation rate increasing periods of (a) 92 ms and (b) 735 ms at flow velocity of 10 m/s (Reynolds number 9.5×10^3) and gas temperature of 313 K. As shown in Fig.3, the surface superheat and heat flux increase exponentially as the heat generation rate increases exponentially.

Heat transfer coefficient, *h*, is defined by the following equation.

$$h = \frac{q}{\Delta T} \tag{3}$$

Figure 4 shows heat transfer coefficients versus times at periods of 92 ms and 8.68 s. The heat transfer coefficients approach constant values from higher initial values when the time passes over a certain time of about 4 times of the period ($t/\tau > 4$). 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.

Figures 5(a) and 5(b) show the relation between the heat transfer coefficient and the period of heat generation rate at gas temperatures of (a) 313 K and (b) 353 K. The heat transfer coefficient, h, becomes to approach asymptotic value at every velocity when τ is longer than about 1 s. The heat transfer in this region is mainly due to convection within 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 τ is shorter than about 1 s, h increases as τ shortens. This shows that the heat transfer process is in the unsteady state, and the heat transfer in this region has received greatly the influence of the temperature gradient within the thermal boundary layer around the plate. In the region of τ shorter than 200 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. Depending on the behaviour of the heat transfer coefficient, the range of the period τ can be subdivided into the two following subranges. The first subrange herein after referred as to the “transient” is observed when $\tau < 1$ s. Within this subrange the asymptotic value attained by the coefficient when the time tends to infinity can be sufficiently larger than that measured at steady state conditions. The second subrange $\tau \geq 1$ s corresponds to the case when the heat transfer coefficient is equal to the quasi-steady-state one. The coefficient of heat transfer increases with the flow velocity as shown in the Figs.5(a) and 5(b).

Figure 6 shows the transient heat transfer coefficients at various temperatures at a definite velocity of 10 m/s. The heat transfer coefficient at 333 K is 4% to 6% higher than that at 290 K. It is considered that the gas temperature shows little influence on the heat transfer coefficient.

In the above discussions, we did not discuss the contribution of natural convection heat transfer on the forced convection heat transfer. The natural convection heat transfer (heat flux) can be estimated by a correlation reported by Takeuchi et al.[11]. They are less than about 5.1% of the measured heat flux. On the other hand, the radiation contribution was also estimated less than 0.27% of the measured heat flux. Based on the estimations, the free convection and radiation effects are small and can be neglected in this research.

3.2 Correlation for Quasi-Steady-State Heat Transfer at Various Velocities

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. They are shown on Nu_{st} versus Re graph. As shown in the figure, for the periods longer than about 1 s, the Nusselt numbers are not influenced by the period, but increase with an increase in flow velocity. They can be correlated by the following empirical equation by the method of least squares within 3%. It was shown by the dashed lines to compare with the experimental data.

$$Nu_{st} = 1.24\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{1/3} \tag{4}$$

Where, $\mathrm{Nu}_{st} = hL/\lambda$, $\mathrm{Re} = UL/\nu$, h (W/m^{2}K) is heat transfer coefficient, L (m) is effective length of the heater, λ (W/mK) is thermal conductivity of helium gas, U (m/s) is flow velocity, and ν(m^2/s) is kinematic viscosity of helium gas. The Prandtl number Pr is about 0.68 in the range of this experiment.

The values calculated by the following correlation [12] for an infinite flat plate at the case of uniform heat flux are shown in the same figure for comparison. They are 35% lower than the values given by Eq.(4). The correlation given by Eq.(5) was derived by assuming a condition of constant heat flux on the surface of the plate with an infinite width. In the case of our research, the plate used in this experimental has a limited width of 4 mm. The thermal boundary layer developed on the heater surface with a limited width is considered to be somewhat different from that on an infinite plate. And a difference in the heat transfer coefficient should come from this difference. It is considered the disagreement between Eq.(4) and Eq.(5) arises from the difference in the thermal boundary layer between the limited plate with the infinite one.

$$Nu_{st} = 0.916\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{1/3} \tag{5}$$

