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# Transient Convection Heat Transfer for Helium Gas at Various Flow Decay Times

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## ABSTRACT

Transient convection heat transfer was experimentally studied for a horizontal cylinder in helium gas under flow decay conditions. The experiment was conducted by using helium gas as the coolant, and a platinum cylinder as the test heater. A uniform heat generation rate was applied to the cylinder. The cylinder temperature was maintained at a design value under a specific initial flow rate and heat generation rate. Then, the flow rate of the helium gas started to decrease according to the designed linear functions, with different flow decay times. The surface temperature of the cylinder and the heat flux were measured during the flow decay transient process for various flow decay times, initial flow velocities, and heat generation rates. It was found that the temperature of the cylinder increased rapidly for a shorter flow decay time during the flow decay process. The increment of the surface temperature difference was higher for a higher heat generation rate. The transient heat transfer coefficient was also obtained during the flow decay process. It was clarified that the heat transfer coefficient decreased to a constant value for each flow decay time for a definite heat generation rate and a definite initial flow velocity, and the decrease rate was higher for a shorter flow decay time.

**Keywords**

Convection heat transfer, Transient, Helium, Decreasing flow rate, Flow decay time, Horizontal cylinder, VHTR

**Nomenclature**

$c_h$ : Specific heat of test heater [J/(kg·K)]
D : Diameter of the test heater (cylinder) [m]
$h$ : Heat transfer coefficient [W/(m$^2$·K)]
$\dot{m}$ : Flow rate [L/min]
$\dot{Q}$ : Heat generation rate per unit volume [W/m$^3$]
$q$ : Heat flux [W/m$^2$]
$r$ : Radial distance in the cylindrical coordinate system [m]
$R$ : Radius of the test heater (cylinder) [m]
$T$ : Temperature [K]
$T_a$ : Average temperature of the test heater [K]
$T_b$ : Bulk temperature [K]
$T_s$ : Average surface temperature [K]
$\Delta T$: Surface temperature difference, $\Delta T = T_s - T_b$ [K]
$t$ : Time [s]
$t_{decay}$ : Flow decay time [s]
U : Velocity [m/s]
$\alpha$ : Thermal diffusivity [m$^2$/s]
$\lambda$ : Thermal conductivity [W/(m·K)]
$\rho_h$ : Density of test heater [kg/m$^3$]

# 1. Introduction

Knowledge of the heat transfer phenomenon under flow decay transient conditions is important for the safety assessment of the very-high-temperature reactor (VHTR) during a loss-of-coolant accident (LOCA). A LOCA is characterized by reactor scram, core-depressurization, and natural convection mechanisms. It occurs when a large break (or breaks) exists in the system pressure boundary (reactor pressure vessel or coolant pipes of the main circulation loop), where the system depressurizes and releases helium gas into the reactor containment vessel. Therefore, it is necessary to study thermal hydraulic problems, such as the transient heat transfer process during the flow decay process.

To the best of the authors' knowledge, there are few experimental and analytical works on the transient heat transfer process for helium gas flowing over a solid surface. Sato et al. [1] conducted a thermal analysis for the VHTR during a LOCA with a simplified one-dimensional cylindrical model. The temperature response was obtained, and a design envelope was suggested for such reactors. Takamatsu et al. [2] demonstrated the spontaneous stabilization of the high-temperature test reactor (HTTR), involving the loss of both reactor reactivity control and core cooling. Additionally, a flow decay experiment was conducted by reducing the coolant flow rate to zero under a reactor power of 30% (9 MW). The experimental data were compared to analytical results, which were also based on a cylindrical core model. It is well known that the cylindrical core model is a simplified one-dimensional model, which does not consider the radial power density distribution, the axial temperature distribution, and the coolant flow rate distribution in the core. Thus, to obtain a higher level of accuracy in predictions of heat transfer conditions, particularly of the transient flow decay process in the reactor core, research should be experiment-oriented. Moreover, a better understanding of the thermal-hydraulic phenomena during the LOCA should be clarified.

Regarding the numerical analysis, Lee et al. [3] performed a full core solution to calculate the coolant flow redistribution after the blockage accident in the prismatic modular reactor with a thermal power of 200 MW (PMR200). Their results showed that the fuel temperatures rise under single- and multiple-channel-blockage accidents. It was found that the maximum fuel temperature exceeded the safety limit in the case of more than 10 channel blockages at the same region of the fuel column. Tung et al. [4] performed CFD calculations for the natural convection currents in the core of a prismatic gas-cooled VHTR, and the turbulence models, including the standard k-ε model, the realizable k-ε model, the Spalart–Allmaras turbulence model, and the Reynolds stress model, were compared to the results obtained from the laminar assumptions. The Reynolds stress model was recommended, since it provided the most conservative prediction while including the buoyancy effect.

In our previous works, Liu et al. [5–8], we obtained the experimental data and correlations for parallel flow of helium gas over a horizontal cylinder and a plate with an exponentially increasing heat generation rate. The diameter and geometric effect of the heaters on the transient heat transfer were investigated under a wide range of experimental conditions. Meanwhile, Zhao et al. [9] have also carried out some simple numerical studies on transient heat transfer. In their study, simulations were based on a simple flat plate structure, and several turbulence models were compared.

