Analysis of Heat Loss in Water Heating Tanks Based on Temperature Setting Variation During Natural Circulation Flow using FASSIP-02 Test Loop

Andrea Shevaladze A.A[1], Putut Hery Setiawan[2], Giarno[2], Ainur Rosidi[2], Dedy Haryanto[2], G.B. Heru K.[2], Adhika Enggar P.[2], Esa Putra A.R[3], Ade Tasri[1], Mulya Juarsa[2, *]

[1]Mechanical Engineering Department, Engineering Faculty, Andalas University, Kampus UNAND Limau Manis, Pauh, Padang City, West Sumatra

[2]Reactor Thermal Fluids System Development (RTFSyD) Research Groups, Research Center for Nuclear Reactor Technology, Research Organization for Nuclear Energy, National Research and Innovation Agency (BRIN), Gd.80 Kawasan PUSPIPTEK Setu, Tangerang Selatan 15314

[3]Pancasila University, Jalan Raya Lenteng Agung No.56-80, Srengseng Sawah, Jakarta, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12640

*** Corresponding author:**

e-mail: juars@batan.go.id

phone/WA: +6281310493808

Received: 26-11-2021
Revision Received: 29-10-2022
Accepted: 24-01-2023

DOI :
10.17146/jstni.2022.23.1.6542

Keywords: FASSIP-02, heat loss, natural circulation, temperature, water heating tank

Abstract: *Based on the nuclear reactor accident in Fukushima, the reactor core melted due to the failure of the active cooling system to cool the reactor core. So experimental research on passive cooling systems based on natural circulation flow to improve the safety system in the event of an accident has been carried out using the FASSIP-02 Test Loop. A critical component in passive cooling simulation is the water heating tank. This study aims to obtain the results of the analysis of heat absorption in water heating tanks and the heat loss value. The research method was carried out experimentally by measuring changes in water temperature in the water heating tank using a thermocouple connected to the LabView software. Then the data obtained in the form of temperature data is used to calculate energy changes in water in the water heating tank and heat loss at variations in water temperature settings from 40°C, 50°C, and 60°C in WHT at steady state conditions for 5 hours of the experiment. The results showed that the entire surface of the tank resulted in a heat loss of 10.85 kW, 9.2 kW, and 8.37 kW, which occurred at temperature settings of 40°C, 50°C, and 60°C overall.*

INTRODUCTION

Passive system nuclear safety is currently being investigated due to the nuclear accident at Fukushima Daiichi, where the cooling pump could not work, causing a station blackout, and could not cool the reactor core (1). That condition shows the need for a cooling system that can work without requiring external energy, such as electricity, to drive the pump. And natural circulation is critical in a nuclear reactor safety system to remove decay heat reactor when an accident or reactor shutdown. When the fluid is heated, the density will decrease so that it can move upwards, and when the fluid is cooled to a certain point, the density of the water will increase again so that it will flow downwards with the help of gravity. With this temperature difference, flow in a natural circulation cycle can occur (2).

Several studies on natural circulation and passive cooling systems have been carried out, such as Eshita Pal et al. in the year 2015 on CFD simulation to study the temperature distribution and the distribution of moderator flow in the Calandria tank (3). Furthermore, research conducted by Rae-Joon Park et al. in the year 2016 explained that the increase in the coolant injection temperature and the water level in the reactor cavity caused an increase in the mass flow rate of circulating coolant, which led to the rise in CHF in the outer reactor vessel wall. CHF is an important factor in the success of IVR-ERVC (4). Further research was conducted by Jian Zhang et al. in 2016, who explained that the natural circulation cooling capacity represented by the average natural circulation flow velocity in the core was calculated from the temperature difference between the outlet temperature and the core inlet temperature. And Jian Zhang concludes that the natural circulating flow velocity in the center increases non-linearly with thermal power (5).