3.3 Correlation for Transient Unsteady State Heat Transfer at Various Periods and Velocities

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. The effect of flow velocity becomes weak for shorter periods with decreasing gradient of the data in the graphs. The solid lines are the values of 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 quasi-steady-state one using a dimensionless period of τ^*($\tau^* = \tau$ U/L, U is flow velocity, and L is characteristic length). The present experimental data can be also correlated using the dimensionless period, τU/L, as shown in Fig.9, and we obtained the following correlation.

$$Nu_{tr} = Nu_{st}\{1 + 0.48(\frac{\tau U}{L})^{-0.6}\} \tag{6}$$

It can be seen from Fig.9, the ratios of Nu_{tr} to Nu_{st} 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.

3.4 Comparison of the Experimental Data of Plate with Authors' Data of Horizontal Cylinders

Figure 10 shows the quasi-steady state and transient heat transfer coefficients compared with those of authors' experimental data [13] measured on single horizontal cylinders with diameters of 0.7 mm, 1.0 mm, and 2.0 mm. The heat transfer coefficients are 14% higher than the data on horizontal cylinder with the diameter of 2.0 mm, and they are lower than the data on the 0.7 mm and 1.0 mm-diameter cylinders.

Figure 11 shows the experimental data for the plate and cylinders on the Nu_{st} versus Re graph. As shown in the figure, the Nusselt number decreases with an increase in diameter. The Nu number for the plate is lower than that of the cylinder. It is 25% lower than that of 2.0 mm-dia. cylinder. The correlation for 2.0 mm-dia. cylinder is $Nu_{st}=1.56Re^{0.5}Pr^{0.4}$, and the correlation for the plate is $Nu_{st}=1.24Re^{0.5}Pr^{1/3}$, as shown in the Figs. 7 and 8.

According to authors' experimental data[11], the heat transfer coefficient shows significant dependence on the size and the geometry (shape) of a heater (cylinder and plate). It is well known that the convective heat transfer coefficient is related to the thermal boundary layer imposed on the heater surface. The temperature gradient at the wall of heater depends on the flow field, and we must develop an expression relating the two dimensional quantities of heat transfer and flow. The difference in results for cylinders and ribbon is physically due to the difference in the thermal boundary layers developed on the cylinder and ribbon surfaces.

4. 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 τ over about 1 s, and it becomes higher for the period of τ shorter than about 1 s. The conductive heat transfer becomes predominant for the period less than about 1 s, especially in the region of less than 200 ms, 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 correlation of steady-state heat transfer for the plate is lower than that for horizontal cylinder. The empirical correlation of the transient forced convection heat transfer was obtained by the quasi-steady-state heat transfer and the dimensionless parameter, $\tau U/L$, based on the experiment data.

Nomenclature

c_h specific heat of test heater, J/(KgK)

h heat transfer coefficient, W/m^2K

L effective length of heater, m

Nu Nusselt number, hL/λ

Pr Prandtl number

$\dot{Q}$ heat generation rate per unit volume, W/m^3

Q_0 nitial heat generation rate per unit volume, W/m^3

q heat flux, W/m^2

Re Reynolds number, UL/ν

T temperature, K

ΔT temperature difference between wall and gas, K

t time, s

U velocity of gas

δ heater thickness, m

ρ_h density of test heater, kg/m^3

λ thermal conductivity, W/mK

ν kinematic viscosity, m^2/s

τ period of heat generation rate (a time needed for $\dot{Q}$ to increase e-fold), s

τ* =τU/L, nondimensional parameter

Subscripts

st: quasi-steady state

tr: transient

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Figure Captions

Fig.1 Schematic diagram of experimental apparatus.

Fig.2 Test section.

Fig.3 The relation of $\dot{Q}$, q, ΔT with t/τ at periods of (a) 92 ms and (b) 735 ms at the temperature of 313 K.

Fig.4 Heat transfer coefficient with the increase of time at periods of 92 ms and 8.68 s.

Fig.5 Heat transfer coefficients at various periods, velocities under temperatures of (a) 313 K and (b) 353 K.

