# Experimental on Transient Heating and Cooling of Natural Circulation Flow using A FASSIP-02 Large Scale Experimental Facility

Juarsa, Mulya
Nuclear Reactor Thermal-Fluids System Research Group, Research Center for Nuclear Reactor Technology, Research Organization for Nuclear Power (BATAN), National Research and Innovation Agency of Indonesia (BRIN)

Giarno
Nuclear Reactor Thermal-Fluids System Research Group, Research Center for Nuclear Reactor Technology, Research Organization for Nuclear Power (BATAN), National Research and Innovation Agency of Indonesia (BRIN)

Haryanto, Dedy
Nuclear Reactor Thermal-Fluids System Research Group, Research Center for Nuclear Reactor Technology, Research Organization for Nuclear Power (BATAN), National Research and Innovation Agency of Indonesia (BRIN)

Rosidi, Ainur
Nuclear Reactor Thermal-Fluids System Research Group, Research Center for Nuclear Reactor Technology, Research Organization for Nuclear Power (BATAN), National Research and Innovation Agency of Indonesia (BRIN)

他

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# Experimental on Transient Heating and Cooling of Natural Circulation Flow using A FASSIP-02 Large Scale Experimental Facility

Mulya Juarsa[1,*], Giarno[1], Dedy Haryanto[1], Ainur Rosidi[1],
G. Bambang Heru K. [1], Adhika E. Pamungkas[1], Arif A. Budiman[1]
[1]Nuclear Reactor Thermal-Fluids System Research Group,
Research Center for Nuclear Reactor Technology, Research Organization for Nuclear Power (BATAN),
National Research and Innovation Agency of Indonesia (BRIN),
Building 80, KST B.J. Habibie, Tangerang Selatan 15310, Banten - Indonesia

*E-mail: mulya.juarsa@brin.go.id

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**Abstract.** The Fukushima Daiichi nuclear plant accident in 2011 has provided important information about the failure of the active cooling system if the installation does not have electrical power. So that research on the phenomenon of natural circulation flow through passive cooling systems is an essential topic in improving the safety management of nuclear power plants in the world. However, research on natural circulation flow experimentally using large-scale facilities has not been widely carried out. This research aims to analyze the natural circulation flow rate phenomenon under transient heating and transient cooling conditions. The research method was conducted experimentally using the FASSIP-02 Test Loop, a large-scale experimental facility with a head height of 9.1 meters. Experiments were carried out by varying the temperature setting in the heat source (WHT), respectively, at 60 °C, 70 °C, and 80 °C. The results showed that the flow regime formed was in a turbulent flow regime, with the Reynolds numbers being 9352, 12634, and 17370, respectively, for variations in temperature settings of 60 °C, 70 °C, and 80 °C.

Keywords: nuclear accident, transient, natural circulation, passive cooling, Reynolds number, FASSIP

## 1. Introduction

The Fukushima Daiichi accident that occurred ten years ago (March 2011) in Japan has illustrated the importance of passive cooling systems. The failure of the active cooling system resulted in the melting of the reactor core in several reactor units. The meltdown of reactor core were appears in several units reactor causing a release of radioactive substance[1–3]. Since the nuclear power plant accident, research and development related to passive cooling systems as a reactor safety feature have increasingly been carried out and used in new reactor designs, such as Korea's SMART (*System-Integrated Advanced Modular Reactor*) reactor design[4,5]. The basic principle of a passive cooling system based on applying the laws of nature, in which the flow in the loop occurs without any force intervention by the system. Instead, fluids flow occurs naturally due to differences in the density of water in the hot and cold parts. The application of a passive cooling system in nuclear power plants during an accident has been conducting by transferring heat from the reactor core to the steam generator section. As the passive cooling system, the hot part inside the steam generator was taken up the heat and transported by natural circulation (NC) flow. The heat from the cold part (upper position) was released into the cooling tank section.