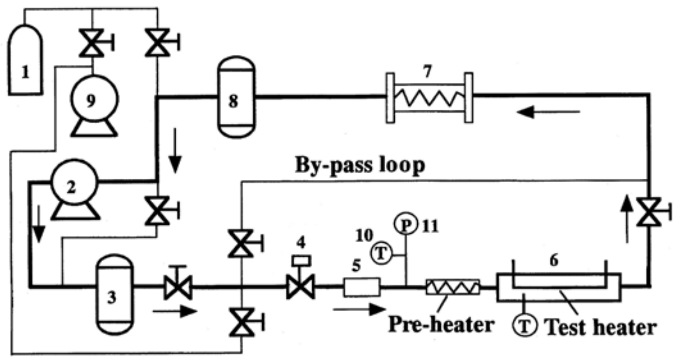
In this study, to clarify the transient heat transfer caused by flow decay, forced convection transient heat transfer for a horizontal cylinder in helium gas under flow decay transient condition was experimentally studied with a uniform heat generation rate. The flow rate of helium gas decreased according to the designed linear functions, with different flow decay times. The surface temperature of the cylinder and the heat flux were investigated during the flow decay transient process at various initial flow velocities, flow decay times, and heat generation rates. The transient heat transfer coefficient was also obtained and discussed.

# 2. Experimental Apparatus and Method

## 2.1 Schematic diagram of the experiment apparatus

The experimental apparatus has been described in previous works [6-7]. A schematic diagram of the experimental apparatus is shown in Fig.1. The experimental system is composed of a gas compressor (2), a flow meter (5), a test section (6), two surge tanks (3, 8), a cooler (7), a flow control valve (proportional solenoid valve) (4), the heat input control system, and the data measurement and processing system.

In the main flow loop, a vacuum pump was used to degas the loop and the test section. Helium gas was circulated by a compressor, and the fluctuations in gas flow and pressure due to the compressor were eliminated by 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 flowed into the compressor. The flow rate in the test section was measured with a turbine flow meter, and the pressure was measured with a pressure transducer. The temperature at the exit of the turbine meter and the temperature near the test section heater were measured with K-type thermocouples with a precision of ±1 K.




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

FIG. 1 Schematic diagram of the experimental apparatus.

The heat input control system [10] used in this experiment includes a changeable low-voltage power supply, amplifiers, an analog to digital (A/D) converter, and a standby current interception. The heat generation rate of the test heater was maintained constant by the heat input control system, with the actual generated heat generation rate (measured value) as the feedback. The voltage of this signal was amplified and fed back to minimize the difference with the reference signal. By adjusting the electric current output, it was possible to sustain a constant heat generation rate throughout a flow decay process, in spite of the rapid variation in the electrical resistance of the heater, due to its temperature variation. In addition, the temperature of the test heater was obtained according to the voltage value through an analog computer. When the temperature or the heat generation rate reached the set value, the current was instantaneously intercepted.

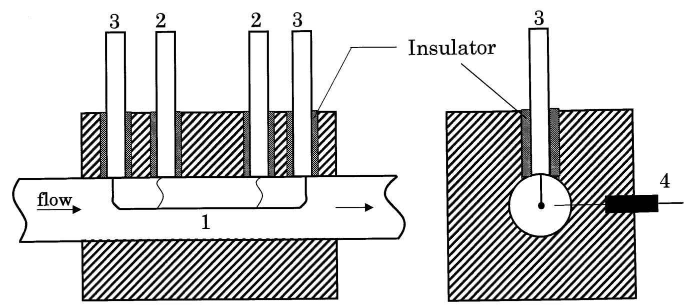
The flow decay process was activated by the flow control valve (proportional solenoid valve), after the test heater was maintained at an initial temperature with a constant heat generation rate. The flow control valve was installed before the flow meter (5), and was designed with a control system to regulate the opening of the valve through which the flow rate could decrease according to a designed linear function.

The data measurement and processing system was built to include a double bridge circuit [6]. The test heater was connected to one of the branches of the double bridge. The electric equilibrium of the double bridge was measured before the heat input. Then, the experiment started with the input of electric current, resulting to a temperature increase in the test heater. The output voltages of the bridge, along with the voltage drops across the potential taps of the heater and across the standard resistance, were amplified and fed to the A/D converter. The resistance of test heater could be obtained according to the double bridge, and then, the average temperature of the test heater was acquired from the calibrated resistance-temperature relation (i.e., the method of resistance thermometry).

### 2.2 Test section and test heater

The test heater was mounted horizontally along the center part of the circular test channel, which was made of stainless steel (with an inside diameter of 20 mm), as shown in Fig.2. A platinum cylinder with a diameter of 1 mm and a total length of 100 mm was used as the test heater. The ends of the heater were connected to two copper electrodes. Two fine platinum wires (50 μm in diameter) were spot-welded to the end parts of the cylinder, as potential conductors. The distance between the potential taps was defined as the effective length on which the transient heat transfer was measured. In this experiment, the effective length was 80.4 mm. As mentioned above, the test heater was heated by direct current from a power source, and the heat generation rates of the heater were controlled and measured via a heat input control system [10].

The average temperature of the test heater was measured via resistance thermometry using a double bridge circuit, including the test heater as a branch [6]. The test heater was annealed, and its electrical resistance versus temperature was calibrated in water, and was washed with an acetone liquid before being used in the experiment.




1. Test heater 2. Potential conductor
3. Current conductor 4. Thermocouple

FIG. 2 Test section.

**2.3 Experimental method and procedure**

The experiment was carried out according to the following procedure. The test loop was first filled with helium gas, after it had been degassed with a vacuum pump. The helium gas was circulated by driving the compressor. The regulation of the initial flow 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 for each flow velocity in the loop, the electric current was supplied to the test heater. With a constant heat generation rate, $\dot{Q}$, the test heater was maintained at a specific initial temperature. Then, the flow decay process started, and the flow rate of the helium gas in the test section decreased to zero at each flow decay time. The test heater's surface temperature, the heat flux, and the heat transfer coefficient accompanying the passage of the time were measured during the whole process. The uncertainties of the measurements of the heat generation rate, the heat flux of the test heater, and the heater surface temperature were estimated to be ±1%, ±2%, and ±1 K, respectively [6].