Fig.6 Heat transfer coefficients at various gas temperatures at a definite velocity of 10 m/s.

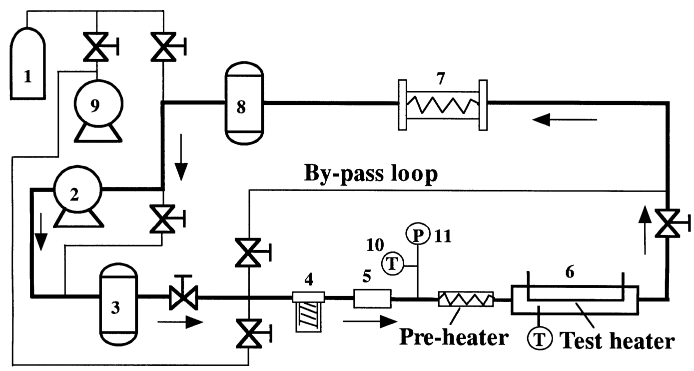
Fig.7 Quasi-steady-state heat transfer at various periods and Reynolds numbers under 333 K.

Fig.8 Quasi-steady-state and transient heat transfer at various periods and Reynolds numbers under 313 K.

Fig.9 Transient heat transfer and its correlation correlated by dimensionless paramer, τU/L.

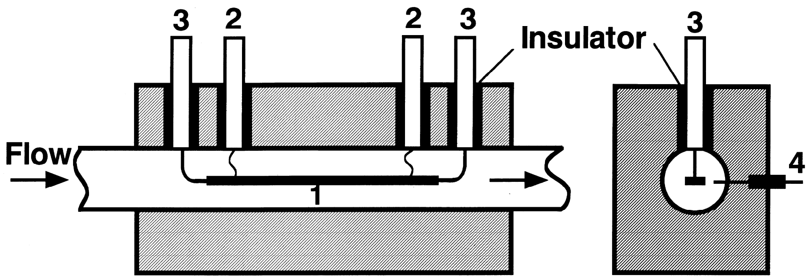
Fig.10 Quasi-steady-state and transient heat transfer coefficients at various periods for the plate and cylinders.

Fig.11 Quasi-steady-state heat transfer at various diameters.



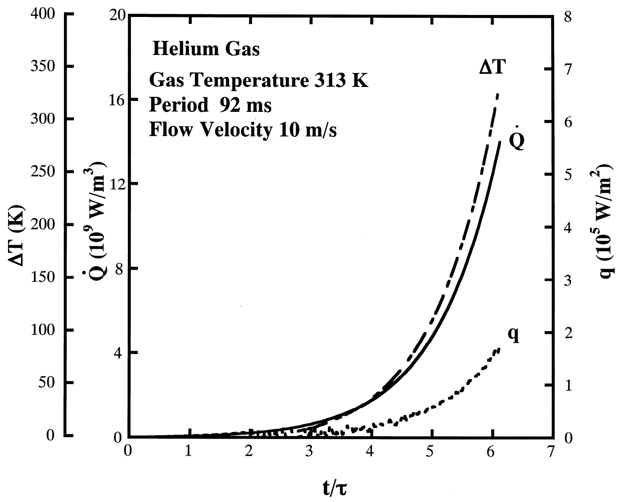
1. Gas cylinder 2. Compressor 3. Delivery surge tank
4. Filter 5. Turbine flow meter 6. Test section 7. Cooler
8. Suction surge tank 9. Vacuum pump 10. Thermocouple
11. Pressure indicator

Fig.1 Schematic diagram of experimental apparatus.

