Experimental Investigation of Natural Circulation in a Single-Phase Loop with Different Widths

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***Abstract*—The natural circulation loop is one of the design concepts of a cooling system in new advanced reactors that has attracted many researchers to develop it. This study aimed to perceive the effect of horizontal width variation on the thermal behavior of a single-phase Natural Circulation Loop (NCL). NCL apparatus with a vertical heater and a vertical cooler was designed for experimental study. The height of the loop was 100 cm while the width of the loop was varied at 50 cm and 100 cm. The heater was designed using Nichrome wire on the outside of the stainless pipe while the cooler was designed using pipe-in-pipe with water flowing through the annulus. Arduino microcontroller and K-type thermocouple sensors were used in temperature data acquisition. XAMPP software was used in data recording. The results of this study indicated that the loop of a 100 cm width has a difference in the temperature of the fluid coming out of the heater and entering the heater that reaches 156,0% higher than the loop of a 50 cm width at the same input voltage. This study is supposed to be one of the references for a single-phase natural circulation loop.**

***Index Terms*—natural circulation, single-phase, temperature, width variation**

I. Introduction

The basic concepts of physics have been widely applied in this era, one of which is natural circulation. Natural circulation is a type of heat transfer in a fluid medium, where fluid flow is produced by differences in fluid density due to temperature gradients or phase changes [1]. Natural circulation leads an important role in the heat transfer from high-temperature sources to low-temperature coolers without external power or mechanical devices [2]. Therefore, a natural circulation loop is extensively applied to energy conversion systems such as cooling systems for solar panels and nuclear reactors [3]-[7]. The results of the paper [8] about natural circulation as a passive cooling system on solar panels or photovoltaic panels indicated a good performance, wherein, increases the electrical efficiency of the photovoltaic panel by 8,3%. Also, the application of passive cooling systems in photovoltaics using natural circulation offers lower costs than active cooling systems due to reduced pumping costs [9]. The results of the paper [10] indicated that natural circulation as a thermal-hydraulic mechanism is suitable to remove large power fractions in pressurized water reactor, provided the possibility to maintain the fission reaction at low core density conditions. In addition, natural circulation is also one of the cooling system designs that are widely applied to new generation reactors [11]. For example, one of the six Generation IV reactor candidates, molten salt reactor, utilizes natural circulation to circulate molten fuel in the reactor core to increase passive safety and simplify the design [12].

Lately, the natural circulation system is being studied extensively by many researchers especially concerning instability because the natural circulation system is more unstable than the active circulation system [13]. Paper [14] conducted an experimental and numerical analysis related to natural circulation loop with low and medium heating power. The experimental and numerical results showed that periodic oscillations occurred at medium power (power of more than 600 Watt) while the steady-states occurred at low power (power of 180 Watt). The study in paper [15] about the effect of pipe diameter on natural circulation loop instability showed that the greater the pipe diameter the less the temperature difference between vertical pipes. The study about the influence of the orientation of cooler and heater on the natural circulation loop in paper [16] showed that vertical heater and vertical cooler provided the most stable condition. The study in paper [17] showed the higher the loop apparatus, the higher the velocity of water flows in the natural circulation loop. Simulations concerning natural circulation loop conducted on paper [18] showed that the temperature difference gets larger, the flow becomes faster. A large number of studies are available in the literature for natural circulation, but there are still lacks especially in the experimental studies of natural circulation loop. Therefore, an experimental investigation of a single-phase natural circulation loop with a vertical heater and a vertical cooler was carried out. This study aimed to determine the effect of horizontal width variations on thermal behavior in a single-phase natural circulation loop. This study is expected to be one of the references concerning the concept of a single-phase natural circulation loop with a vertical heater and a vertical cooler.

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II. Experimental Setup

The Natural Circulation Loops (NCL) experimental apparatus were designed vertically. The height of the loops was designed of 100 cm while the width of the loops was varied, that was, 50 cm and 100 cm. Natural circulation loops were designed using Polyvinyl Chloride (PVC) pipes, stainless steel pipes, and a borosilicate pipe with a uniform radius of ½ inches. A borosilicate pipe was a transparent pipe that was installed in the forearm of the loop and was used to visually observe the fluid flow. Because of good thermal conductivity, stainless steel pipes were used to arrange the cooler and heater. The cooler with a length of 28 cm was installed vertically on the upper arm of the loop to cool the fluid. The cooler was arranged of pipe-in-pipe with cooling fluid flowing through the annulus. In this case, the outer pipe was designed using a 3 inches radius pipe while the inner pipe was designed using a ½ inches radius stainless steel pipe. The cooling fluid flowing through the annulus was circulated using a pump. The temperature and flow rate of cooling fluid were set in the range of 26°C-28°C and 1,5 dm^3/min, respectively. The heater with a length of 18cm 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 with a length of 3,5 meters and resistivity of 13,43 Ω/m that was wrapped around the outside of the stainless steel pipe. The heater input voltage was varied at 28, 56, 84, and 112 volts that come from the alternating current voltage regulator (variac). The NCL sketch in this study is shown in Fig. 1.