The heat flux, $q$, of the heater was calculated via the following equation:

$$q = \frac{D}{4}\left(\dot{Q} - \rho_h c_h \frac{dT_a}{dt}\right), \tag{1}$$

where $\rho_h$, $c_h$, $D$, and $T_a$ are the density, specific heat, diameter, and average temperature of the test heater, respectively.

The instantaneous surface temperature of the test heater was calculated via the following equation, assuming the surface temperature of test heater to be uniform.

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) + \frac{\dot{Q}}{\rho_h c_h} \tag{2}$$

Equation (2) is an unsteady heat conduction equation, which was used to calculate the instantaneous surface temperature of the test heater, by assuming the surface temperature around the test heater to be uniform. The boundary conditions are as follows:

$$\left.\frac{\partial T}{\partial r}\right|_{r=0} = 0, \quad -\lambda \left.\frac{\partial T}{\partial r}\right|_{r=R} = q \, , \tag{3}$$

$$T_a = \frac{\int_0^R T(2\pi r)dr}{\int_0^R (2\pi r)dr} = \frac{2}{R^2}\int_0^R Trdr \, , \tag{4}$$

where $\alpha$ and $\lambda$ are the thermal diffusivity and thermal conductivity, respectively; $T_a$ is the average temperature of the heater.

Both the inlet gas temperature of the test section, $T_{in}$, and the outlet gas temperature, $T_{out}$, were measured with K-type thermocouples. Since the differences between the inlet and the outlet temperatures are not significant, the bulk temperature of helium was calculated as the average value of the inlet and outlet gas temperature:

$$T_b = \frac{T_{in} + T_{out}}{2} \, . \tag{5}$$

The physical properties of the fluid were calculated based on the film temperature $T_f$, where $T_f = (T_s + T_b)/2$. The variables $T_s$ and $T_b$ are the surface temperature of test heater, and the bulk temperature of flowing gas, respectively.

### 2.4 Experimental conditions

The experimental conditions are listed in Table 1. The transient heat transfer experimental data were measured at flow decay times of 5 s, 10 s, and 15 s. Here, the flow decay time, $t_{decay}$, corresponds to the time needed for the flow rate to decrease to zero. The heat generation rate was set to values ranging from $1.69 \times 10^8$ to $6.65 \times 10^8$ W/m$^3$, and the corresponding initial temperature differences were approximately 100 K, 200 K, and 300 K, respectively. The initial temperature difference is the difference between the average surface temperature of the test heater and the fluid at the initial steady state, before the flow decay process starts. The initial flow velocities ranged from 4 to 10 m/s, and the corresponding Reynolds numbers ranged from 2000 to 8000.

TABLE 1 Experimental conditions

| | |
|---|---|
| Test fluid | Helium gas |
| Test heater | Platinum cylinder |
| Cylinder diameter | 1 mm |
| Effective length | 80.4 mm |
| Gas temperature | 304 K |
| System pressure | 503 kPa |
| Heat generation rate | $1.69 \times 10^8 \sim 6.65 \times 10^8$ W/m$^3$ |
| Initial temperature difference | 100 K, 200 K, 300 K |
| Flow decay time | 5 s , 10 s, 15 s |
| Initial flow velocity | 4 m/s, 6 m/s, 8 m/s, 10 m/s |
| Reynolds number | 2000 ~ 8000 |

## 3. Experimental Results and Discussions

### 3.1 Time-dependence of the heat generation rate, the flow rate, and the velocity

The experimental data were obtained for the flow rate, the velocity, the heat flux, the surface temperature difference $\Delta T$ ($\Delta T = T_s - T_b$, where $T_s$ is the surface temperature of test heater, and $T_b$ is the bulk gas temperature), and the heat transfer coefficient at a helium gas inlet temperature of 304 K under 503 kPa. The heat generation rate, $\dot{Q}$, was maintained by the heat input control system at a constant value for each initial flow velocity, as shown in Fig.3; the initial temperature difference was set to approximately 100 K for the initial flow velocity of 10 m/s, after 5 seconds of heating with a heat generation rate of $2.2 \times 10^8$ W/m$^3$. The flow rate was controlled to decrease linearly during the flow decay process. As shown in Fig.4, the dashed line indicates the steady state flow with a gas flow velocity of 10 m/s, and the rest of the symbols refer to the flow decay process, starting at 7 s, with different flow decay times of 5 s, 10 s, and 15 s. The flow velocity decreases linearly during the flow decay process, although some small fluctuations may occur as the flow rate approaches zero, as indicated in Fig.4.

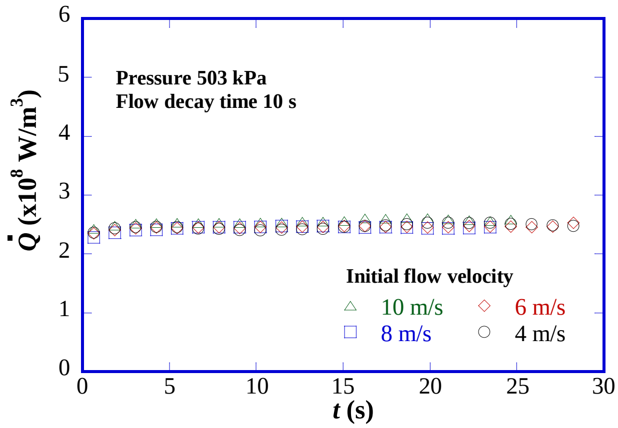



FIG. 3 Heat generation rates at various velocities.