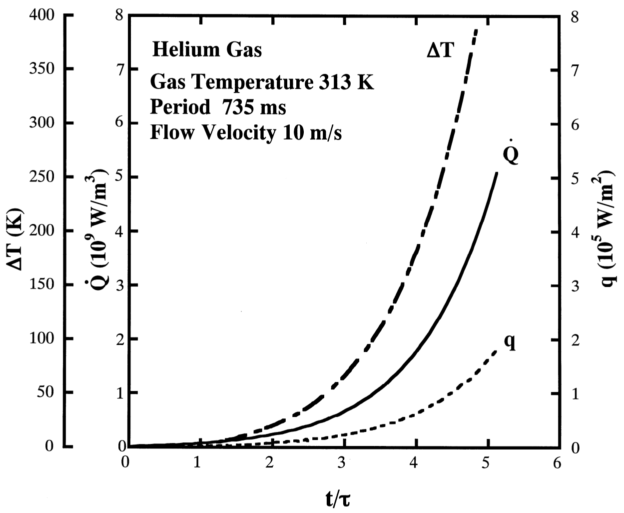


1. Test Heater 2. Potential Conductor
3. Current Conductor 4. Thermocouple

Fig.2 Test section.



(a)



(b)

Fig.3 The relation of $\dot{Q}$, q, ΔT with t/τ at the periods (a) 92 ms and (b) 735 ms at the temperature of 313 K.

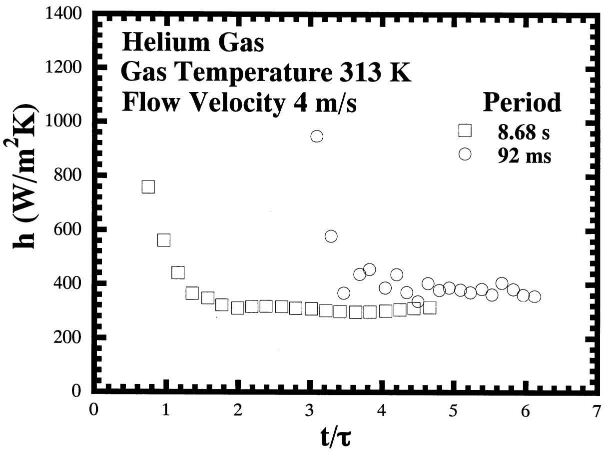
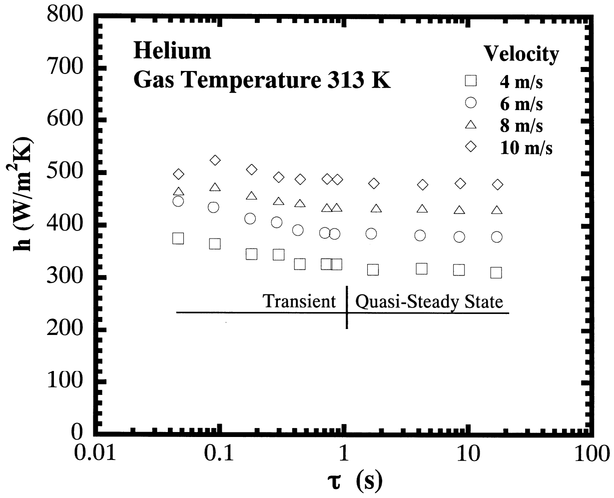
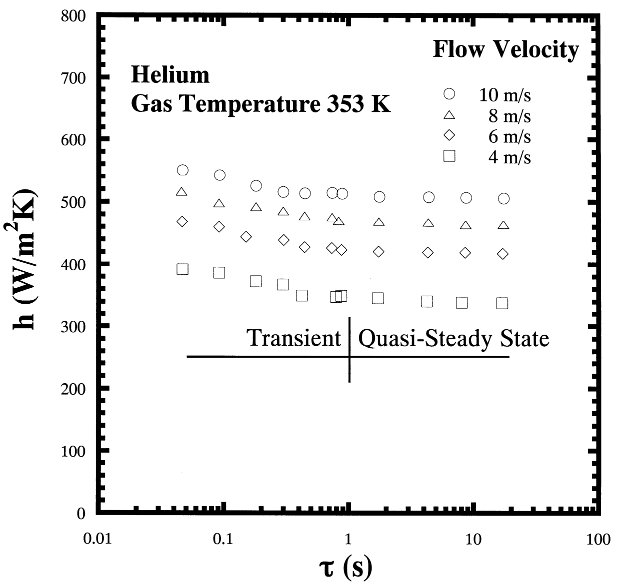


Fig.4 Heat transfer coefficient with the increase of time at periods of 92 ms and 8.68 s.