The investigation on mass flow stability in the passive cooling system, especially the passive heat removal system (PHRS) SMART reactor, becomes an important research topic because the flow stability will affect the ability to remove the heat during an accident condition. The working principle of the passive cooling system in the SMART reactor applies the principle of natural circulation which occurs due to the driving force caused by the difference in height of the heat and coolant sources in the system[6–9]. Through this natural circulation, the residual heat in the reactor core during shutdown conditions can be distributed outside to prevent overpressure or even fuel meltdown without using an equipment that requires external power. Analysis of flow stability and performance of passive heat exhaust systems has been carried out through simulations with the codes RELAP5/MOD3.2, MARS/SMR (restructuring from RELAP5/MOD3.2.1.2 and COBRA-TF), MARS-KS, TASS/SMR, MATRA, and TASS/SMR-S[10)6,9,11)11–14].

The work of a PHRS that applies the principle of natural circulation cannot be separated from testing and validation based on thermohydraulic characteristics. The two-phase natural circulation thermohydraulic characteristics of the system are the basis for validating the safety of the SMART reactor[9]. During the development of the SMART reactor, KAERI carried out thermohydraulic testing using the VISTA-ITL experimental facility, the SCOP facility for flow testing in the SMART reactor, the SWAT facility for evaluation of the injection safety system, and FTHEL for the development of the SMART core design code[7,15]. The simulation code and experimental facilities have contributed to obtaining the license/approval of the SMART reactor.

Many researchers have conducted experiments and numerical simulations related to the passive cooling system and NC phenomenon, both for single-phase and two-phase flow[16–19]. However, some numerical simulation results are still experiencing problems regarding the initial conditions (IC) and boundary conditions (BC) determined for calculation. Meanwhile, the experimental method is the most practical method to use as an excellent scientific reference to understand and master the concept of NC flow for passive cooling systems. Moreover, several countries have large-scale experimental facilities to study and develop passive cooling systems based on NC regarding the experimental method[20–22]. For example, in Indonesia, especially in the Laboratory of Thermal-hydraulics Experimental (Lab.THE), Reactor Thermal-Fluids System Development, Research and Technology Center for Nuclear Reactor Safety, Nuclear Power Research Institute (BATAN), National Research and Innovation Agency of Indonesia (BRIN), studies and research on NC phenomena have been carried out (since 2014) experimentally using two small and medium-sized experimental facilities in a rectangular loop model. The first research related to the investigation of the NC phenomenon from the year 2014 until the year 2016 has been performing using a small-scale facility called NC-QUEEN loop[23,24]. The NC-QUEEN loop main components consist of (1) A loop of rectangular (height 2.7 m, wide 0.5 m) made by SS316 tubes with a diameter of 3/4 inch with a total length is 6.4 m, (2) expansion tank, (3) refrigerant as a cooling section, (4) heating section (heater), and (5) a 25-kW voltage regulator. The results of flow rate calculations using temperature data indicate the flow formation from a laminar to a turbulence regime based on the height difference between the heating and cooling positions. The Experiments also show the relationship between the increasing temperature difference between the water in the hot and cold parts, causing an increase in the NC flow rate.

Then, from the year 2016 until the year 2019, Lab.THE CRNRST-BATAN has built a medium-scale experimental facility called FASSIP-01 Loop (FASSIP, *FAsilitas Sirkulasi SIstem Pasif*). The loop is rectangular with a height of 6 m and wide 3.5 m and made by SS304 pipe with a diameter of 1 inch with a total length of 19 m. Investigation of the effect of thermohydraulic parameters on NC flow based on scenarios of variations in cooling system flow and variations in heating power on NC flow has been carried out using the FASSIP-01 loop to obtain NC flow rate data using magnetic flowmeters[25–27]. The analysis results show that the effect only occurs on the response time for the stability flow from the unstable flow. For example, the increase in HSS flow in the cooling area from 21.57 LPM to 43.1 LPM in respectively makes a response time from 5041 to 7325 is faster, only 31.18%. On the other hand, in terms of heating, the increase in power in the heating area to respond time from 4855 s to 3857 s is faster, only 20.55%.

