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Effect of water temperature variation on natural circulation flow regimes and Reynolds Number in passive cooling system

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Abstract

Research on natural circulation flow is an important phenomenon of passive cooling systems, especially for developing nuclear reactor thermal management during accidents. This study aims to determine the changes in water temperature that affect the natural circulation flow rate, which is indicated by changes in the Reynolds number. Natural circulation, in addition to being a passive cooling system, is also utilized as an emergency core cooling system in thermal nuclear reactors. This research was conducted experimentally using the Passive System Simulation Facility (FASSIP)-04 Ver.2 rectangular-TP loop with a height of 6 m and a width of 1.32 m, using SS304 pipe with a diameter of 1 inch. The water temperature settings inside the heating tank vary from 45°C, 55°C, 65°C, and 75°C, with a heating power of 4.2 kW, and the cooling tank was maintained at a temperature of 10°C. The research was conducted by observing three thermal conditions, namely transient heating, steady state, and transient cooling, by maintaining steady-state conditions for 3 hours. The study's results showed that the increase in water temperature in the Water Heater Tank (WHT) affected the decrease of fluid density and increased buoyancy, which increased the natural circulation flow rate. The flow regimes changed from the lowest water temperature setting in the WHT from 45°C to the highest of 75°C, giving the flow regimes laminar, transition, and turbulent. The study observed the unstable flow conditions that characterize the natural circulation phenomenon.

Keywords:
FASSIP-04 Ver.2, passive cooling system, natural circulation, Reynolds Number, thermal management, nuclear reactor accident

1 Introduction

The Fukushima Daiichi accident in March 2011 was mainly caused by an earthquake and tsunami waves that flooded part of the nuclear reactor area, and the entire reactor system experienced an event called the Station Blackout (SBO). The failure of the diesel generator due to being submerged in the tsunami water resulted in the interruption of all electric power as a backup system. This condition caused the circulation pump not to work to circulate the cooling water so the reactor core experienced overheating, and three units in the Fukushima Nuclear Power Plant (NPP) experienced core melting. Core melting occurs as a result of damage to the Reactor Pressure container (RPV). [1]. The Fukushima NPP accident is classified as a severe accident and is rated at level 7 on the International Nuclear and Radiological Event Scale (INES) [2].

The Fukushima nuclear Power Plant accident due to a failed active cooling system has provided crucial information for improving reactor operations in the design of future nuclear reactors. Anticipation of similar events in the future is to conduct R&D that focuses on the reactor cooling system without external power, one of which is using a passive cooling system (natural circulation) [3]. Several researchers have conducted studies and investigations on the phenomenon of natural circulation that works without electrical power [4][5]. Other research has also been done about the movement of fluids in pipes with a rectangular loop shape that is heated at the bottom and cooled from the top. The system has a natural circulation phenomenon with warm fluid rising on one side of the pipe and cold fluid falling on the other. Research on natural circulation using rectangular loops has been widely carried out. One of them is by simulating the orientation of the heater and cooler. The orientation of the heater and cooler in the natural circulation system was used to determine the efficiency of the heat transfer and fluid flow patterns. Some orientations of the heater and cooler in the natural circulation flow are Heater Horizontal Cooler (HHHC). The heater and cooler are placed horizontally, where the heater is at the bottom and the cooler is at the top of the loop [6]. The orientation of the heater and cooler in the Horizontal Heater Vertical Cooler (HHVC) position was also studied, where in this configuration, the heater is placed in a horizontal position and the cooler in a vertical position. Other studies related to natural circulation were also conducted on the orientation of the Vertical Heater Horizontal Cooler (VHHC), where the heater is in a vertical position. The cooler is in a horizontal position [7]. T VHVC where the heater is placed in a vertical position and the cooler is in a vertical position [8].

