Experimental Study of Thermal Behavior of a Single-phase Natural Circulation Loop with Vertical Heater and Cooler

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Abstract. The natural circulation systems have been widely applied to various technologies, for example, safety systems in molten salt reactors. Hence the instability of the natural circulation system became an exciting topic to study. This study aimed to find out the effect of horizontal width variation on the thermal behavior of a single-phase natural circulation loop (NCL) with vertical heater and vertical cooler. Three loops with horizontal widths of 50 cm, 100 cm, and 150 cm, respectively, were designed for experimental studies. Meanwhile, the vertical height of all three loops was 100 cm. The cooler was installed vertically on the upper arm of the loop to cool the fluid. The heater was installed vertically on the forearm on the other side of the loop to heat the fluid. K-type thermocouples integrated with the data acquisition system were used to measure the temperature distribution in several zones of the loop directly. The conclusion obtained in this study was a single-phase natural circulation loop with vertical heater and vertical cooler did not indicate a reversal of the direction of heat transfer at each operating power and geometry configuration. This study is expected to be one of the references to the design of a single-phase natural circulation loop as an advanced nuclear reactor passive safety system.

1. Introduction

The natural circulation system is a physics concept that has been widely applied in various technologies, for example, in solar panel passive cooling systems, electronic component thermal control, and nuclear reactor safety systems [1-6]. Natural circulation in nuclear reactor safety systems leads a role in the heat transfer from high-temperature fluids to low-temperature fluids without mechanical devices [7, 8]. Therefore, natural circulation begins to be applied to overcome the failure of active cooling devices due to a lack of electricity supply, as happened in March 2011 at Fukushima Daiichi, Japan [9-11]. The thermal-hydraulic mechanism in pressurized water reactors based on natural circulation could remove large power fractions [12]. One of the six Generation IV reactor candidates, a molten salt reactor, utilizes natural circulation to circulate molten fuel in the reactor core to increase passive safety and simplify the design [13]. In this case, the molten salt reactor is a reactor that uses fuel in the form of molten salt from a mixture of LiF-BeF₂-ThF₄-²³⁵UF₄ or LiF-BeF₂-ThF₄-(PuMA)Fₓ, as reported in papers [14-17].
Experimental studies of the natural circulation loop using molten salt as working fluid have been carried out in paper [18], where molten salt used was a mixture of NaNO₃ and KNO₃ with a ratio of 60:40. Research on the instability of the natural circulation loop is an interesting topic to study. It is supported by the natural circulation loop designs that have been proposed and verified experimentally by many researchers. Paper [19] compared four orientations of heater and cooler in a single-phase natural circulation loop, namely horizontal heater horizontal cooler (HHHC), horizontal heater vertical cooler (HHVC), vertical heater horizontal cooler (VHHC), and vertical heater vertical cooler (VHVC). Paper [20] compared three loops that have a different height between heater and cooler. Paper [21] proposed a heater and cooler design, which was arranged from a tube-in-tube with water flowing through the annulus. Paper [22] submitted a cooler by using a thermoelectric cooler, which was controlled by using a microcontroller.

Motivated from the description above, was carried out an experimental study of the thermal behavior of the natural circulation with vertical heater and vertical cooler. In this research, the thermal behavior of three loops with a vertical height of 100 cm and a horizontal width of 50 cm, 100 cm, and 150 cm was studied. Where the heater utilized an electric heating wire, and the cooler utilized a pipe-in-pipe system with water flowing through the annulus. This study is expected to be one of the references to the design of a single-phase natural circulation loop as an advanced nuclear reactor safety system.

2. Experiment Setup

The natural circulation loop (NCL) experimental apparatus was designed using polyvinyl chloride (PVC) pipes, stainless steel pipes, and a borosilicate pipe with a uniform radius of ½ inches. A borosilicate pipe is a transparent pipe so that it could be utilized to observe the fluid flow in the loop visually. The length of the borosilicate pipe used was 34 cm. The borosilicate pipe was installed on the forearm of the loop. In this study, stainless steel pipes were utilized to arrange the cooler and the heater. The NCLs apparatus were designed vertically with different widths, as shown in Table 1.