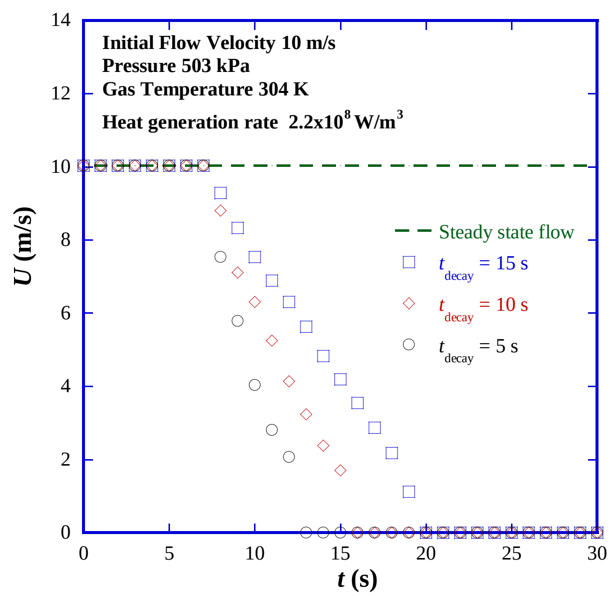
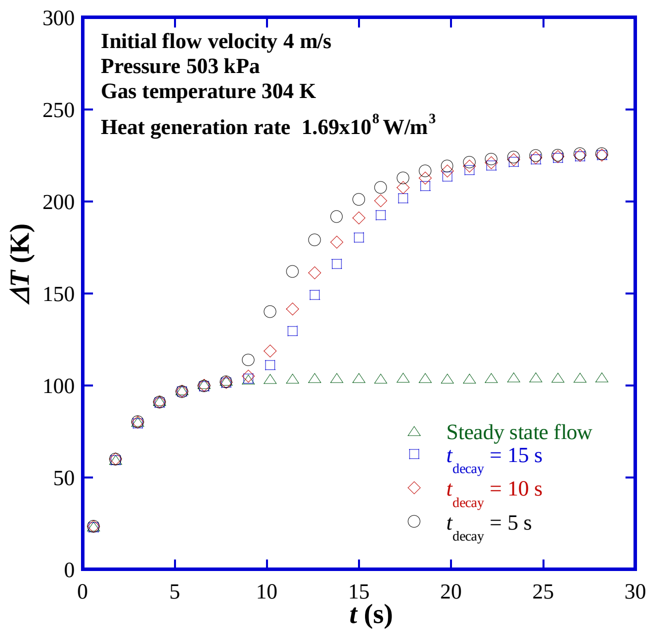


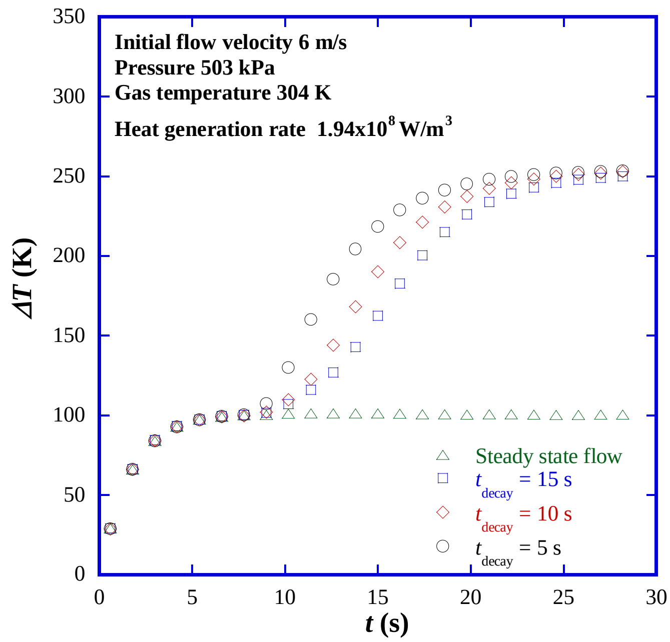

FIG. 4 Linear decreased velocity during flow decay process.

### 3.2 Time-dependence of the surface temperature difference

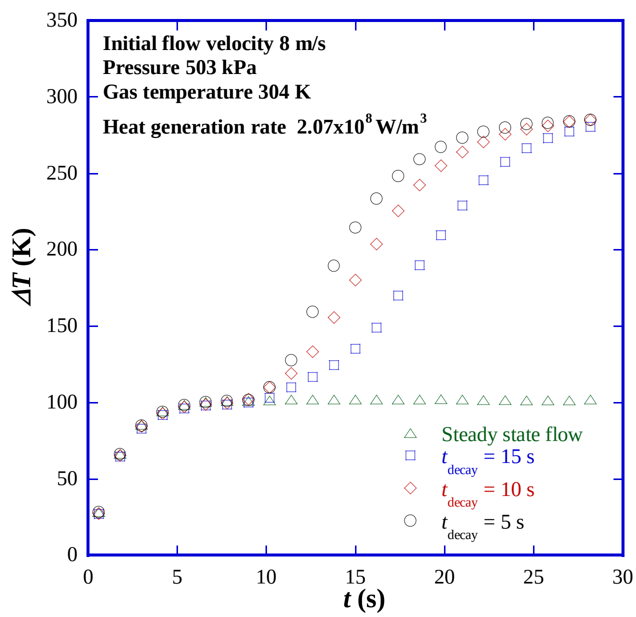
Figures 5(a)–(d) show the surface temperature difference $\Delta T$ during the flow decay process at various velocities and flow decay times. Transient increases in surface temperatures were experimentally studied for three flow decay times. As indicated in Fig.5, the decrease in the gas flow rate (starting at 7 s) has a negative effect on the forced convection heat transfer, and thus leads to the increase in the heater temperature. The surface temperature differences start to increase at a