The Passive System Simulation Facility (FASSIP) rectangular loop is a passive cooling testing facility that uses the natural circulation simulation experiment and is used to simulate the residual heat generated by the reactor core when an accident occurs [9][10]. Several research facilities on natural circulation are at the Research Central for Nuclear Reactor Technology of the National Research and Innovation Agency (BRIN). The facility is the FASSIP-01 rectangular loop [11], which was then developed by building the FASSIP-02 general loop facility [12][13], the FASSIP-03 general loop [14][15] and the Passive System Simulation Facility-04 rectangular loop consisting of the FASSIP-04 Ver.0 [16] rectangular loop and the FASSIP-04 Ver.2 rectangular-TP loop.

Research activities were carried out on the FASSIP-04 Ver.2 rectangular-TP loop, where activities were carried out to determine the performance of the system by varying the temperature to determine the natural circulation flow rate and the type of flow that occurs in the FASSIP-04 Ver.2 rectangular-TP loop. The research activity carried out in this paper is an initial experimental activity using a FASSIP-04 Ver.2 rectangular-TP loop. The experiment aims to determine the magnitude of the natural circulation flow regime that occurs by measuring the flow rate of the Reynolds number with a flowmeter. The analysis compared the average Reynolds number at a steady state with a change in the density and viscosity of water fluid based on the temperature setting in the water Heater Tank (WHT).

2 Research Methods

2.1 Experimental method

The FASSIP-04 Ver. 2 The rectangular loop experimental facility consists of a primary system (rectangular loop) and a secondary system (cooler system). The primary system's components consist of loops, WHT, Expansion Tanks (ET), Water Cooling Tanks (WCT), electromagnetic flowmeters (EF), and pumps. In comparison, the secondary system's components consist of a Cooling Thermal Bath (CTB), condenser, cooler, pump, and flowmeter. The experimental setup and technical parameters are described in fig. 1 and Table 1, respectively.

Table. 1. Technical Parameters for FASSIP-04 Ver. 2 rectangular-TP loop

Material	SS201 Unit
Outside Diameter	25.4 mm
Inside Diameter	23.4 mm
Loop Width, L	1320 mm
Loop Height, H	6000 mm
Total Length of Loop, L_t	14640 mm
Dimensionless Parameter, N_G	653.6
Volume of the working fluid informed, V	30 liter
Working Fluid	Demineralize water
Heating Power, P_h	4.2 kW
Cooling Power, P_c	2 HP
Temperature sensors	Thermocouple K-type
Flowmeter	Electromagnetic flowmeter

Thermocouples are placed at several points of the primary and secondary systems with an error rate of 1.5°C, which is used to obtain the temperature data. The calibration was carried out by comparing the measurement results between the standard thermocouple (Master) and the artificial thermocouple (type K). Calibration was conducted for 4 hours duration at a temperature range of 40°C, 50°C, 60°C, 70°C, 80°C, and 90°C with 30 minutes steady state period for each temperature setting. The flow rate value is obtained from the results of experiments using an electromagnetic flowmeter with a maximum measurement error of 0.8%, which is used to determine the Reynolds number based on volumetric flow rate measurement data.

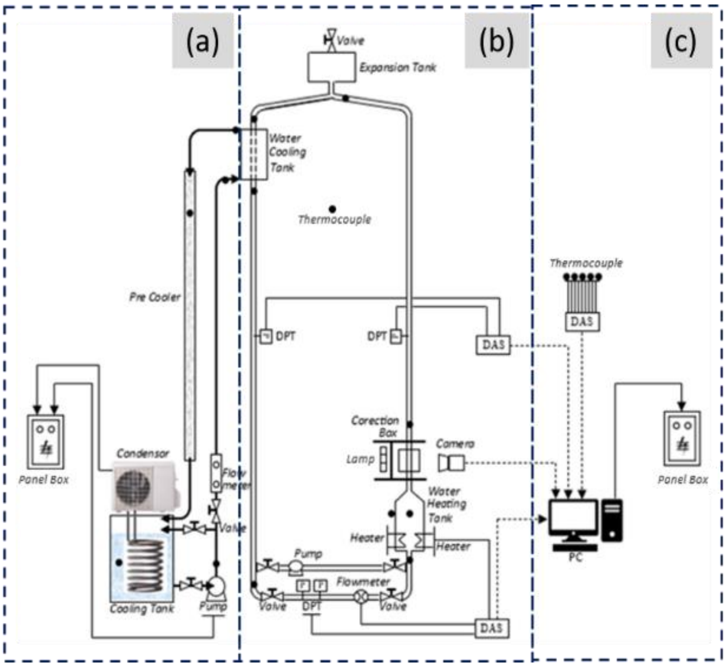


Fig 1. Experimental setup of FASSIP-04 Ver.2 rectangular loop the secondary system, (b) the primary system (c) interface