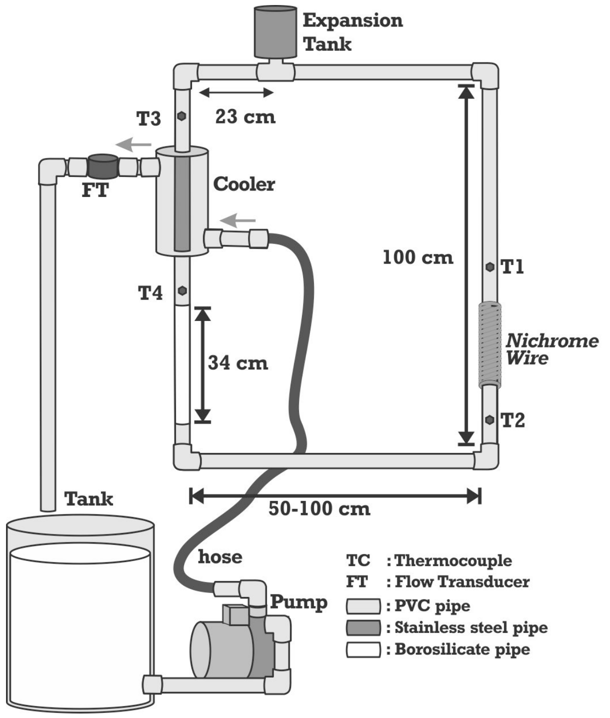

Figure 1. Sketch of single-phase natural circulation loops experiment apparatus.

At the top of the loop, an expansion tank with a radius of 1 inch was installed to release excess pressure and maintain fluid thermal expansion. The natural circulation loop was filled with water until full. The loop was given vibration when water was inserted to minimize air bubbles. With the expansion tank at the top of the loop, it was ensured that the NCL was fully filled with water. The setting of the expansion tank on the loop of a 100 cm width divided into two, namely the expansion tank close to the cooler arm and the expansion tank close to the heater arm, as shown in Fig. 2. That aimed to find out the effect of the expansion tank on the loop. The configuration of the experimental natural circulation loop apparatus in this study, as listed in Table I.

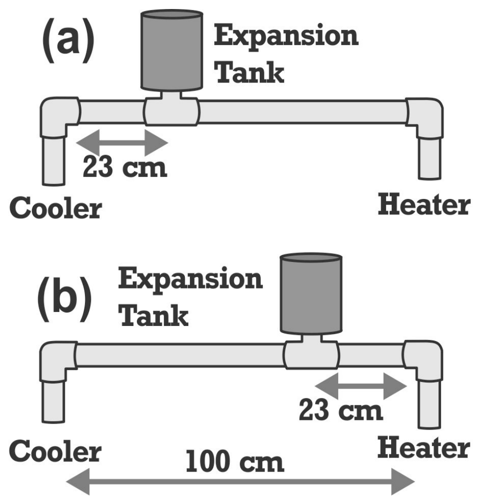

Figure 2. The loop of a 100 cm width with (a) the expansion tank close to the cooler arm and (b) the expansion tank close to the heater arm.

TABLE I. The Configuration of the Loops

No.	Loop name	Horizontal width (cm)	Total length of PVC pipe (cm)	The distance of the expansion tank from the cooler arm (cm)
1	Loop A	50	220	23
2	Loop B	100	320	23
3	Loop C	100	320	77

Four K-type thermocouples sensors integrated with the data acquisition system were used to directly observe differences of fluid temperatures at several zones in the loop. Four K-type thermocouples were installed at 6 cm above the heater (T1), 6 cm under the heater (T2), 6 cm above the cooler (T3), and 6 cm under the cooler (T4). The thermocouples have a resolution of 0,25°C. The data acquisition system which was arranged by an Arduino microcontroller, Wiznet W5100 module, and XAMPP software could receive data at the rate of ± 1 second.

III. Results and Discussion

Experiments were carried out for 60 minutes in each natural circulation loop configurations. The main observation in the experiment was thermal behavior at several zones in the NCL that was detected by K-type thermocouples. The results obtained are as follows.