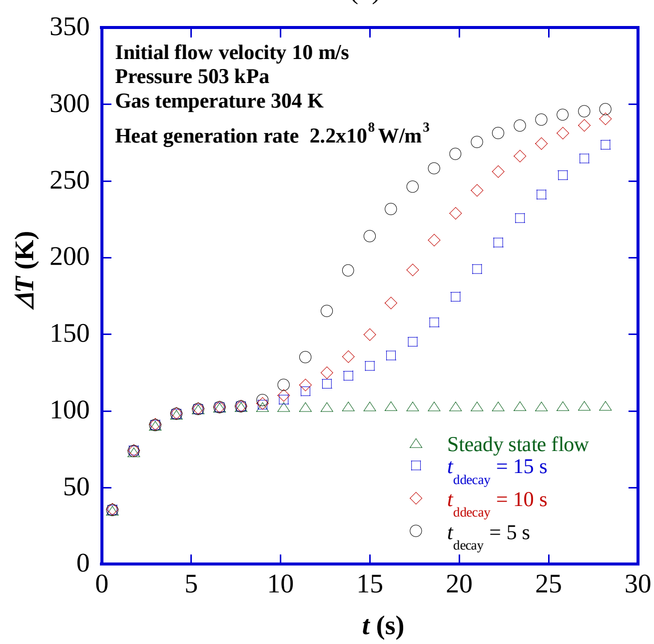

(a) 4 m/s




(b) 6 m/s




(c) 8 m/s




(d) 10 m/s

FIG. 5 The surface temperature difference during flow decay process at different decay time and initial flow velocity.

specific time, with different gradients; the increase in $\Delta T$ is steeper at a lower flow decay time. It can also be observed that it still takes some time for the surface temperature difference $\Delta T$ to reach a stable value after the flow decay process has finished. This is because of the time needed for the boundary layer to be fully developed. Therefore, the maximum temperature of the test heater still takes some time to be reached after the flow decay process. As it can be seen in Fig.5 (d), for the decay time of 10 s, the flow rate starts to decrease at approximately $t = 7s$, and decreased to zero at $t = 17s$, while the temperature difference does not approach a constant value until approximately 28 s.

Figures 6(a)–(d) show the surface temperature difference $\Delta T$ versus time at different heat generation rates. The flow decay time is 10 s for all three cases, with different heat generation rates. The initial flow velocities were set to 4 m/s, 6 m/s, 8 m/s, and 10 m/s. All flow decay processes start at approximately *t* = 7 s. The forced convection heat transfer for the test heater remains at the steady state between 5 s to 7 s, and the surface temperature differences are maintained at constant values. The initial $\Delta T$ is higher at a higher heat generation rate. It can be seen from Fig.6(b) that $\Delta T$ is 100 K, 200 K, and 300 K at heat generation rates of $1.94 \times 10^8$, $4.07 \times 10^8$, and $6.23 \times 10^8$ W/m$^3$, respectively. When the flow decay process starts at 7 s, the surface temperature difference of the test heater starts to increase. In the energy conservation equation, Eq.(1), at the steady state $dT_a / dt = 0$, the heat flux, *q*, is proportional to the heat generation rate, $\dot{Q}$. According to Newton's law of cooling, Eq.(6), when the heat transfer coefficient *h* is constant, the heat flux is proportional to the temperature difference. Therefore, at both steady states, i.e., before the flow decay process and after the flow decay process, when *h* is constant the surface temperature difference is a linear correlation of the heat generation rate, as shown in Eq.(7).