Fig. 1 shows a schematic of FASSIP-04 ver. 2 rectangular-TP loop, which is divided into 3 units there are (a) the secondary system, consisting of a cooling unit CTB, (b) the primary system, consisting of a rectangular loop FASSIP-04 Version 2, and (c) the interface system, consisting of a watershed and a PC device for the data acquisition and monitoring.

Fig. 2 shows a photograph of the FASSIP-04 Vers.2 rectangular-TP loop facility components, a fluid (water) transfer method inside a closed system that works without external force[17]. The water fluid in the WHT is heated using a heater with a fixed power of 4.2 kW, and the water temperature in the WHT is set at 45°C, 55°C, 65°C and 75°C. When the experiment is carried out, the water temperature in the WHT will increase, causing the density of water to become lower so that the fluid becomes lighter and buoyancy occurs. At the top, there is an expansion tank, which functions to maintain atmospheric pressure in the pipe.

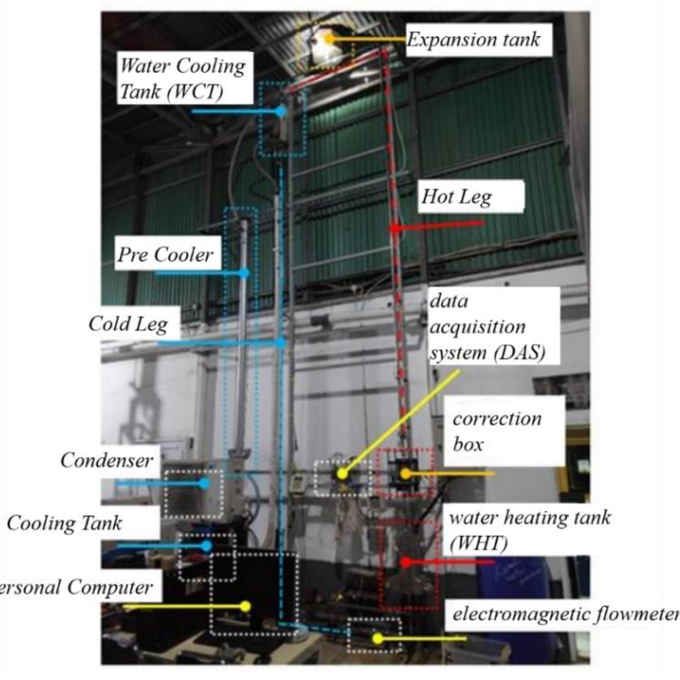


Fig 2. Photograph of experiment facility

Furthermore, the fluid goes to the WCT, where in the WCT there is a countercurrent flow as a coolant (CTB) with a temperature maintained at 10°C. This causes the temperature of the flowing fluid to become lower, and the density of the fluid increases, so the water fluid becomes heavier and the flow falls back to the bottom of the system. Maintaining this situation will result in a recurring circulation flow known as natural circulation, which is only caused by the buoyancy force caused by the difference in density and does not require the assistance of a pump.

2.2 Analysis method

The analysis method used in this research focuses on the natural circulation system occurring in the FASSIP-04 Ver.2 rectangular loop. The analysis was conducted by considering the principles of heat transfer and fluid dynamics, including the buoyancy force generated by density differences due to temperature variations. Based on the experimental results, the approach involves calculating the fluid density, viscosity, and flow velocity.