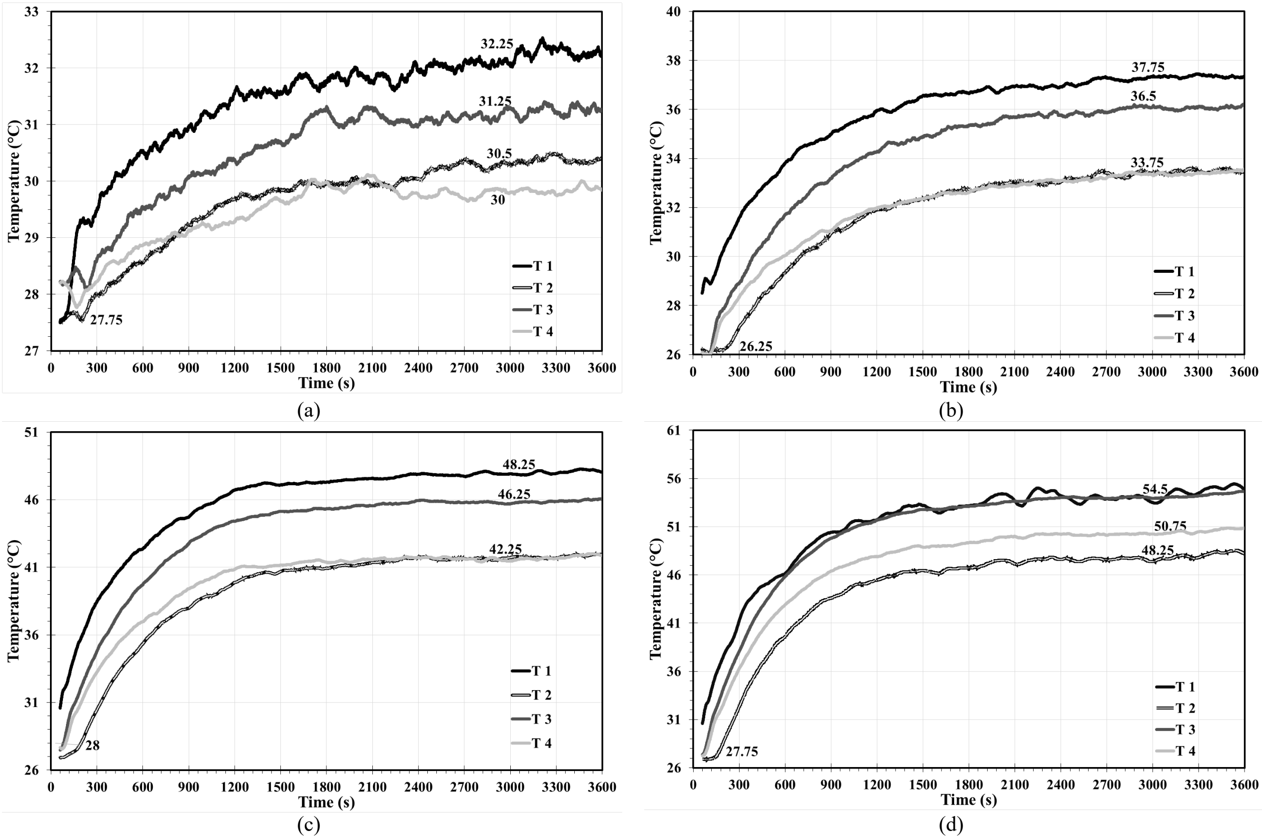

Figure 3. Results of the loop of a 50 cm width at heater voltage (a) 28 volts (b) 56 volts (c) 84 volts (d) 112 volts.

A. Results for Loop A

Fig. 3 (b) shows the results of a natural circulation loop experiment with a horizontal width of 50 cm and a heater input voltage of 56 volts. The initial temperature measured by the thermocouples before the heater activated is 26,25°C. After the heater activated, the temperature increases up to reach a stable value in 1800 seconds. After 1800 seconds, the temperatures are still increasing but in a small range of values, at around 0,5°C. The increase in temperature from the initial conditions measured by T1 is 43,8%. While T3 is 39,0%, T4 and T2 are 28,5%.

The initial temperature shown in Fig. 3 (c) is 28,00°C. After a voltage of 84 volts is applied to the heater, the temperature measured by each thermocouple shows an increase up to reach a stable value in about 1800 seconds. The increases in temperature measured by T1 and T3 are 72,3% and 65,1%, respectively. While T4 and T2 show the increases in temperature at the same value of 50,8%.