| Loop name | Vertical height (cm) | Horizontal width (cm) | Total length of PVC pipes (cm) | Total length of stainless steel pipes (cm) | Distance between expansion tank and cooling arm (cm) |
|-----------|----------------------|-----------------------|-----------------------------|----------------------------------------|----------------------------------|
| Loop A    | 100                  | 50                    | 220                         | 46                                     | 23                                |
| Loop B    | 100                  | 100                   | 320                         | 46                                     | 23                                |
| Loop C    | 100                  | 150                   | 420                         | 46                                     | 23                                |

The cooler was installed vertically on the upper arm of the loop to cool the fluid. The cooler was arranged from pipe-in-pipe with cooling fluid flowing through the annulus. In this case, the outer pipe was a PVC pipe of 30 cm length and 3 inches radius. Meanwhile, the inner pipe was a stainless steel pipe of 28 cm length and ½ inches radius. The cooling fluid flowing through the annulus was circulated using a pump. The temperature and flow rate of the cooling fluid were set in the range of 26°C-28°C and 1.5 dm³/min, respectively. The heater was installed vertically on the forearm on the other side of the loop to heat the fluid. The heater was designed using a nichrome wire wrapped around an 18 length stainless steel pipe. The length and resistivity of the nichrome wire used were 3.5 meters and 13.43 Ω/m, respectively. Variac was used as a heater voltage source. An expansion tank that opens to the atmosphere was installed at the top of the loop. With the expansion tank at the top of the loop, it was ensured that the natural circulation loop was entirely filled with water. The physical form of the natural circulation loop with a horizontal width of 50 cm, as shown in Figure 1.
The temperature distribution in each natural circulation loop configuration was measured directly using four K-type thermocouples with a measurement resolution of 0.25°C. Four K-type thermocouples were installed 6 cm above the heater (TC1), 6 cm under the heater (TC2), 6 cm above the cooler (TC3), and 6 cm under the cooler (TC4). The thermocouples were integrated with a data acquisition system designed using an Arduino microcontroller, Wiznet W5100 module, and XAMPP software. The data acquisition system could receive data at a rate of 1.5 seconds.

3. Result and Discussions
The experiments were carried out for 70 minutes in each natural circulation loop configuration. The duration of the experiment was based on the results of the research that have been conducted in the papers [23, 24]. In this case, the natural circulation loop reached a stable condition in less than 35 minutes. The main observation in the experiment was the thermal behavior at several zones in the NCL that was detected by K-type thermocouples.
3.1. The temperature distribution

In this study, the effect of horizontal width variation on the temperature distribution in the loop was studied at the heater power of 257 watts. The observations of the temperature distribution in Loop A, Loop B, and Loop C are shown in Figure 2, Figure 3, and Figure 4, respectively. All of them show a significant temperature rise when the heater activated. In this case, the temperature rise starts from TC1 then followed by TC3 and TC4, and finally, TC2. Therefore, the direction of water temperature rise in all three loops is counter-clockwise.

In Loop A, the initial temperature of the water before the heater activated, measured by each thermocouple, is 27.50°C. Furthermore, up to 1.800 seconds, the percentage of water temperature rise measured by TC1 is 92%, then TC3 is 90%, TC4 is 78%, and TC2 is 71%. After 1.800 seconds, the water temperature shows a stable condition. The measured temperature of TC1 and TC3 tends to be the same. It indicates that the water temperature along the pipeline connecting the top of the heater and cooler is homogeneous when a stable condition achieved. The temperature measured by TC2 is lower than TC4. Where the temperature difference between them is 2.50°C.

Before the heater activated, the water temperature measured by each thermocouple in Loop B is 27.25°C. The percentage of water temperature rise measured by TC1 up to 1.800 seconds is 87%, then
TC3 is 85%, TC4 is 78%, and TC2 is 71%. The temperature measured by TC1 shows several peaks, but it can be observed that a stable condition is dominant. The tendency of stable temperature can also be observed after 1,800 seconds. Then, the temperature measured by TC1 and TC3 tends to the same as happened in Loop A. Meanwhile, the temperature measured by TC2 is also lower than TC4 with a temperature difference of 1.5°C. It indicates that the water temperature tends to be homogeneous in the pipeline connecting the top of the heater and cooler as well as in the pipeline connecting the bottom of the heater and cooler when a stable condition achieved. This result resembles the experimental result using a natural circulation loop of 100 cm height and 100 cm width with horizontal heater and horizontal cooler at the heater power of 180 watts that performed in paper [24].