(a)



(b)

Fig.5 Heat transfer coefficients at various periods, velocities under temperatures of (a) 313 K and (b) 353 K.

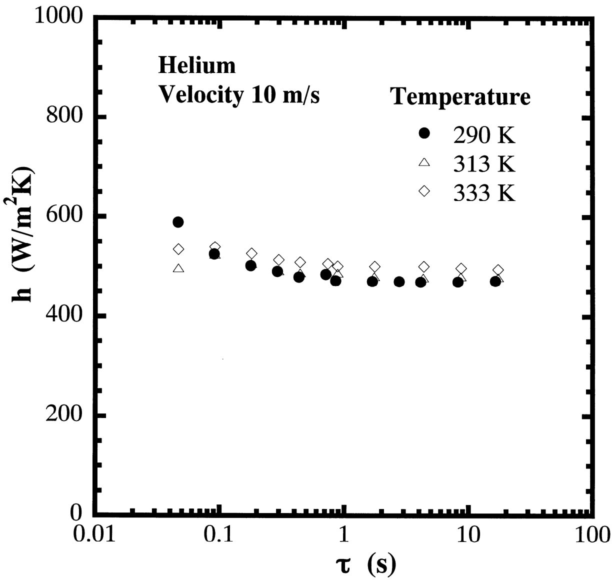


Fig.6 Heat transfer coefficients at various gas temperatures at a definite velocity of 10 m/s.

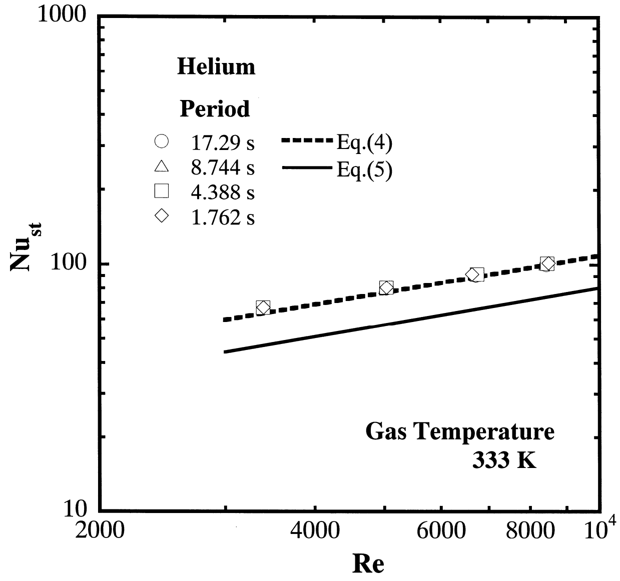


Fig.7 Quasi-steady-state heat transfer at various periods and Reynolds numbers under 333 K.

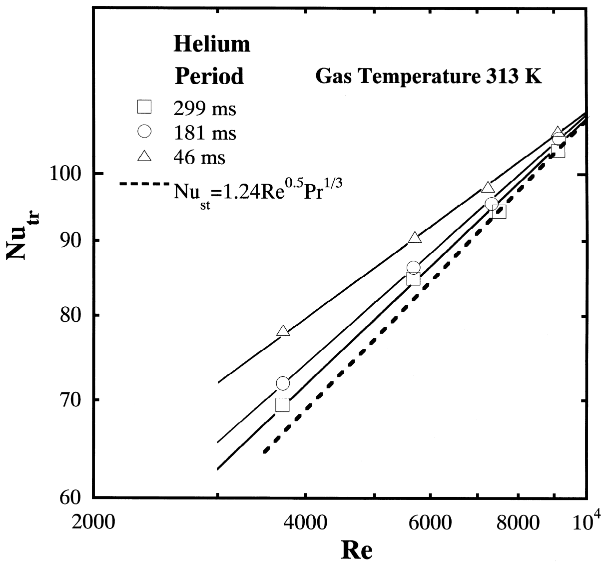


Fig.8 Quasi-steady-state and transient heat transfer at various periods and Reynolds numbers under 313 K.