Fig. 3 (d) shows the experimental results on the loop of a 50 cm width and an input voltage of 112 volts. Before the heater activated, the initial temperature measured by each thermocouple is 27,75°C. After 1800 seconds, the temperature measured by T1, T3, T4, and T2 increase by 98,1%, 96,3%, 82,8%, and 73,8%, respectively. A stable condition can be observed at T2, T3, and T4. The temperature measured by T1 shows oscillations that can be caused by the appearance of water bubbles or the water begins to change phase.

The difference in temperature of the fluid coming out of the heater (measured T1) and the fluid entering the heater (measured T2) for a heater voltage of 28 volts is 2,25°C in a stable condition. Then for heater voltages of 56 volts, 84 volts, and 112 volts are 4,0°C, 6,0°C and 6,25°C, respectively. It shows that the cooler arranged by the pipe-in-pipe in this study can provide a temperature difference of around 6°C for the loop with a 50 cm width and a heater voltage in the range of 28-112 volts.

B. Results for Loop B

Fig. 4 shows the experimental results of a natural circulation loop with a width of 100 cm and an expansion tank close to the cooler arm (loop B) at various input voltages. After the heater activated, the temperature measured by T1 increase, then followed by T3, T4, and T2, as shown in Fig. 4 (a-d). It is the same as happened in the loop of a 50 cm width (loop A). Therefore, the direction of heat flow in the natural circulation loop of a 100 cm width with an expansion tank close to the cooler arm is counterclockwise. Fig. 4 (a) shows the results of fluid temperature measurements with a heater input voltage of 28 volts. After the heater activated, the initial temperature of 26,25°C increase by 17,1%, 14,2%, 8,5%, and 6,6%, each of which is measured by T1, T3, T4, and T2. The trend line measured by each thermocouple shows oscillations, as shown in Fig. 3 (a) due to the measurement resolution of the thermocouple. Thus, the temperature of the fluid inside the loop is stable even though the measurement results oscillate.