The working principle of a passive cooling system occurs because of the natural circulation flow, where the concept of natural flow occurs due to the difference in the density of the fluid at the bottom (hot section) with the fluid density at the top (cold section). The synchronization of the natural circulation flow due to differences in the fluid density triggers a buoyant force (upward flow in the hot pipe section) and frictional resistance forces (downward flow in the cold pipe section). Passive cooling technology has been widely applied in various fields, including coffee makers and CPU coolers in laptop computers. Meanwhile, researchers worldwide are still conducting research on natural circulationary worldwide are still researching natural circulation, both with experimental and simulation methods [18].

The fluid flow velocity is different at each pipe cross-section and is determined based on the internal flow type in the FASSIP-04 Ver.2 rectangular-TP loop. The different types of flow are called natural circulation flow regimes, which are represented by the Reynolds number. Therefore, it is necessary to perform calculations using the Reynolds number on the flow rate conditions that occur due to differences in the working fluid temperature in the heating tank and cooling tank sections. The Reynolds number is the ratio between the inertial and viscous forces, indicating the flow regime that occurs in the pipe during natural circulation [19]. The Reynolds number equation is shown in equation (1).

$$\mathrm{Re} = \frac{\rho v D}{\mu} \qquad (1)$$

Where Re is Reynolds Number (-), v is the average velocity of the natural circulation flow (m/s), D is the inner diameter of the pipe (m), ρ is the density of water (kg/m³), μ is the dynamic viscosity of water (kg/ms).

The Reynolds number shown in equation (1) will depend on the value of the density of water, and the dynamic viscosity of water is very dependent on changes in water temperature during the natural circulation process. Thus, the density of water is a function of the temperature change, as shown in equation (2). At the same time, the dynamic viscosity of water is also a function of the temperature, as shown in equation (4) [20].

$$\rho = \mathrm{a} + \mathrm{b}T_f + \mathrm{c}T_f \qquad (2)$$

Where ρ is the fluid density (kg/m³), with constants number are a = 1004.789042, b = -0.046283, T_f= 1.8T+32, c = -7.9738 x 10^4. The average velocity of the natural circulation flow under the steady state condition using Eq. (3).Where Q is the volumetric flow rate (m³/s), and A is the area of the cross-section pipe (m²).

$$v = \frac{Q}{A} \qquad (3)$$

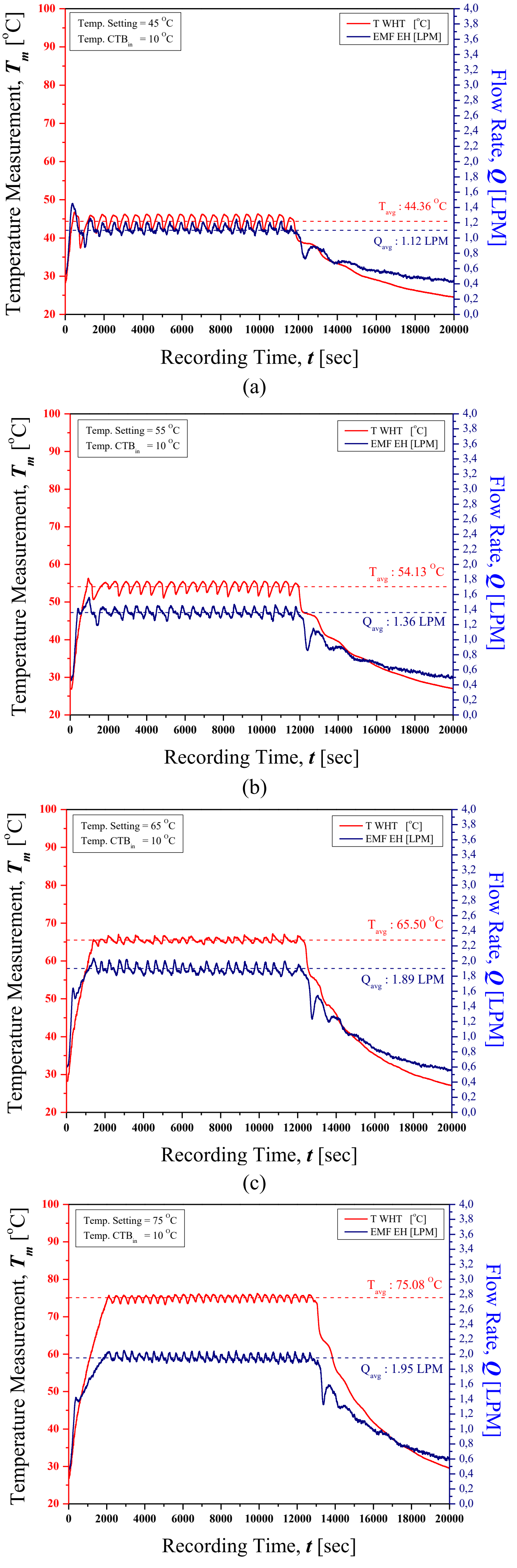
$$\mu = \exp\left[\frac{\mathrm{a} + \mathrm{c}T}{1 + \mathrm{b}T + \mathrm{d}T^2}\right] \qquad (4)$$