Another experiment used a vertical orientation loop with varying power on the heater. Experiments show that the behavior of the circle is always unstable for all power levels; after a short transient, the flow constantly reverses. At low power, the temperature oscillations are regular. In contrast, as the power increases, two different oscillatory modalities can be recognized by repeated flow reversal and oscillation period around the average value, which eventually leading a turnaround. This explains that any increase in the flow rate will cause an increase in friction and decrease the total buoyancy force (6). There are also studies using natural circulation loops built on an experimental platform of six degrees of freedom. It was found that a slight flow acceleration would not cause a significant change in the flow rate of the natural circulation loop. Then, the mechanism of influence of the rolling motion on the natural circulation loop is different due to the changing center axis of rotation. The additional increase in inertial force due to the process along the direction of coolant flow causes more significant flow fluctuations. The coefficient of periodic average friction shows two flow fluctuations, where flow fluctuations with a Re value below 5000 and turbulence areas with a Re value between 5000 to 35000. This indicates that rolling motion can encourage heat transfer with a small flow rate. At the same time, moving motion affects the heat transfer characteristics mainly by influencing the flow rate under conditions of significant flow rates (7).

Then, from the year 2016 until the year 2019, Thermal-hydraulics experimental laboratory 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 of 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 flow meters (8). Experiments were also carried out to analyze the pipe’s flow rate and heat transfer by looking at the phenomena during the investigation and performing calculations based on the derivative of the natural circulation flow formula. (9). And testing the flow rate simulation and energy balance on the addition of power to the heater using RELAP 5/mod 3.2, it was concluded that the higher the power supplied, the higher the energy balance and flow rate (10).

One of the passive cooling system studies, BATAN, has designed and built a large-scale test facility, the FASSIP-02 test loop. It aims to make analytical calculations using multiple correlations to estimate the natural circulation flow rate. (8). Conceptually the design in FASSIP-02 was adapted from SMART, where SMART has a passive cooling system, namely a passive residual heat removal system (PRHRS) to prevent overheating and excess pressure in the reactor core during emergency events, such as SBO, with natural circulation. Then further research was carried out using an advanced passive system DRHRS (direct passive residual heat removal system) with its components, namely the heat output pipe from the pressurizer, a condensation heat exchanger (CHX) contained in the emergency cooling tank (ECT), and direct safety injection nozzles as pipes. Back into the steam generator (SG)(12). And FASSIP-02 test loop also has two main components: Water Heating Tank (WHT) and Water Cooling Tank (WCT). WHT has four heaters helpful in increasing the temperature to the set temperature WCT works to take the heat contained in the flow through the heat exchanger pipe. WHT is a tank installed with four heaters, each of which has a power of 5 kW, which means the total heater is 20 kW. The energy that remains in the water inside the heating tank is received from the heater. It reduces due to heat loss from the tank to the environment. Heat loss is something important that needs to be considered in the system. Therefore, this experiment aims to see the characteristics of the water temperature at WHT, then calculate the amount of energy absorbed by the water from the heater and the amount of heat loss wasted to the environment due to changes in temperature settings. With the hope that this experiment can be a reference for improvement in subsequent experiments regarding passive cooling systems.

METHODOLOGY

Analytical Methods

The heat loss inside WHT between the heat changes given by the heater to WHT and the heat in the WHT calculate using the equation (13) (1.1).

$$\Delta q_{H-Loss} = q_{in} - q_{H-in} \qquad (1.1)$$

Where is heat from the heater [watt], and is heat internal WHT [watt]? And to calculate the heat supplied by the heater to the WHT, one can use the equation as shown in the equation (13) (1.2).

$$q_{in} = \frac{Q_{in}}{\Delta t_{H-on}} \quad (1.2)$$

Where is energy when the heater is on [Joule], and is the total time when the heater is on [s] during the steady-state condition?

The calculation of internal heat from WCT is shown in equation (13) (1.3).

$$q_{H-in} = \dot{m} c_P (T_{H-out} - T_{H-in}) \quad (1.3)$$

where is the mass of WCT [kg], c_P heat specific [kJ/kg°C], temperature WHT in [°C], and temperature WHT out [°C]?

As for methodology in conducting experiments and writing the analysis of the different heat loss in WHT with natural circulation on steady-state conditions, heat specific in the investigation, "The energy required to raise the temperature of a unit mass of a substance by one degree" can be calculated by the equation (14) (1.4).

$$c_P = \sqrt{\frac{A+CT}{1+BT+DT^2}} \quad (1.4)$$

Where;

A = 17.48908904
B = -1.67507 x 10-3
C = -0.03189591
D = -1.8748 x 10-6
T = temperature setting [°C]

The methodology in the research is divided into several stages; first, the preparation stage, which includes electricity or measuring instruments from experimental instruments, then geometric measurements from the FASSIP-02 test loop and WHT, as well as experimental matrices and methodology in taking experimental data, and finally, data processing.