Nevertheless, the measurement of NC flow rate using FASSIIP-01 is not satisfactory, considering that the type of flow obtained falls into the category of laminar flow regime. Moreover, the cause of low flow NC is a bubble trap inside the pipe that blocks the flow, so from this condition is necessary to modify the FASSIP-01 loop. The process of modifying the FASSIP loop is still being carrying, and almost finished. In addition to experimental research, simulations using RELAP5/SCDAP to investigate geometry-based NC flow rates and thermal parameters on the FASSIP-01 loop have also been carried out[28,29].

Based on the research experience using NC-QUEEN loop (small-scale) dan FASSIP-01 loop (medium-scale) facilities, since 2017, further research has been carried out to investigate NC phenomena for applications in passive cooling systems in order to improve nuclear reactor safety management when experiencing transient conditions (accidents). Furthermore, to further explore the thermal management aspects of passive cooling systems through experimental studies, finally, a large-scale experimental facility with a maximum height of 11 meters and a height difference between hot and cold sections of 9.1 meters was designed and constructed starting in 2017. Hence, the facility was called the FASSIP-02 test loop. In addition, several preliminary analyses of the NC phenomenon due to changes in thermohydraulic parameters based on geometric variables and fluid properties in FASSIP-02 have been performing using CFD software, RELAP5/SCDAP simulations, and calculations[30–32]. Based on the description of the experimental activities and simulations carried out above, further experimental activities to investigate NC flow in the FASSIP-02 test loop have been carried out by varying the water temperature setting in the hot section (WHT, water heating tank) for transient heating and cooling conditions. This paper presents the results of measuring NC flow using a magnetic flowmeter and calculating the Reynolds number to show the flow regime that appears in this large-scale experimental facility.

## 2. Methodology

Research has been done experimentally using large-scale experimental facilities. The measurement results obtained are in the form of temperature data and NC flow rate data. The calculations were carried out based on the NC flow rate data to show the flow regime formed based on three variations of setting water temperature in the hot section (WHT), namely 60ºC, 70ºC, and 80ºC.

### 2.1 Experimental Setup

A Large-Scale Test Loop Facility was designed and constructed to perform an experimental study on NC phenomenon to investigate the passive cooling systems in nuclear reactors for large-scale and SMR (small modular reactors) types. The facility was named FASSIP-02 (FAsilitas Simulasi SIstem Pasif) unit 02 Test Loop, and Fig. 1 shows the experimental setup of the FASSIP-02 test loop.

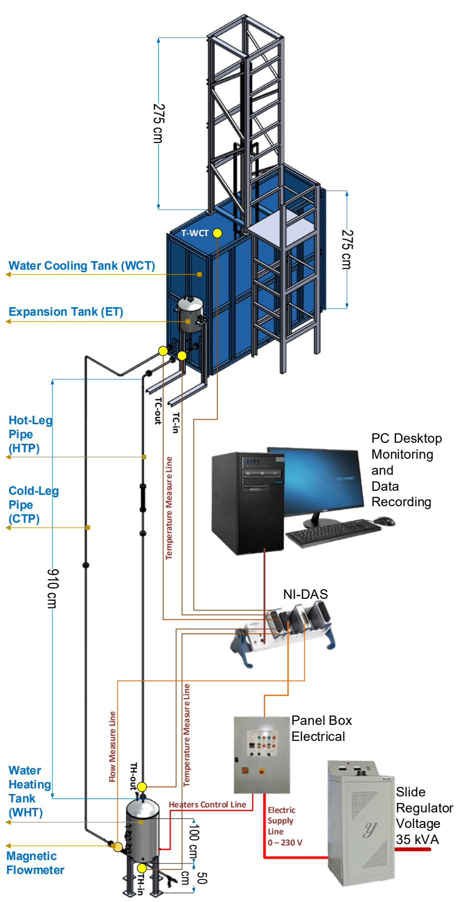


**Fig.1:** Experimental setup of the FASSIP-02 test loop

Base on Fig. 1, several thermal-hydraulics parameters that affect the natural circulation flow are fluid temperature (T), the geometrical parameter is the height difference between heater and cooler (H), the total loop length (L), and pipe diameter (D). The loss frictional of pipe defined base on the elbow, tee, enlargements, and contractions with K constantan. Table 1 shows the geometry of the FASSIP-02 test loop.