$$q = h\Delta T \tag{6}$$

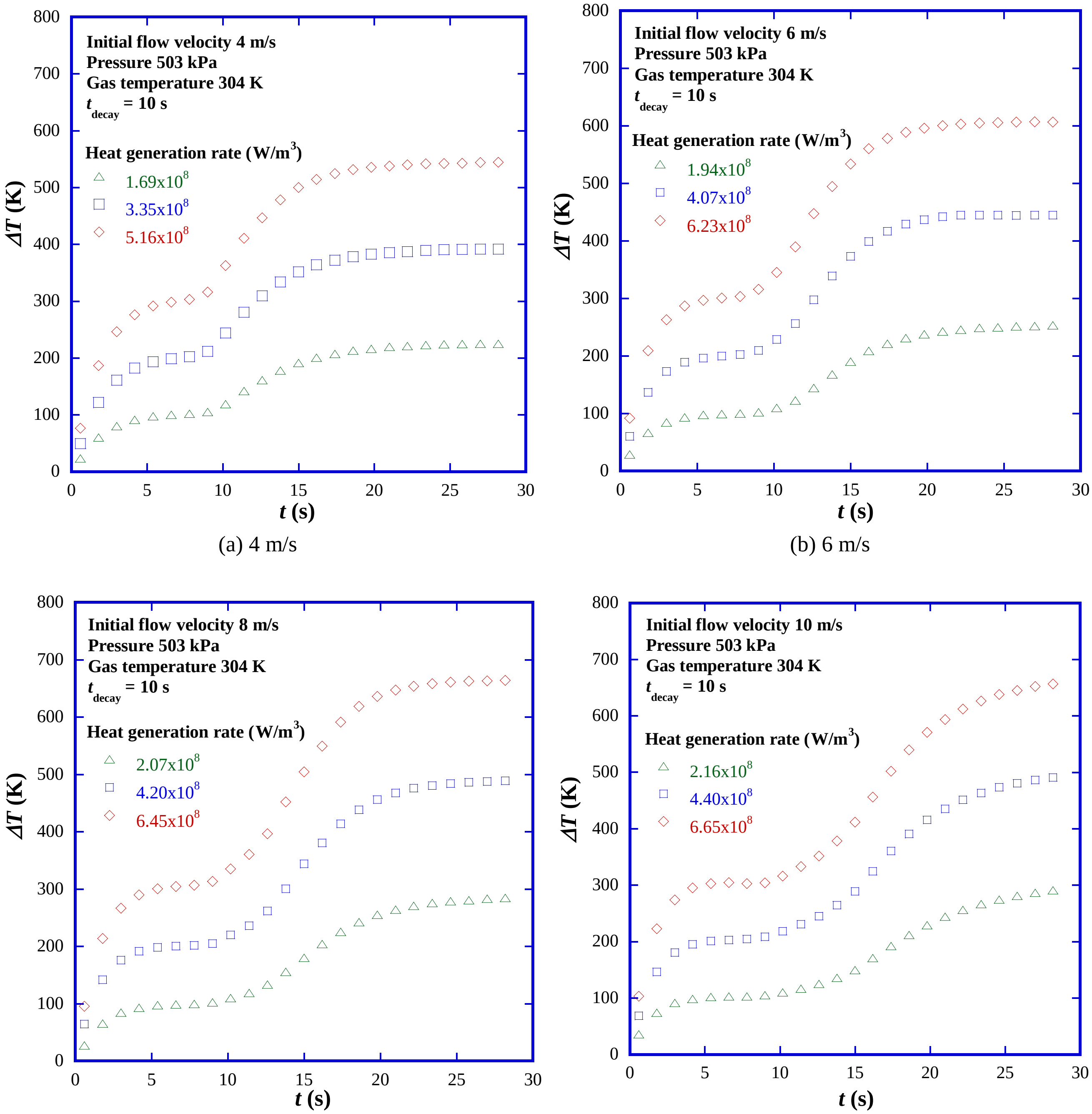
$$\Delta T = \frac{D}{4h}\dot{Q} \tag{7}$$

After the flow decay process, the velocity in the channel decreased to zero and the heat transfer in the cylinder became a natural convection heat transfer. The natural convection heat transfer coefficient for the three cases with different heat generation rates varied slightly owing to the different final surface temperature of the heater; a higher final surface temperature (or a higher heat generation rate) would result in a higher natural convection heat transfer coefficient. As seen in Fig.6 (b), the values of $\Delta T$ increase to 250 K, 440 K, and 600 K after the flow decay process, for heat generation rates of $1.94 \times 10^8$, $4.07 \times 10^8$, and $6.23 \times 10^8$ W/m$^3$, respectively. The increments of surface temperature differences during the flow decay processes are approximately 150 K, 240 K, and 300 K, respectively. The higher the heat generation rate, the higher the increment. Therefore, while a VHTR operates at high power, the heat generation rates of the fuel rods will be high; the passive safety design will be more challenging to ensure the temperature limitation of the fuel rods during a loss-of-coolant accident.

Furthermore, the steady state surface temperature difference of the test heater after the flow decay process directly relies on the natural convection heat transfer. Therefore, in the design of passive cooling, an improved natural convection will be required to lessen the increase in the surface temperature of the test heater (fuel rod).

### 3.3 Time-dependence of the heat flux

The heat flux on the surface of the test heater is shown in Fig.7 (a)–(d). It can be observed that the heat flux starts to decrease with the decrease in the flow rate, which starts at 7 s. However, after some time, it then increases again to approach the initial value, for each flow decay time. The heat flux was obtained through the energy conservation equation, as shown in Eq.(1). During the flow decay process, the temperature time derivative is higher than zero, compared to that of the steady state flow ($dT_a / dt = 0$), as shown in Fig.5. Thus, a lower heat flux would be generated in this process compared to that of the steady state flow. Referring again to the curve of the temperature difference versus time in Fig.5, we can derive that the temperature time derivative during the flow decay process increases from zero to a maximum value, and it then decreases to zero, according to the curve shape. Therefore, the heat flux can be divided into two regions: first, a decrease region, and second, an increase region, as the flow decay process progresses.