T is the water temperature (°C). The constant number is a = -6.325203964, b = 8.705317x10 $^{-3}$, c= -0.088832314, and d = -9.657x10 $^{-7}$. The distribution of the flow regimes that occur based on the magnitude of the Reynolds number is divided into 4 flow regimes [21]: Re < 2300 is Laminar flow regime, 2300 < Re < 4000 is Transition flow regime, 4000 < Re <10000 is Partially Turbulent flow regime, and Re > 10000 is Fully turbulent flow regime.

3. Results and Discussion

3.1. Temperature and natural circulation flow characteristics

An experiment using the FASSIP-04 Ver. 2 rectangular-TP loop was done for steady-state conditions for 10800 seconds (3 hours) with variation temperatures of 45°C, 55°C, 65°C, and 75ºC. The steady-state condition is where the fluid temperature has reached the specified temperature (water temperature setting in WHT). The curve of the characteristics relationship between the recording time to temperature and the natural circulation volumetric flow rate is shown in figs 3.



(a)

(b)

(c)

(d)

Fig. 3. Characteristic relationship between recording time to temperature and natural circulation volumetric flow rate for (a) 45˚C, (b) 55˚C, (c) 65˚C, and (d) 75˚C

Fig. 3(a) shows that time heating (*transient heating*). Condition steady at 45°C at 404 seconds with rate average flow of 1.12 LPM, change time condition steady shown in fig. 3(b) conditions steady at 5°C in sec to 883 seconds with rate the average flow is 1.36 LPM, as well as fig. 3(c) conditions temperature steady 65°C in 1390 seconds with rate average flow of 1.89 LPM and fig. 3(d) conditions temperature steady 7°C in 2073 seconds with rate average flow of 1.95 LPM. Table 2 summarizes experimental data on water temperature variations in the WHT versus recording time.

Table 2. Variations of WHT water temperature and flow rate versus recording time.

T_{SET} (°C)	T_{AVE} (°C)	Transient heating (s)	Steady state (s)	Transient cooling(s)	Q (LPM)
45	44.36	475	± 10800	8220	1.12
55	54.13	950	± 10800	8084	1.36
65	65.50	1407	± 10800	7745	1.89
75	75.08	2113	± 10800	7212	1.95

The results of time recording observations of temperature measurements with variations in water temperature at the WHT 45°C, 55°C, 65°C and 75°C, that the higher the temperature setting, the longer the time needed to reach a steady state. In the same way with the flow rate that occurs, the greater the temperature setting, the greater the flow rate value. Meanwhile, the analysis results show that the periods to reach the steady state tend to increase with increasing water temperature settings inside the WHT. This condition occurs because the fluid requires more energy and time to reach a higher temperature due to the increasing temperature difference between the water in the heater and cooler, strengthening the natural circulation in the rectangular loop. The average natural circulation flow also increases with increasing temperature. Meanwhile, the heating efficiency appears to be more optimal at higher temperatures because the flow rate increases. However, the time to reach the steady state condition is longer. The increase in time to reach a steady-state and the increase in natural circulation rate due to the increase in water temperature inside the WHT can affect the effectiveness of passive cooling. The stronger natural circulation in the rectangular loop indicates an increase in heat transfer, accelerating the release of thermal energy into the heat sink.