Experimental Setup

Measuring instruments in this experiment's temperature and flow rates were measured by National Instrument (NI). We use two NI series: NI 9214 module for temperature measurement and NI 9203 module for current measurements such as pressure and flow. Both NI series are connected to Data Acquisition System (DAS) in the form of NI 9188 DAQ chassis installed in slots 1 and 7. Data retrieval speed in the watershed moment is set at a rate of one data per second. Installation of the instrument can be seen in Figure.1.

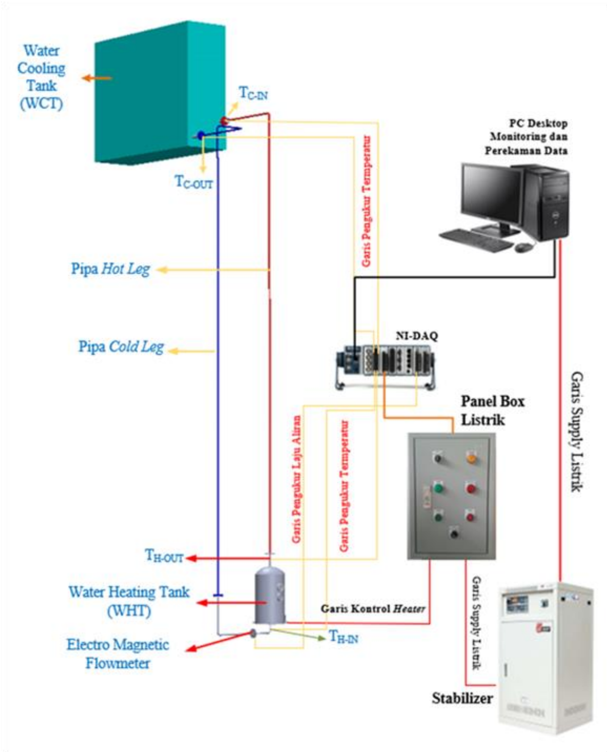

Figure 1. Experimental setup of FASSIP-02 Test Section

Table 1.

Component	Purpose
cDAQ 9188	Chassis to house the NI module
NI 9214	Voltage module for thermocouples
NI 9203	Flow module for fluid flow data input
NI 9476	Voltage module for heater control, which is connected to SSR