The experiment was carried out by varying the water temperature setting in the WHT at 60ºC, 70ºC, and 80ºC. The setting increases the four heaters until they reach the temperature setting through the NI-DAS control system. After that, the electricity disconnects from the SSR module in the electrical box panel when the specified temperature value is achieved. Heating time and cooling time, and temperature changes are observed and recorded into the computer through the National Instruments Data Acquisition System (NI-DAS). The graph made using the Origin 8 software base on experimental data and calculations is pointed out to determine the Reynolds number.

Table 1. The FASSIP-02 Test Loop data-sheet

| No | Items | Descriptions |
|---|---|---|
| 1. | Water Cooling Tank (WCT) | Square tank, carbon-steel thickness 8 mm, geometry: 1 x 3 x 2.75 m, total weight with water = 10150 kg. |
| 2. | Water Heating Tank (WCT) | Cylinder tank, stainless-steel 304, dia. 24 inches, sch.40, height=1 m, cup height=0.1572 m. |
| 3. | Submerged Heaters (4 heaters) | Length = 30 cm, power = 5 kW/heater (total power = 20 kW) |
| 4. | Heat Exchanger inside WCT | U-shape HE, cooper material, thickness 3 mm, dia. 1 inch. |
| 5. | Piping | Stainless-steel pipe, dia. 1 inch, Sch.20 |
| 6. | Total pipe length of the loop | 23.5 meters (1-inch pipe) |
| 7. | Height differences between WCT (inlet) and WHT (outlet), *H* | 9.1 meters |
| 8. | Total height of the facility/the loop | 17.76 meters/11 meters |
| 9. | Total loss-coefficient (*K*) | 12.71 |
| 10. | Electromagnetic flowmeters | M921, reading value accuracy: 0.25% of 0.03 to 12 m/s<br>Max. media temperature 150ºC, output : 4 – 20 mA. |

| | | |
|---|---|---|
| 11. | Thermocouples | Type K wire, with accuracy 0.15% for range -20 to 200°C |

### 2.2 Calculation

The determination of flow regime type that occurs in a closed or open loop needs Reynolds number calculation, in this case for flow inside a 1-inch pipe due to free convection or natural circulation. Reynolds number correlation is,

$$\mathrm{Re} = \frac{\rho D_h v}{\mu} \quad (1)$$

Where,

Water density (in kg/m3) is

$$\rho(T) = 1004.789041 - 0.046283(1.8T + 32) - 7.9738 \times 10^{-4}(1.8T + 32)^2 \quad (2)$$

and then dynamics viscosity (N.s/m2) is

$$\mu(T) = \mathrm{e}^{\left[-\frac{6.325203964 + 0.088832314T}{1 + 0.008705317T - 9.657 \times 10^{-7} T^2}\right]} \quad (3)$$

Therefore, water velocity, $v$ (m/s), was obtained using an electromagnetic flowmeter to measure the flow rate ($Q$ in LPM). As a result, the velocity of NC obtains from correlation $v = 1.667 \times 10^{-5} Q$.

## 3 Results And Discussion

### 3.1 Temperature Measurements

The experiment was carried out for an interval of 24 hours (86400 seconds), but the data presented in this paper is only up to 18 hours. Based on the water temperature setting in the WHT starting from 60 °C, 70 °C, and 80 °C, a graph of temperature measurement against time is obtained, which are shown in Fig. 2, Fig. 3, and Fig. 4.