In Loop C, the initial temperature measured by the thermocouple is 26.25°C. After the heater activated, the temperature rise sharply occurs at the temperature measured by TC1, reaching 172%. Meanwhile, the temperature rise measured by TC3, TC4, and TC2 is 113%, 34%, and 27%, respectively. Unlike the results obtained in Loop A and Loop B, the water temperature in the pipeline connecting the top of the heater and cooler in Loop C is not homogeneous. The temperature difference measured by TC1 and TC3 after 1,800 seconds reaches 15.5°C. As a result of receiving high temperatures for a long time, Loop C that is dominantly made from the PVC pipe, becomes bent. It can occur because the location of the expansion tank that does not allow excess pressure resulting from water heating decreases quickly. This result correlates with experimental and numerical studies in paper [25]. In this case, the expansion tank has an important role in a single-phase natural circulation loop to release excess pressure and maintain the thermal expansion of water.

The observation of the temperature distribution in Loop A, Loop B, and Loop C shows that the wider the loop, the lower the water temperature along the pipeline connecting the bottom of the heater and cooler when a stable condition achieved. It can occur because of the cooler more full-length than the heater. It makes the amount of water-cooled more than the amount of water-heated. Where the more significant the loop dimension, the more volume of water in the loop. Therefore, the more extensive the loop, the more the amount of water with low temperature.

3.2. The temperature difference between TC1 and TC4
The thermal behavior of the natural circulation loop conducted in this study, was also observed from the temperature difference between the water coming out of the heater (measured by TC1) and the cooler (measured by TC4) in Loop A and Loop B. Meanwhile, Loop C was not observed because it has broken. This experiment was carried out at the heater power of 16 watts, 66 watts, and 257 watts.

![Figure 5. The temperature difference between TC1 and TC4 in the loop of 50 cm width](image-url)
Figure 6. The temperature difference between TC1 and TC4 in the loop of 100 cm width

At the heater power of 16 watts and 66 watts, the temperature difference of the water coming out of the heater and the cooler in Loop A shows a stable condition, as shown in Figure 5. The temperature difference oscillation of the water coming out of the heater and the cooler in Loop A occurs at the heater power of 257 watts. However, the oscillation does not occur in a negative value. The same case also occurs in loop B, as shown in Figure 6. Based on the experimental results obtained in Loop A and Loop B, a single-phase natural circulation loop with vertical heater and vertical cooler does not show a reversal of the direction of heat transfer. Therefore, a single-phase natural circulation loop with vertical heater and vertical cooler tends to have a stable condition at each operating power and geometrical configuration. Similar results were also shown in studies conducted in papers [19, 26-28].

Figure 5 and Figure 6 show the higher the heating power, the higher the value of the temperature difference of the water coming out of the heater and the cooler. However, the temperature difference of the water coming out of the heater and the cooler has a maximum point, as shown in the two loops at the heater power of 257 watts. When the maximum point reached, the temperature difference of the water coming out of the heater and the cooler tends to be stable or oscillating at that point.

Also, it can be observed that Loop B has a value of the temperature difference of the water coming out of the heater and the cooler higher than Loop A. This result supports the results discussed in subsection 3.1. It can occur because of the volume of water in Loop B more than Loop A. Besides, the horizontal distance of water flowing in Loop B more full-length than Loop A, so that allows the frictional force which received by water in Loop B higher. Therefore, a higher buoyancy force is needed to circulate water in Loop B. Where the natural circulation occurs when the buoyancy force produced by the temperature difference overcomes the frictional force in the loop. This result correlates with the results discussed in papers [29-32].

4. Conclusions
An experimental study of the thermal behavior of a single-phase natural circulation loop with vertical heater and vertical cooler (VHVC) has been carried out. Stable heat transfer with the counter-clockwise direction was found in each loop configuration. In this case, the temperature rise started from above the heater then followed by above and under the cooler, and finally, under the heater. Thus, a single-phase natural circulation loop with vertical heater and vertical cooler did not show a reversal of the direction of heat transfer at each operating power and geometry configuration. The setting of the expansion tank is crucial in the design of a single-phase natural circulation loop to release excess pressure and maintain the thermal expansion of water. The loop of 100 cm width had a value of the temperature difference of the water coming out of the heater and the cooler 58% higher than the loop of 50 cm width at the same heater power. The future work is to find out a method to measure the rate of fluid flow in the loop without disrupting the natural circulation system.
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