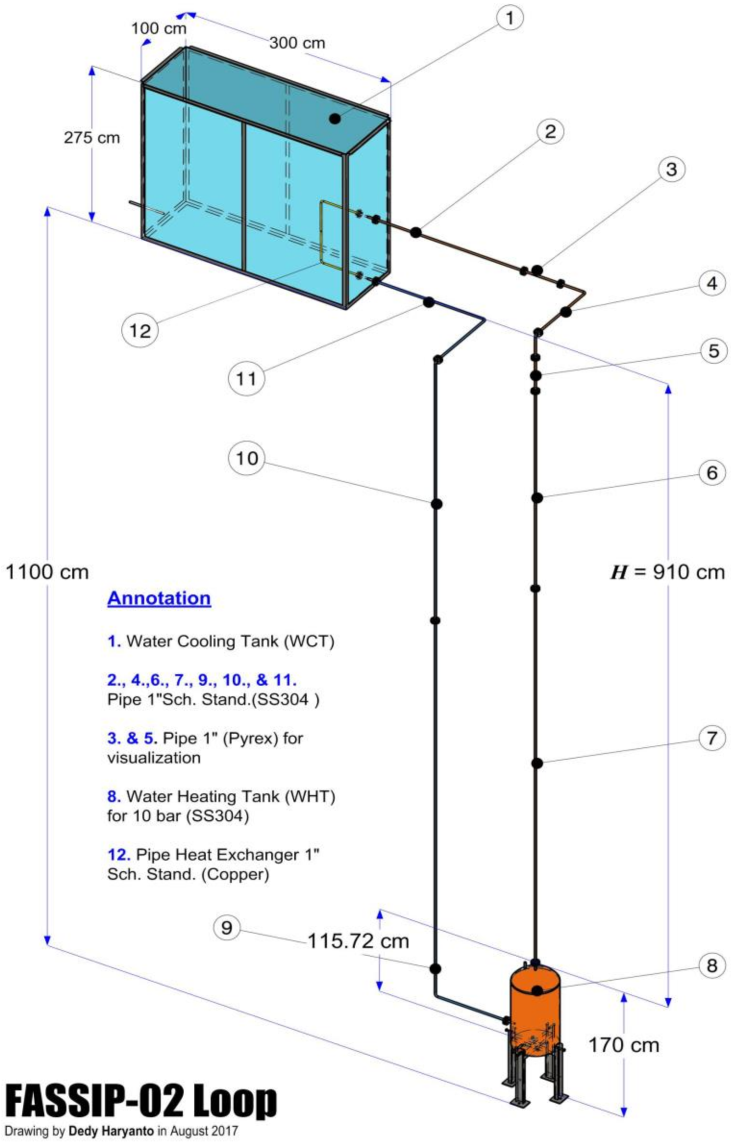

Figure 2. Design FASSIP-02.(8).

Besides taking measurements with a computer, we can control the heater on WHT to reach the set temperature. Heating control can use NI 9476 module, which can trigger a Solid State Relay (SSR) to turn on the heater and control it by the set temperature.

FASSIP-02 Test Loop

The FASSIP-02 test loop is a second-generation passive system built by the experimental Thermohydraulic research team. The component of the FASSIP-02 test loop consists of Water Heating Tank (WHT), Water Cooling Tank (WCT), Heat Exchanger Pipe, and Expansion Tank (ET). Figure 3 is overall from the FASSIP-02 test loop

This article will show a water heater tank that functions as a heat receiver from four heaters. The dimensions and structure of the WHT can be seen in Figure 3 (9).

The geometry for WHT presented in Figure 2 consists of several sizes shown in Table 2.

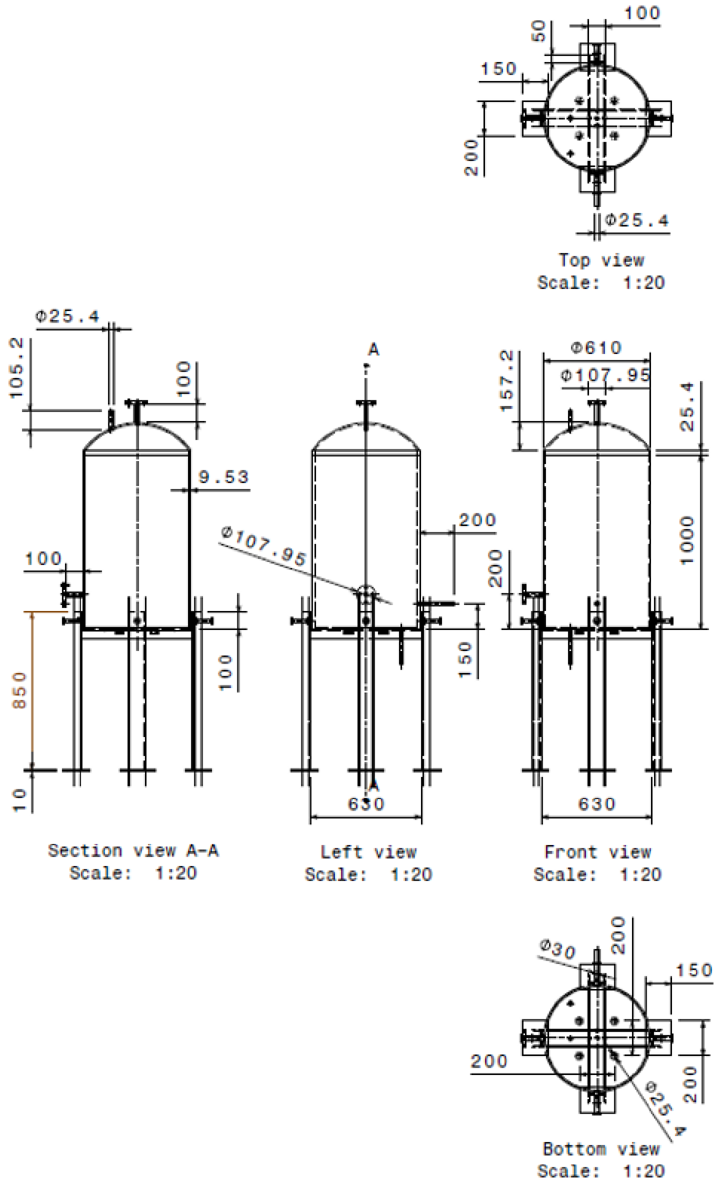

Figure 3. Design WHT (9)