Figure 2 shows that heating with a maximum power of 20 kW raises the water temperature from the initial condition (31 °C). It takes about 4505 seconds to reach 60 °C, where the heater is automatically turned off (a non-power increase around 2 °C to 62 °C). Then, the water temperature in the WCT increased by about 3 °C from 31 °C to 34 °C for 14108 seconds, while during heating, the water temperature only rose about 32 °C. Therefore, during heating, the power used to raise 1 °C of water of mass 7461.8 kg in the WCT for 4505 seconds requires 6.92 kW.

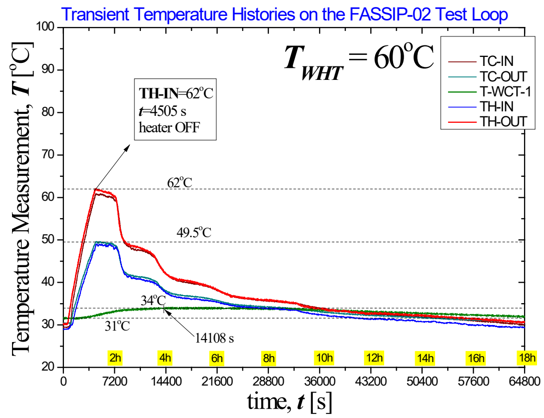


**Fig 2**: Transient temperature histories f or setting temperature WHT is 60°C

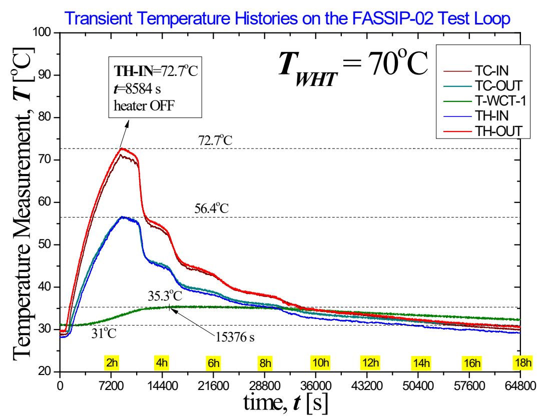


**Fig. 3**: Transient temperature histories for setting temperature WHT is 70°C

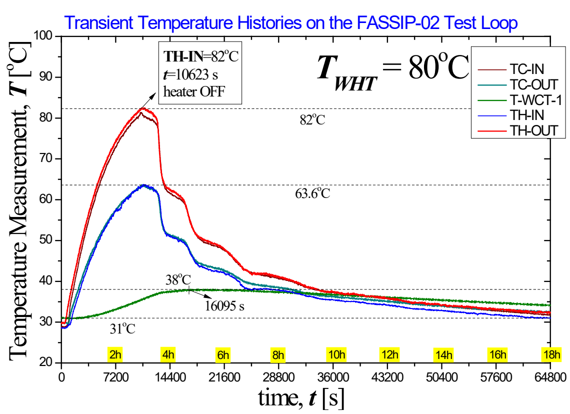


**Fig. 4**: Transient temperature histories for setting temperature WHT is 80°C

Figure 3 shows that heating with a maximum power of 20 kW raises the water temperature from the initial condition (31 °C). It takes about 8584 seconds to reach 70 °C, where the heater is automatically turned off (a non-power increase around 2.7 °C to 72.7 °C). Then, the water temperature in the WCT increased by about 4.3 °C from 31 °C to 35.3 oC for 15376 seconds, while during heating, the water temperature only rose about 33.3 ºC. Therefore, during heating, the power used to raise 2.3 ºC of water of mass 7461.8 kg in the WCT for 8584 seconds requires 8.34 kW.

Figure 4 shows that heating with a maximum power of 20 kW raises the water temperature from the initial condition (31 ºC). It takes about 10623 seconds to reach 80 ºC, where the heater is automatically turned off (a non-power increase around 2 ºC to 82 ºC). Then, the water temperature in the WCT increased by about 7 ºC from 31 ºC to 38 ºC for 16095 seconds, while during heating, the water temperature only rose about 35.5 ºC. Therefore, during heating, the power used to raise 4.5 ºC of water of mass 7461.8 kg in the WCT for 10623 seconds requires 13.19 kW.