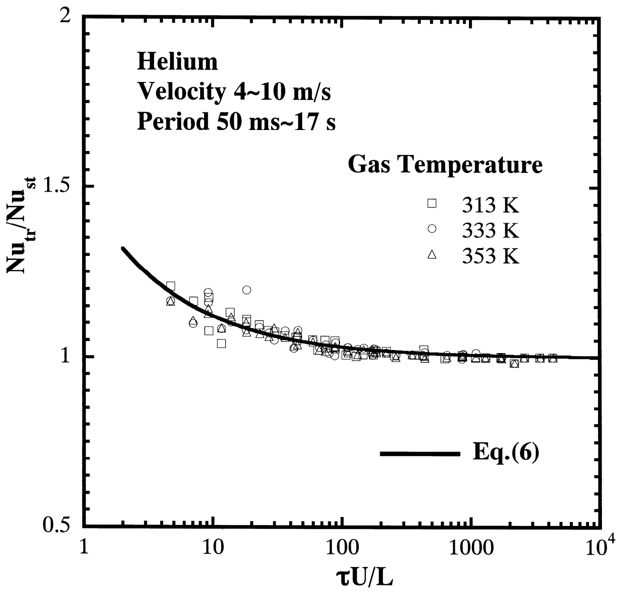


Fig.9 Transient heat transfer and its correlation correlated by dimensionless paramer, τU/L.

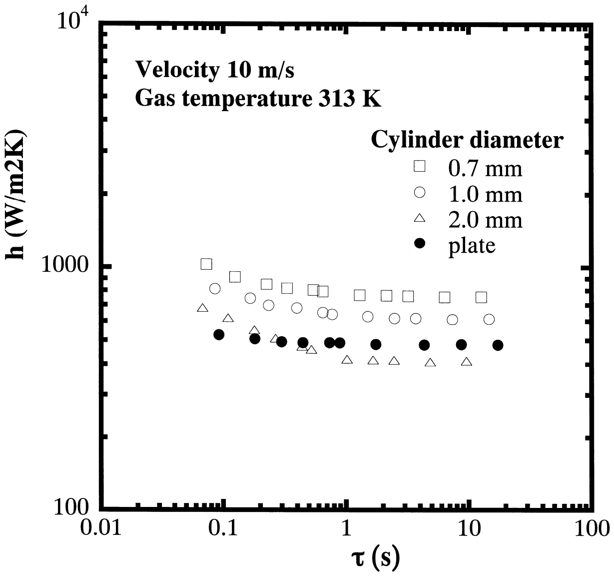


Fig.10 Quasi-steady-state and transient heat transfer coefficients at various periods for the plate and cylinders.

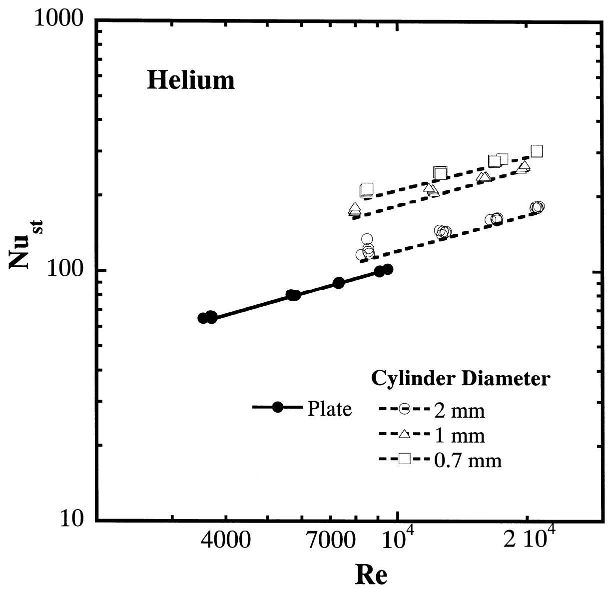


Fig.11 Quasi-steady-state heat transfer at various diameters.