Table 2. FASSIP-02 Geometry Data

Component	Shape	Size and Material
Water Cooling Tank	Shape	1.02m x 3.33m x 2.67m (Carbon Steel 8mm)
Water Heating Tank	Cylinder	⦰ 24 inches, sch 40 h=1m (cup= 15.27 cm) (Stainless Steel 404)
Pipe	Cylinder	⦰ 1 inch, sch 20 (Stainless Steel 3040)
Heat Exchanger	Cylinder	⦰ 1 inch, t= 3mm (Cooper)
Heater (4 pieces)	-	Length = 3, P= 5000 W

Table 3. Experiment Matrix

Setting Temperature WHT [°C]	Steady-state flow discharge Q [m^3/s]	*TH-in* [°C]	*TH-out* [°C]
40	Measuring data	Measuring data	Measuring data
50	Measuring data	Measuring data	Measuring data
60	Measuring data	Measuring data	Measuring data

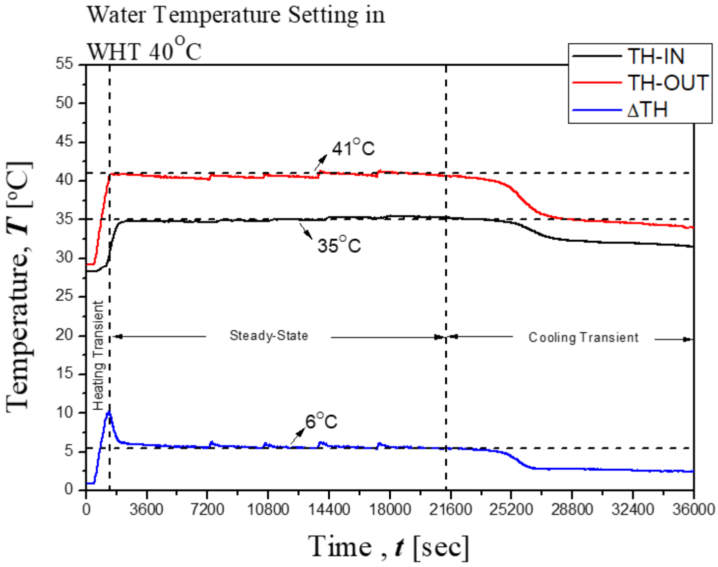

Figure 4. Temperature Characteristics at 40°C

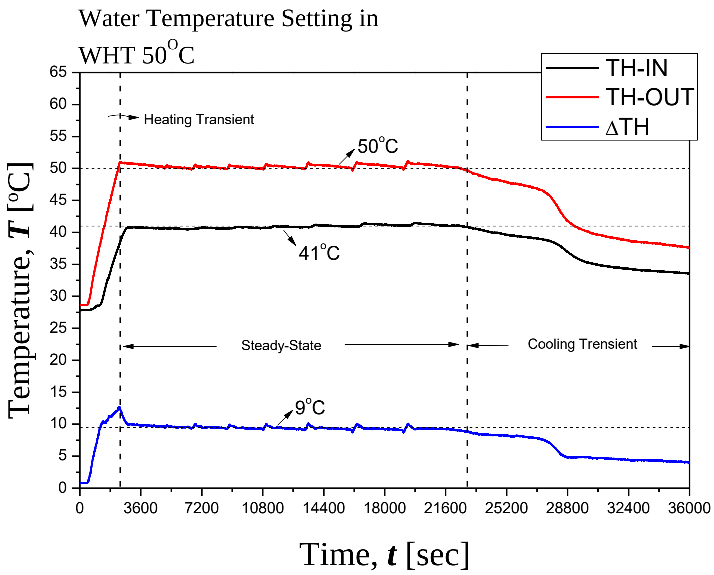

Figure 5. Temperature Characteristics at 50°C

Experiment Matrix

This experiment was conducted by heating the WHT with a heater until it reached the set temperature and keeping it steady-state for five hours. After five hours of steady-state, the heater will be turned off for the natural cooling process. The matrix of the experiment shows in Table 3.