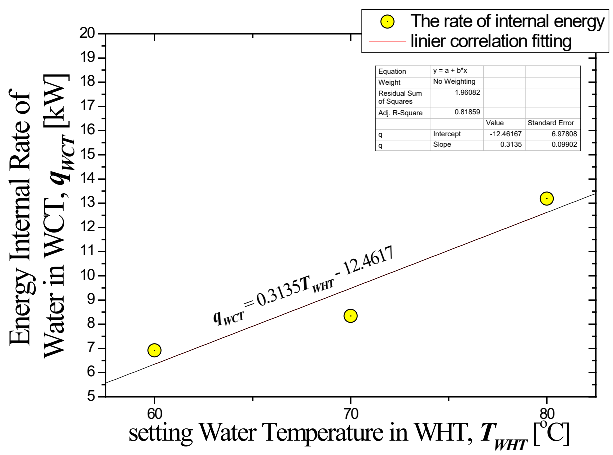


**Fig. 5:** Relation the rate of water internal energy for water temperature variations inside WHT

Based on Figure 2, Figure 3, and Figure 4, by combining the amount of power consumed (the rate of internal water energy) by the water in the WCT and causing an increase in water temperature inside WCT during heating, there is a relationship between the rate of change of internal air energy in the WCT and the variations of water temperature inside the WHT as shown in Fig. 5.

The linear fitting from Fig. 5 shows that the correlation is $q_{WCT} = 0.3135T_{WHT} - 12.4617$ with Adj. R-square 0.81859. This relationship is reasonable, that the increase in water temperature setting in WHT causes an increase in energy consumption by water in WCT, although with a confidence level of around 81.86%.

### 3.2 NC Flow Velocity Measurements and Reynolds Number

NC flow rate measurements were also carried out for 24 hours, but the data presented was only 18 hours. All NC flow rate data were smoothed using the adjacent-averaging with 200 iteration method so that the ripples that appear during the measurement can be smoothed out. The measurement results present in meters per second, with the highest NC flow velocity variations of 0.208 m/s, 0.243 m/s, and 0.291 m/s. The graphs of flow velocity against time are shown in Fig. 6.