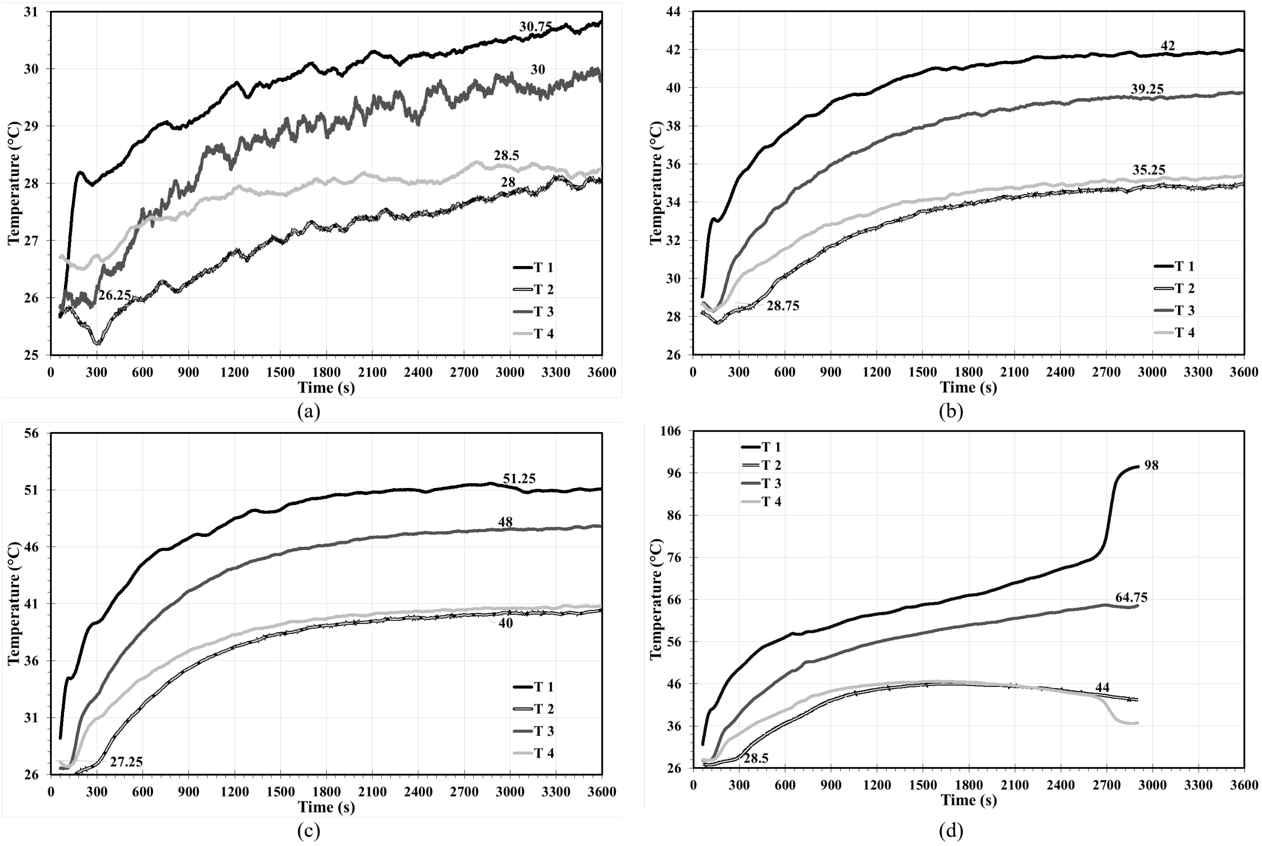

Figure 4. Results of the loop of a 100 cm width with the expansion tank close to the cooler arm at heater voltage (a) 28 volts (b) 56 volts (c) 84 volts (d) 112 volts.

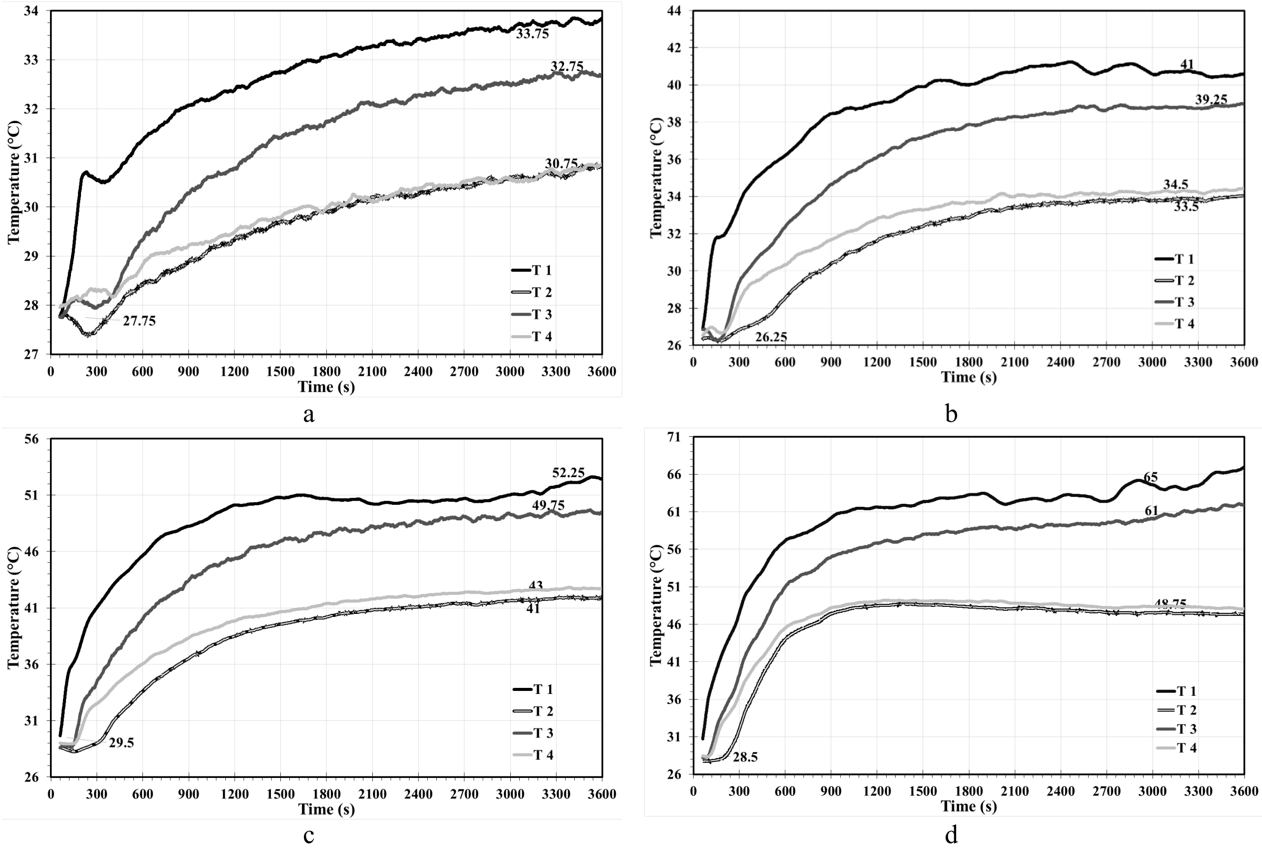

Figure 5. Results of the loop of a 100 cm width with the expansion tank close to the heater arm at heater voltage (a) 28 volts (b) 56 volts (c) 84 volts (d) 112 volts.