RESULTS AND DISCUSSIONS

Temperature Characteristics

A temperature chart can show the temperature results in WHT with variable temperature settings. The graph shows the temperature change for 36000 seconds. The Steady-State condition lasts for 5 hours (shown in

Fig.4, Fig.5, and Fig.6). And there are three lines shown on each graph, with each line representing water temperature data in the inlet pipe to WHT (*TH-in*), water temperature data in the WHT output pipe (*TH-out*), and water temperature difference data at *TH-in* and *TH-out*.

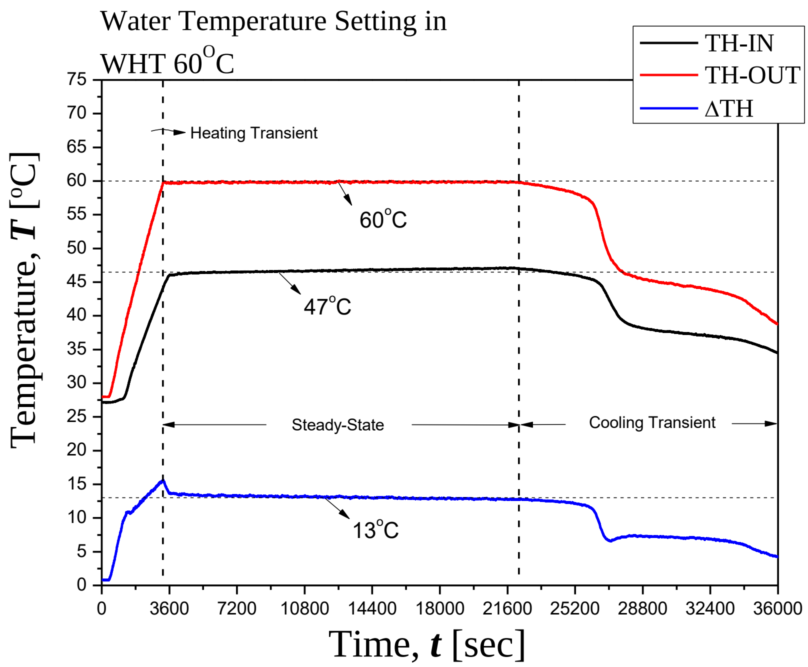

Figure 6. Temperature characteristics at 60°C

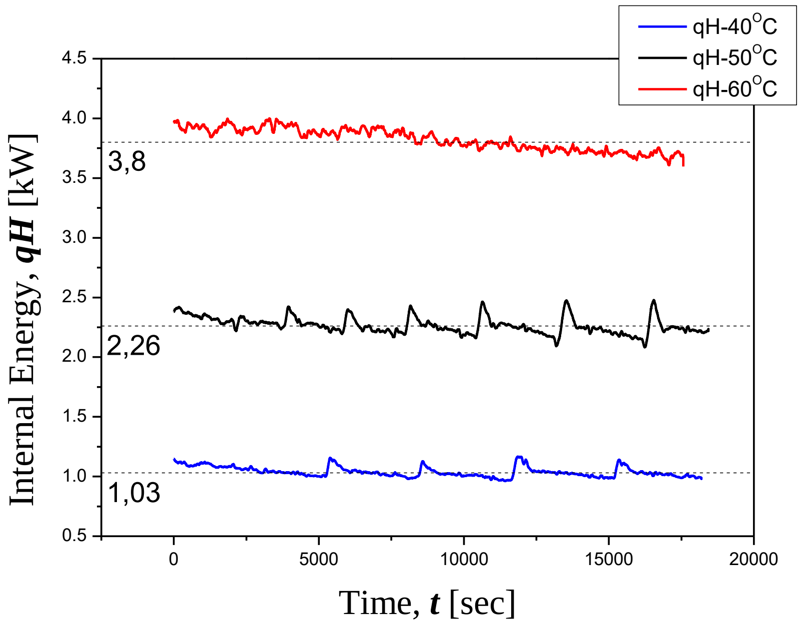

Figure 7. The Rate At Which Water Internal Energy Changes

On the TH-out line, there are fluctuations in each temperature variation, which can be seen in Figure 4, Figure 5, and Figure 6, where the temperature increases from the beginning point and the distance between the fluctuations gets smaller. That condition occurs caused by related to the on-off that happens in the heater, where at steady-state, the heater will experience an on-off state to regulate the water temperature in the heating tank to remain at the set temperature. Next, regarding the temperature difference that occurs between TH-in and TH-out. It can be seen that the value of the temperature difference that occurs is more significant as the setting temperature increases. For example, at a temperature of 40°C, it has a temperature difference of 6oC; at a temperature of 50°C, with a value of 9°C; and at 60°C, it has a value of 13°C. The differences are due to the cooling in the heat exchanger against the WCT, which is in an open tank state. The higher the temperature from the heat pipe, the greater the heat absorbed by the water in the WCT, causing the temperature in the TH-in to get smaller.

Water Internal Energy Changes in WHT

The results of the calculation of changes in the internal energy of water in WHT after 5 hours of research in steady conditions can be seen in Figure 7. The graph shows changes in water temperature in WHT based on variations in setting temperature.