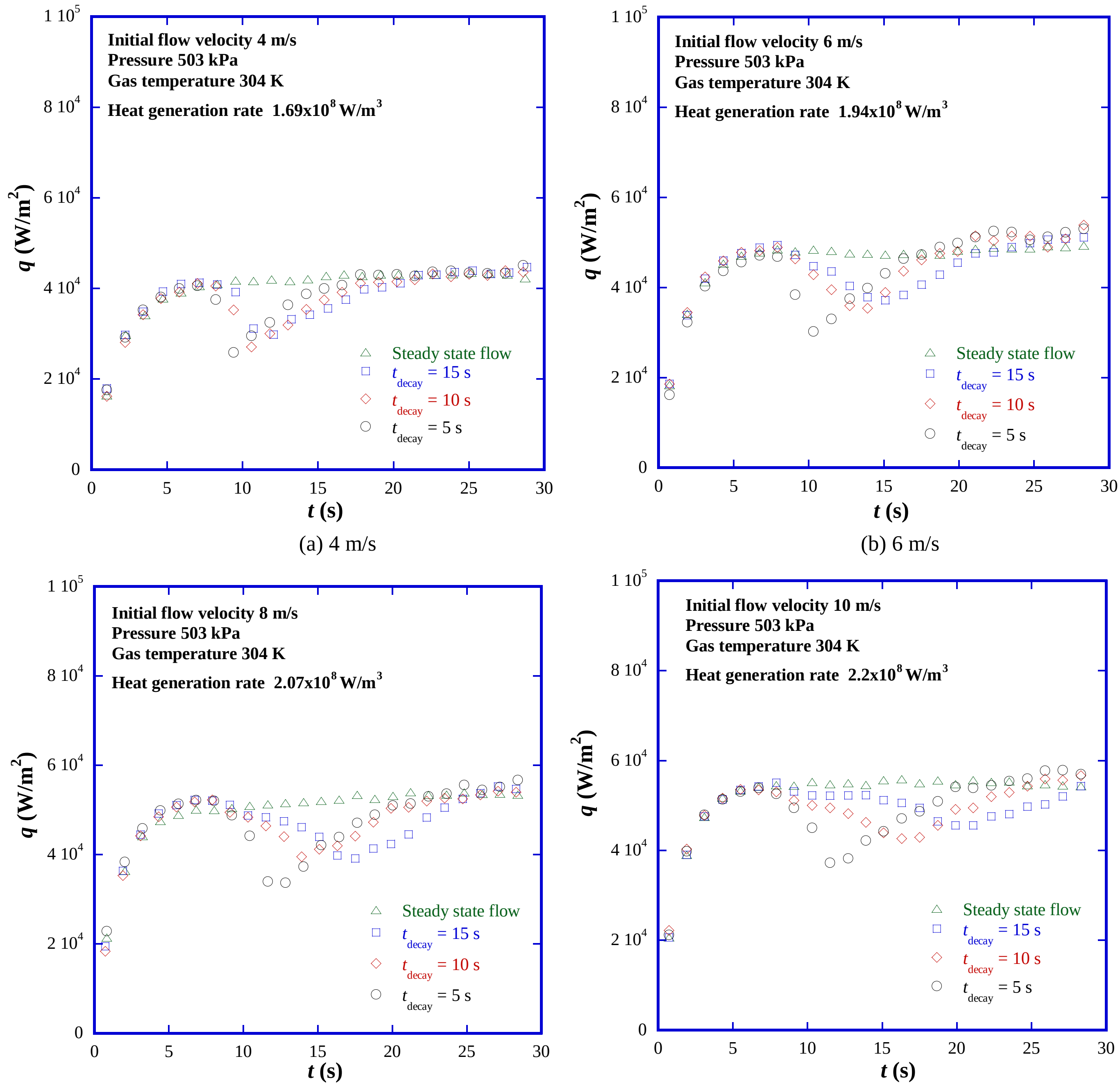

(c) 8 m/s (d) 10 m/s

FIG. 6 The surface temperature differences of test heater at various heat generation rates and initial flow velocities.

### 3.4 Heat transfer coefficient during the transient flow decay process

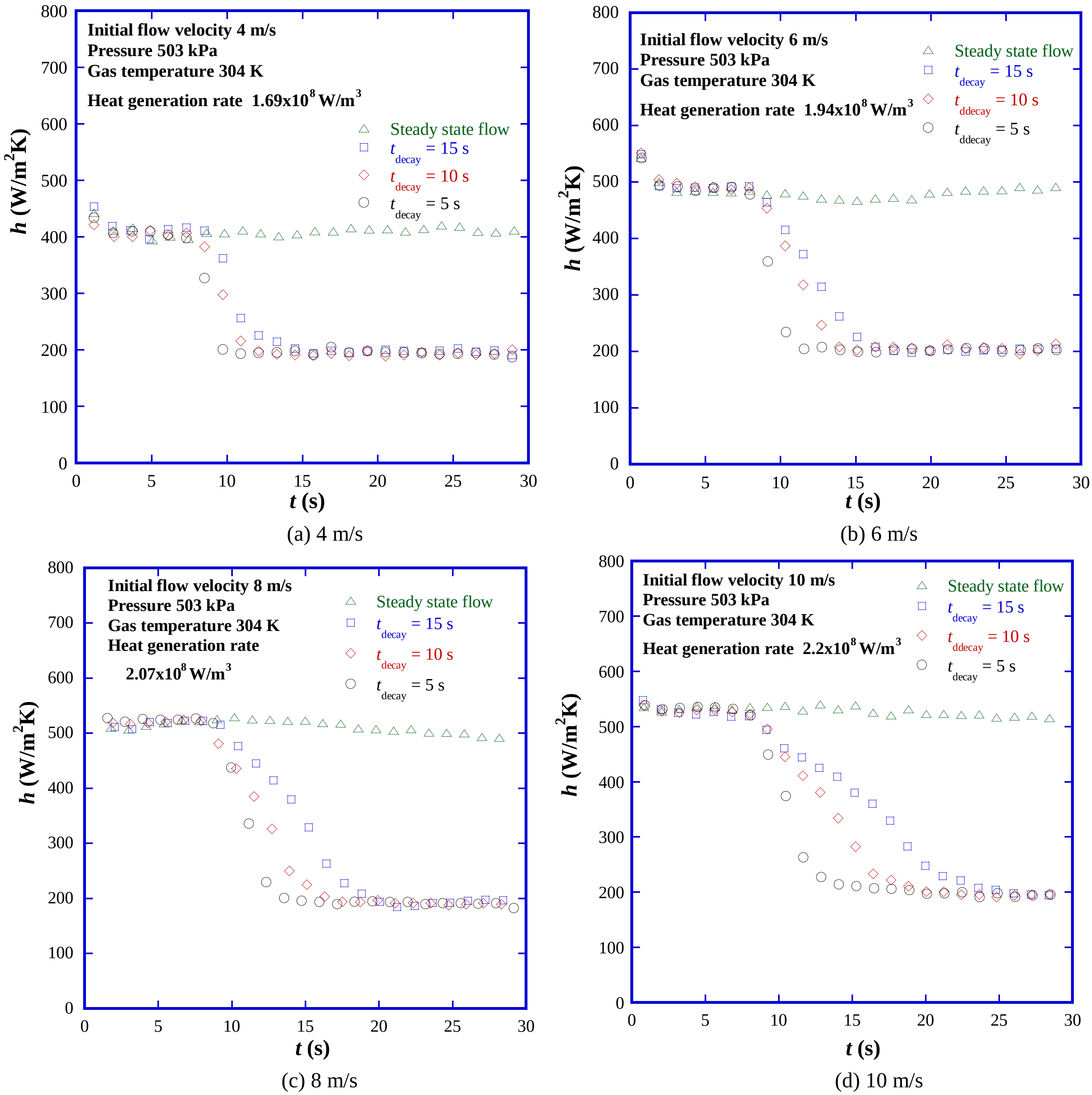
Figures 8 (a)–(d) show the heat transfer coefficient versus time, at various flow decay times and initial flow velocities. As it can be seen, the heat transfer coefficient decreases to a constant value at each flow decay time, and the decrease rate is higher at a shorter flow decay time. This clarified that heat transfer process is directly influenced by the flow decay time.