The results of temperature measurements by thermocouples at a 56 volts heater voltage are shown in Fig. 4 (b). The initial temperature measured by each thermocouple is 28,75°C. Until reaching a stable value, the temperature measured by T1 increases by 46,0%, T3 by 36,5%, while T4 and T2 by 22,6% within 1800 seconds. At the heater input voltage of 84 volts, the initial temperature of 27,25°C also increases up to reach a stable value, as shown in Fig. 4 (c). In this case, the increase in temperature measured by T1 is 88,0%, T3 is 76,1%, while T4 and T2 are 46,7% within 1800 seconds.

Fig. 4 (d) shows the results of the measurement of fluid temperature in the loop B at a heater voltage of 112 volts. After the heater activated, the temperature measured by each thermocouple increases. About 2700 seconds later, the temperature measured by T1 rises sharply to reach 98°C, which is the temperature point of boiling water. It makes the loop that is designed by PVC pipes cannot withstand the heat of the water. Finally, the PVC pipes become bent. After that, water comes out of the expansion tank. It can be caused by the location of the expansion tank that does not allow excess pressure to decrease quickly.

The difference in temperature measured by T1 and T2 at a heater voltage of 28 volts, 56 volts, and 84 volts is 2,75°C, 6,75°C, and 11,25°C, respectively. These results indicate that the difference in temperature of the fluid coming out of the heater and the fluid entering the heater in loop B is higher than loop A. It can be caused by the amount of fluid-heated and cooled in loop B is more than loop A. Besides, the cooler is longer than the heater. So, it makes the amount of fluid-cooled is more than the amount of fluid-heated.

C. *Results for Loop C*

Fig. 5 shows the temperature measured by the thermocouples in the loop of a 100 cm width and an expansion tank close to the heater arm (loop C). After the heater activated, the temperatures rise in the same sequence as in loops A and B occurred in loop C. In this case, the temperature rise starts from T1, then follows T3, T4, and T2. This result also shows that the direction of heat flow in loop C is counterclockwise. Based on the results of experiments on loop A, loop B, and loop C, a single-phase loop with vertical heater and vertical cooler tend to have a stable condition in each operation and geometry configuration. This result is also shown in the paper [16]-[19].

When a voltage of 28 volts applied to the heater for about 1800 seconds, Fig. 5 (a) shows the increase in temperature measured by T1 is 21,6%, T3 is 18,0%, while T4 and T2 are 10,8%. In this case, the initial temperature measured by each thermocouple is 27,75°C. After a voltage of 56 volts applied to the heater for 1800 seconds, the temperature measured by each thermocouple rises to a stable value, as shown in Fig. 5 (b). Where, the initial temperature of 26,25°C measured by T1, T3, T4, and T2 each increased by 56,1%, 49,5%, 31,4%, and 27,6%. The results of temperatures measurement by the thermocouples in loop C with a heater voltage of 84 volts are shown in Fig. 5 (c). After the heater activated for 1800 seconds, the initial temperature of 29,5°C increases up to reach a stable value. The increases in temperature measured by T1, T3, T4, and T2 are 77,1%, 68,6%, 45,7%, and 38,9%, respectively.

Fig. 5 (d) shows the fluid temperature in the loop of a 100 cm width with an expansion tank close to the heater arm (loop C) at a heater voltage of 112 volts. Unlike loop B, loop C can withstand the increase in temperature after the heater is activated. It caused by the location of the expansion tank allows the pressure to be maintained stable. This result indicates that the expansion tank has an important role in a single-phase natural circulation loop. This result has also been demonstrated experimentally and numerically in paper [20]. The initial temperature measured by each thermocouple is 28,5°C, as shown in Fig. 5 (d). After 1200 seconds, the temperature of the fluid increases up to reach an almost stable value. The increase in temperature measured by T1 is 128,0%, T3 is 114,0%, while T4 and T2 are 71,0%.

The difference in temperature of the fluid coming out of the heater and the fluid entering the heater in loop C at 28 volts, 56 volts, 84 volts, and 112 volts is 3,0°C, 8,0°C, 11,0°C, and 16,0°C, respectively. This result supports the result of experiments on loop B. Thus, the difference in temperature of the fluid coming out of the heater and the fluid entering the heater in the loop of a 100 cm width is higher. Based on the previous discussion, the amount of low-temperature fluid in the loop of a 100 cm width is more than in the loop of a 50 cm width. In this case, the percentage of water volume in the loop of a 100 cm width is approximately 33,3% more than the loop of a 50 cm width.