Figure 7 shows the difference in the value of the internal energy of water in WHT, namely, at a temperature of 40°C, it has the lowest value with a value of 1.03 kW. At a temperature of 50°C and 60°C, it has a value of 2.26 kW and 3.8 kW, respectively. The shape of the line shown in the graph fluctuates due to heating conditions that adjust depending on the water temperature condition in the WHT. So that the incoming energy from the heater into the water also changes up and down

Heat Lost from WHT

The comparison of heat loss that occurs in each temperature setting variation can be seen in Figure 8, where the heat loss calculation is carried out on changes in the internal energy of water in WHT during controlled conditions. This steady-state is set for 5 hours starting when the water temperature reaches the set temperature.

It is shown in Figure 8 that the most significant heat loss occurs at a set temperature of 40°C of 10.85 kW, at a temperature of 50°C has a value of 9.2 kW, and 60°C is 8.37 kW which shows that the higher the temperature, the smaller the heat loss that occurs. The conditions happen because heat loss is inversely proportional to internal energy—the more significant the internal energy, the smaller the heat loss. And the internal energy is influenced by the temperature difference, where the more significant the temperature difference, the greater the internal energy.

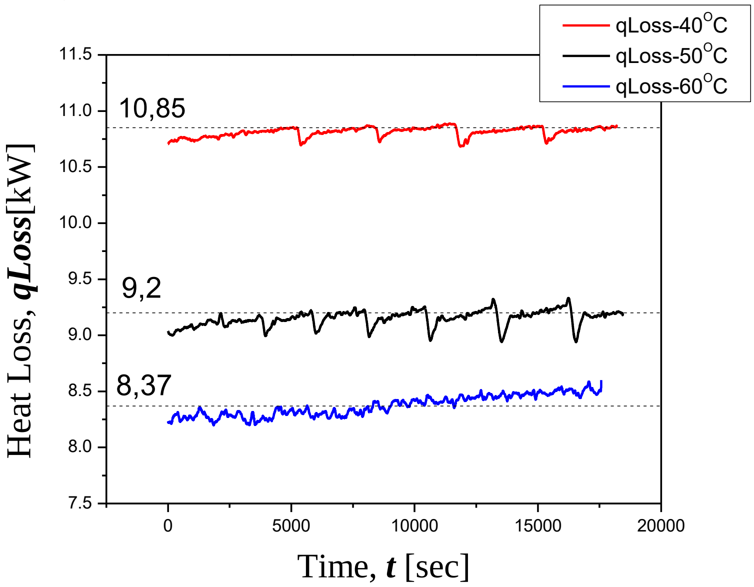

Figure 8. Heat loss based on temperature setting variations

CONCLUSION

The energy balance in the water in the WHT tank is the internal energy contained in the WHT tank and the heat energy wasted from the tank to the environment. The internal energy of the water in the heating tank increases with increasing temperature. From the calculation results, the inner energy values at temperatures of 40°C, 50°C, and 60ˣC are 1.03 kW, 2.26 kW, and 3.8 kW, respectively. And in the absence of insulation installed on the entire surface of the tank resulted in heat losses of 10.85 kW, 9.2 kW, and 8.37 kW, which occurred at temperature settings of 40ºC, 50ºC, and 60ºC as a whole.