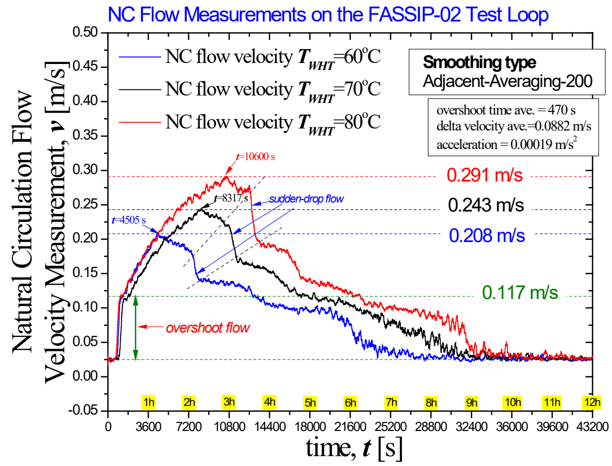


**Fig 6**: NC flow velocity measurements based on the differences of water initial temperature in WHT

The exciting thing from the NC flow rate measurement results (see Fig. 6) is that there is an overshoot flow since the heater was turned on where there is an increase in the NC flow velocity from 0 m/s to 0.117 m/s in the average time interval of about 516 seconds for all variations of water temperature settings in WHT. The overshoot flow condition can be assumed that when the heater is turned on, the water in the WHT with a large volume is heated and receives a large amount of energy, resulting in a significant expansion of the water and causing a buoyancy force that pushes water into the output pipe of the WHT with a smaller volume. The difference in the area of the WHT tank (24 inches) and the WHT drain pipe (1 inch) causes a sudden increase in the flow rate and lasts for 516 seconds. After 516 seconds, the temperature difference between the inlet and outlet WHT begins to decrease. Then, gradually the flow rate increased until it reached the maximum speed (heater off). It can see in Fig. 6 that during the transient cooling process, it takes longer to reach the initial speed (about 0 m/s), or the NC rate in the loop has stopped. Thus, the time required for NC flow to stop is about 6 hours to 7.5 hours. In addition to overshoot flow during transient heating, there is also a sudden-drop flow during transient cooling. The decrease in flow rate gradient occurs almost the same for all WHT water temperature setting variations. Therefore, it can also be assumed that there is a massive reduction of the internal energy inside the WHT, resulting in a sudden drop in the buoyancy force and a drastic reduction in the NC flow rate.

Reynolds number calculation has been carried out using equation (1) after converting NC flow rate measurement data into NC flow velocity, then obtaining density values (equation 2) and dynamic viscosity of water (equation 3) based on changes in the average temperature of water from the part of WHT and HE (heat exchanger) in WCT. The Reynolds number calculated for the three variations of water temperature settings in WHAT is shown in Fig. 7.

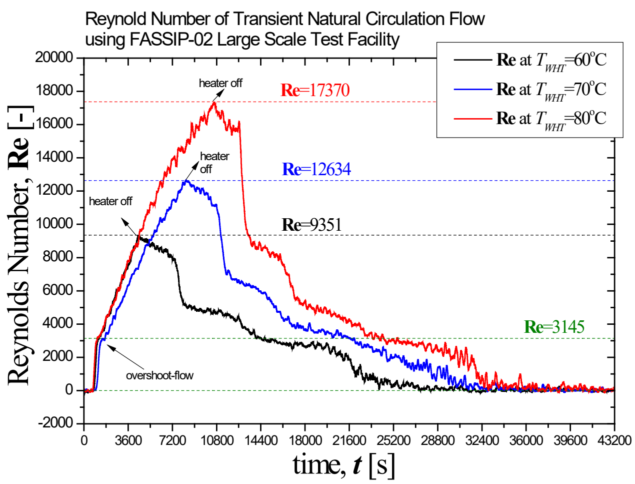


**Fig 7**: Reynolds number for three variations of water temperature inside WHT

As seen in Fig. 7, the Reynolds number when the overshoot-flow occurs from the zero flow state is in the transition flow regime. Then, after reaching the peak point of NC flow at Reynolds number 3145 (transition regime), the Reynolds number gradually increased until the peak point when it turned the heater off. The highest Reynolds numbers are 9351, 12634, and 17370, respectively, based on the water temperature setting in WHT starting from 60 ºC, 70 ºC, and 90 ºC. The results of this experiment show that the FASSIP-02 Test Strand facility can produce NC flow rates with a high Reynolds number (turbulent regime) without any pump assistance at all. Thus, the application of passive cooling systems in nuclear reactor safety systems, especially in an accident, can effectively carry out the heat transferred from the reactor core based on the flow capability into the full transition regime (above 10000).

## 4. Conclusion

The experiments have been done by varying the temperature setting in the heat source (WHT), respectively, for water temperature are 60 ºC, 70 ºC, and 80 ºC. The results showed that the flow was formed in a fully turbulent flow regime, with the Reynolds numbers 9352, 12634, and 17370, respectively, for variations in temperature settings of 60 ºC and 70 ºC, and 80 ºC. Furthermore, during the experiment, there is an interesting phenomenon: the overshoot-flow and sudden-drop flow phenomenon. The temporary assumption of these two phenomena is caused by boundary conditions with volumetric differences in the hot section of the tank and the FASSIP-02 test loop piping system. So that further and more in-depth research needs to be performed to find out the causes of the overshoot-flow and sudden-drop flow phenomena based on the geometry of the facility.

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