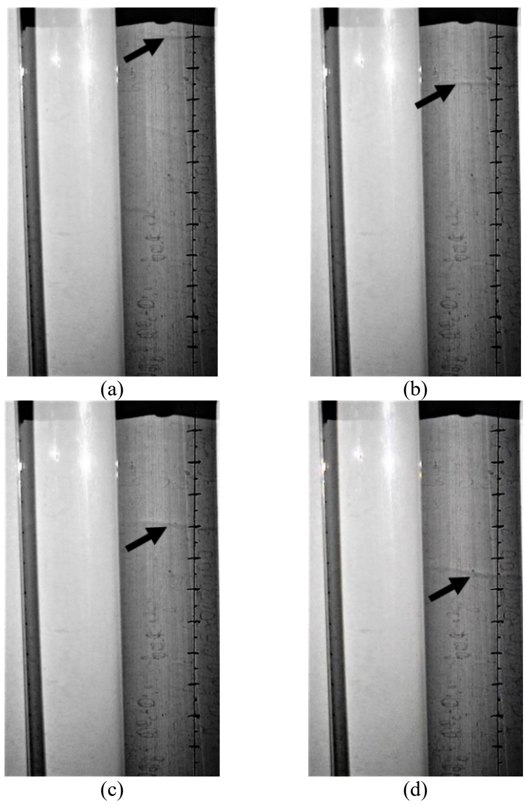

Figure 6. Visual observations of a natural circulation loop of 50 cm width at (a) 56,68 s, (b) 57,01 s, (c) 57,34 s, and (d) 57,68 s.

D. Results of Visual Observations

The trend line in Fig. 3, Fig. 4, and Fig. 5 illustrate that the heat convection flow in the loops is counterclockwise. This is supported by visual observations on borosilicate pipes. Fig. 6 shows the results of visual observations on the loop of a 50 cm width (loop A) at a heater input voltage of 112 volts. Fig. 6 is obtained by recording the fluid flow shadow that passes through the borosilicate pipe. In this case, the borosilicate pipe is illuminated with enough light to form a shadow on a screen. The shadow of the fluid flow is the horizontal line that is indicated by a black arrow. The horizontal line leads from the top to bottom, that is, from under the cooler to under the heater. Therefore, the direction of fluid flow is counterclockwise. Also, counterclockwise fluid flow can be observed in loop B and loop C. The fluid flow is generated by the temperature difference in the fluid. Wherein, the temperature difference generates a change in fluid density resulting in a buoyancy force that overcomes the magnitude of the frictional force. This result has also been demonstrated experimentally in paper [21].

IV. Conclusions

An experimental investigation of a single-phase natural circulation loop with vertical heater and vertical cooler had been carried out. The experimental results showed that stable conditions could be found in a single-phase natural circulation loop with vertical heater and vertical cooler. In the loop of a 50 cm width, the increase in temperature measured by the thermocouple above the heater reached 98,1% while in the loop of a 100 cm width, it reached 128,0%. The loop of a 100 cm width has a difference in the temperature of the fluid coming out of the heater and entering the heater that reaches 156,0% higher than the loop of a 50 cm width at the same input voltage. The expansion tank has an important role in a single-phase natural circulation loop to maintain excess pressure. In this case, the expansion tank close to the heater arm allows the loop to withstand the increase in high-temperature. The increase in temperature started from above the heater, followed by above and under the cooler and finally, under the heater showed the counterclockwise fluid flow direction. In the future work, the results of visual observation must be analyzed intensively by considering the magnification of the shadow and the ability of the camera so that an estimated flow rate of the fluid can be obtained.

Conflict of Interest

The authors declare no conflict of interest

Author Contributions

Duwi Hariyanto as a master's student and Sidik Permana as a supervisor. All authors conducted the research, analyzed the data, and wrote the paper. All authors had approved the final version.

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References

[1] D. Lu, X. Zhang, and C. Guo, “Stability analysis for single-phase liquid metal rectangular natural circulation loops,” *Ann. Nucl. Energy*, vol. 73, pp. 189-199, November 2014.

[2] M. Misale, “Overview on single-phase natural circulation loops,” in *Proc. Conf. Adv. Mech. Auto. Eng.*, Rome, 2014, pp. 72-83.