ACKNOWLEDGEMENTS

This research was funded by Research Grant for, "Riset Inovasi untuk Indonesia Maju" (RIIM) batch 1 year 2022-2025 with contract number B-811/II.7.5/FR/6/200 dan B-2103/III.2/HK.04.03/7/2022. Thank you to The Head of Research Centre for Nuclear Reactor Technology, Research Organization for Nuclear Energy (BATAN), National Research and Innovation Agency (BRIN). Also, special thanks to all members of Reactor Thermal-Fluids System Development (RTFSyDev.) Research Group and also all Research Students.

The contributor-ships in this paper are Mulya Juarsa and Andrea Shevaladze A.A. as main contributors, the member of contributors is Putut Hery Setiawan, Giarno, Ainur Rosidi, Dedy Haryanto, G.B. Heru K., Adhika Enggar Pamungkas, Esa Putra A., Ade Tasri.

REFERENCES

1. Steinhauser G, Brandl A, Johnson TE. Comparison of the Chornobyl and Fukushima nuclear accidents: A review of the environmental impacts. Sci Total Environ [Internet]. 2014;470–471:800–17. Available from: http://dx.doi.org/10.1016/j.scitotenv.2013.10.029
2. Juarsa M, Witoko JP, Giarno, Haryanto D, Purba JH. An experimental analysis on Nusselt number of natural circulation flow in transient conditions based on the height differences between heater and cooler. Atom Indonesia. 2018;44(3):123–30.
3. Pal E, Kumar M, Joshi JB, Nayak AK, Vijayan PK. CFD simulations of moderator flow inside Calandria of the Passive Moderator Cooling System of an advanced reactor. Nucl Eng Des. 2015;292:193–203.
4. Park RJ, Ha KS, Kim HY. Detailed evaluation of natural circulation mass flow rate in the annular gap between the outer reactor vessel wall and insulation under IVR-ERVC. Ann Nucl Energy [Internet]. 2016;89:50–5. Available from: http://dx.doi.org/10.1016/j.anucene.2015.11.022
5. Zhang J, Shen X, Fujihara Y, Sano T, Yamamoto T, Nakajima K. Experimental study on the safety of Kyoto University Research Reactor at natural circulation cooling mode. Ann Nucl Energy [Internet]. 2015;76:410–20. Available from: http://dx.doi.org/10.1016/j.anucene.2014.10.010
6. Misale M. Experimental study on the influence of power steps on the thermohydraulic behavior of a natural circulation loop. Int J Heat Mass Transf [Internet]. 2016;99:782–91. Available from: http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.04.036
7. Lai Z, Tian W, Chen C, Wang M, Zhang K, Qiu S, et al. Experimental study on thermal-hydraulic characteristics of natural circulation loop under motion condition. Appl Therm Eng [Internet]. 2022;207(October 2021):118122. Available from: https://doi.org/10.1016/j.applthermaleng.2022.118122
8. Tangkesalu A, Kusuma I, Suarnadwipa IN. Analisis Perpindahan Panas Pada Cooler Tank FASSIP-01. J METTEK [Internet]. 2017;3(1):11–20. Available from: https://ojs.unud.ac.id/index.php/mettek/article/download/31946/19669
9. Juarsa M, Girano, Heru GB, Haryanto D, Prasetyo J. Passive Safety Sistem Simulation (FASSIP) Loop for Natural Circulation Study. Pros Semin Nas Teknol Energi Nukl. 2016;673–82.
10. Susyadi, Widodo S, Juarsa M. Study on Single Phase Natural Circulation Cooling Characteristic in FASSIP-01 Facility Using RELAP5. Pros SENTEN 2016. 2016;657–63.
11. Juarsa M, Antariksawan AR, Kusuma MH, Haryanto D, Putra N. Estimation of natural circulation flow based on temperature in the FASSIP-02 large-scale test loop facility. IOP Conf Ser Earth Environ Sci. 2018;105(1):0–7.
12. Kim YS, Bae SW, Cho S, Kang KH, Park HS. Application of direct passive residual heat removal system to the SMART reactor. Ann Nucl Energy [Internet]. 2016;89:56–62. Available from: http://dx.doi.org/10.1016/j.anucene.2015.11.025
13. Cengel YA, Boles MA. Thermodynamics: An Engineering Approach. 2006;5:280.
14. C. Allen. Thermophysical Properties of Saturated Light and Heavy Water for Advanced Neutron Source Applications. 1993;25–9.