A comparison of the heat transfer coefficients at various initial flow velocities is shown in Fig.9. The flow decay time is set to 10 s. It can be observed that the heat transfer coefficient increases with the increase in the initial flow velocity. Moreover, the heat transfer coefficient decreases to the constant value more quickly at a lower initial flow velocity during the flow decay process. It should be noted that the heat transfer coefficient at each initial flow velocity approaches the same value, which corresponds to the value of a free convection heat transfer for a cylinder with helium gas.




(c) 8 m/s (d) 10 m/s

FIG.7 The heat flux behavior during flow decay process at various initial flow velocities.




(a) 4 m/s

(b) 6 m/s

(c) 8 m/s

(d) 10 m/s

FIG.8 The heat transfer coefficient versus time at various flow decay times and initial flow velocities.

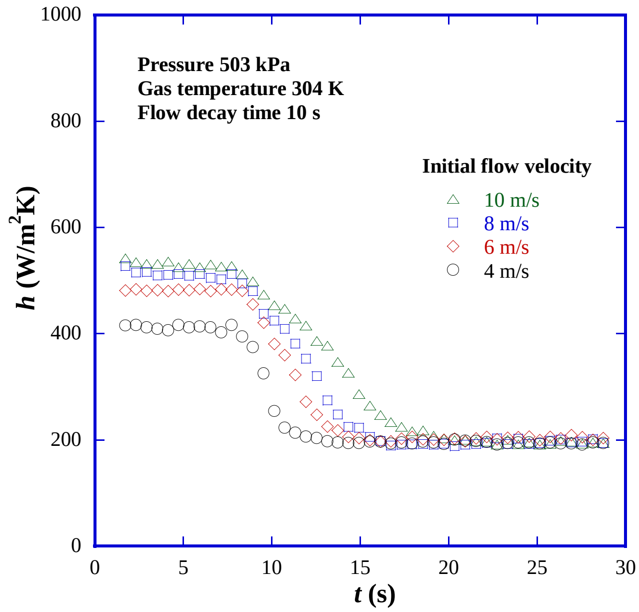



FIG.9 The heat transfer coefficient at various initial flow velocities.

## 4. Conclusions

In this study, the forced convection heat transfer for a horizontal cylinder in helium gas was experimentally studied under linear flow decay transient conditions. The following results were obtained:

(1) The surface temperature difference increased with different gradients during the flow decay process; it was higher for a shorter flow decay time.

(2) It required more time than the flow decay time for the surface temperature and the heat flux to reach steady-state values, owing to the time needed for the boundary layer to be fully developed.

(3) During the flow decay process, the increment of the surface temperature difference was almost proportional to the heat generation rate.

(4) A minimum heat flux existed during the flow decay process owing to the changing with time of the temperature derivative ( $dT_a / dt$ ) under the flow decay process.

(5) It was clarified that the heat transfer coefficient linearly decreased to a constant value for each flow decay time, and the decrease rate was higher for a lower flow decay time.

(6) The heat transfer coefficient decreased to the constant value more quickly for a lower initial flow velocity.

In the present study, to clarify the transient heat transfer caused by flow decay, the forced-convection transient heat transfer for a horizontal cylinder with helium gas under flow decay transient conditions was experimentally studied, with a uniform heat generation rate. As a fundamental research concerning the R&D of the VHTR, the main purpose of this research was the study of the transient heat transfer performance and the temperature increase range of the test heater during the flow decay process. However, the shape and diameter of the flow channel, as well as the size of the test heater, also affect the transient process. For instance, with a larger heat capacity, the temperature would increase more slowly and it would require more time to reach a constant value. Moreover, the flow channels in a VHTR are vertically distributed, hence, the effect of gravity should be considered. Therefore, regarding an actual transient process in a VHTR core, further experimental research on the scale, the materials, and the shapes needs to be conducted. In this experimental study, a fundamental database for the transient heat transfer was obtained. It is considered that the database could contribute some knowledge of heat transfer to the thermal analysis of the reactor core and the intermediate heat exchanger (IHX). In addition, the experimental data obtained in this experiment are also expected to be useful in further works on the numerical simulation of thermal hydraulics in the reactor core or the IHX, as a basis for validation.

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