[3] M. Misale and M. Frogheri, “Stabilization of a single-phase natural circulation loop by pressure drops,” *Exp. Ther. Fluid Sci.*, vol. 25, no. 5, pp. 277-282, November 2001.

[4] Y. Zvirin, “A review of natural circulation loops in pressurized water reactors and other systems,” *Nucl. Eng. Design*, vol. 67, no. 2, pp. 203-225, January 1982.

[5] F. D’Auria, G. M. Galassi, and M. Frogheri, “Natural circulation performance in nuclear power plants,” in *Proc. the 2nd Conf. the Croatian Nuclear Society*, Croatia, 1998, pp. 213.

[6] F. D’Auria, M. Frogheri, and U. Monasterolo, “Removable power by natural circulation in PWR systems,” in *Proc. the 5th Int. Conf. Nucl. Eng.*, France, 1997, pp. 1-9.

[7] K. Naveen, K. N. Iyer, J. B. Doshi, and P. K. Vijayan, “Investigations on single-phase natural circulation loop dynamics part 1: Model for simulating start-up from rest,” *Prog. Nucl. Energy*, vol. 76, pp. 148-159, September 2014.

[8] S. Wu and C. Xiong, “Passive cooling technology for photovoltaic panels for domestic houses,” *Int. J. Low-Carbon Tech.*, vol. 9, no. 2, pp. 118-126, June 2014.

[9] F. Grubišić-Čabo, S. Nizetic, and G. M. Tina, “Photovoltaic panels: A review of the cooling techniques,” *Transactions of FAMENA*, vol. 40, no. SI, pp. 63-74, June 2016.

[10] F. D’Auria and G. M. Galassi, “Natural circulation situations relevant to nuclear power plants,” in *Proc. the GCNEP-IAEA Course on Natural Circulation Phenomena and Passive Safety Systems in Advanced Water Cooled Reactors*, Pisa, 2009.

[11] Q. Wu and J. J. Sienicki, “Stability analysis on single-phase natural circulation in Argonne lead loop facility,” *Nucl. Eng. Design*, vol. 224, no. 1, pp. 23-32, September 2003.

[12] A. M. Pauzi, A. Cioncolini, and H. Iacovides, “Parametric study of natural circulation flow in molten salt fuel in molten salt reactor,” *AIP Conf. Proc.*, vol. 1659, no. 1, April 2015.

[13] P. K. Vijayan, A. K. Nayak, D. Saha, and M. R. Gartia, “Effect of loop diameter on the steady state and stability behaviour of single-phase and two-phase natural circulation loops,” *Sci. Tech. Nucl. Installations*, vol. 2008, pp. 1-17, 2008.

[14] R. Saha, S. Sen, S. Mookherjee, K. Ghosh, A. Mukhopadhyay, and D. Sanyal, “Experimental and numerical investigation of a single-phase square natural circulation loop,” *J. Heat Transfer*, vol. 137, no. 12, pp. 101-108, December 2015.

[15] H. Cheng, H. Lei, and C. Dai, “Heat transfer of a single-phase natural circulation loop with heating and cooling fluids,” *Energy Procedia*, vol. 142, pp. 3926-3931, December 2017.

[16] P. K. Vijayan, M. Sharma, and D. Saha, “Steady state and stability characteristics of single-phase natural circulation in a rectangular loop with different heater and cooler orientations,” *Exp. Ther. Fluid Sci.,* vol. 31, no. 8, pp. 925-945, August 2007.

[17] H. Abdillah, G. Saputra, Novitrian, and S. Permana, “Study of natural convection passive cooling system for nuclear reactors,” *J. Phy.: Conf. Ser.*, vol. 887, 2017.

[18] R. R. Septiawan, H. Abdillah, Novitrian, and Suprijadi, “Preliminary study on liquid natural convection by temperature differences,” in *Proc. the 2014 Int. Conf. Adv. Edu. Tech.*, Bandung, 2015.

[19] S. Thomas and C. B. Sobhan, “Stability and transient performance of vertical heater vertical cooler natural circulation loops with metal oxide nanoparticle suspensions,” *Heat Transfer Eng.*, vol. 39, no. 10, pp. 861-873, July 2017.

[20] K. Naveen, K. N. Iyer, J. B. Doshi, and P. K. Vijayan, “Investigations on single-phase natural circulation loop dynamics part 3: Role of expansion tank,” *Prog. Nucl. Energy*, vol. 78, pp. 65-79, January 2015.

[21] H. Abdillah and Novitrian, “Experiments on natural convection as cooling system mecanism on nuclear reactors,” *J. Phy.: Conf. Ser.,* vol. 1204, 2019.

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