3.2. Reynolds number calculation

The Reynolds number was determined using calculations based on the flow rate conditions and temperature changes during the experiment. The experiment was conducted with variations in the WHT temperature of 45°C, 55°C, 65°C, and 75°C, and the cooling thermal bath temperature ranged around ±10°C. The Reynolds number indicates the flow regime during the experiment under steady-state conditions, and differences in the results were observed for each temperature variation.

Fig. 4 shows the results of the data processing and Reynolds Number calculations for the T_{WHT} setting of 45°C with T_{CTB} maintained at ±10 °C. In the steady-state condition time range of around 1370 seconds to 11990 seconds, the Reynolds number is in the laminar area, which is marked by an average value of 1705. Fig. 5 explains the relationship between the recording time and Reynolds Number with T_{WHT} setting of 55°C with T_{CTB} also maintained at ±10 °C. The steady-state condition time range is 1122 seconds with the Reynolds number average Re of 2393. Fig. 6 shows the relationship between the Reynolds number and the recording time at a setting 65°C inside WHT with water temperature inside CTB around 10°C. The time required to reach steady-state is 1336 seconds with an average Re value of 3949. At the fluid temperature settings of 55°C and 65°C, the Reynolds Number is in the transition flow regime in the 2300 <Re< 4000 range. Fig.7 explains the change in the Reynolds number value when setting a temperature of 75°C.

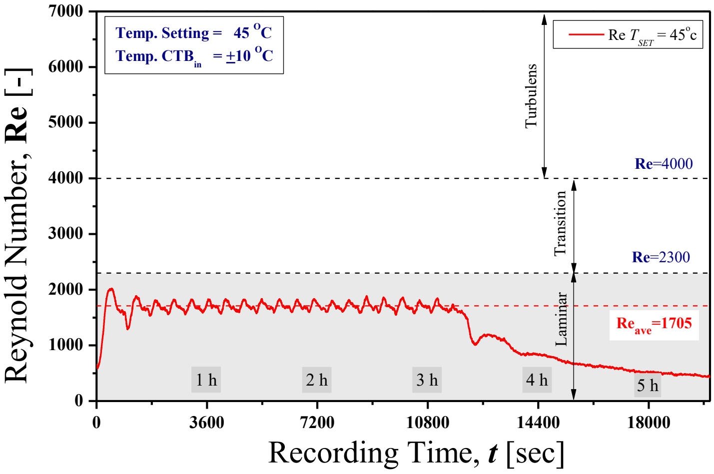


Fig. 4. Reynolds number at a setting temperature 45°C

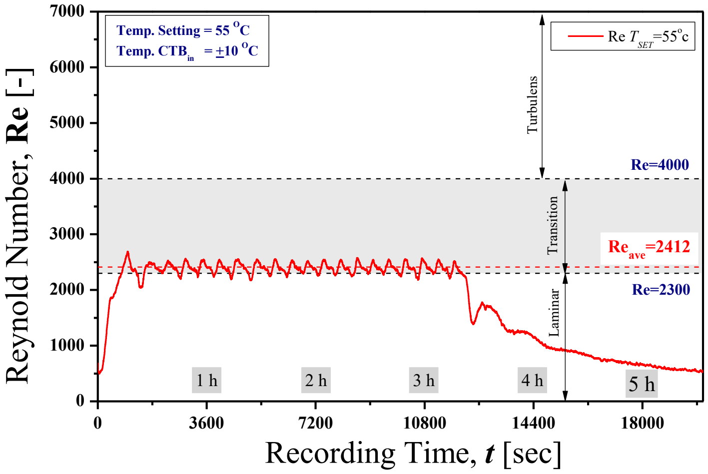


Fig. 5. Reynolds number at setting temperature of 55°C

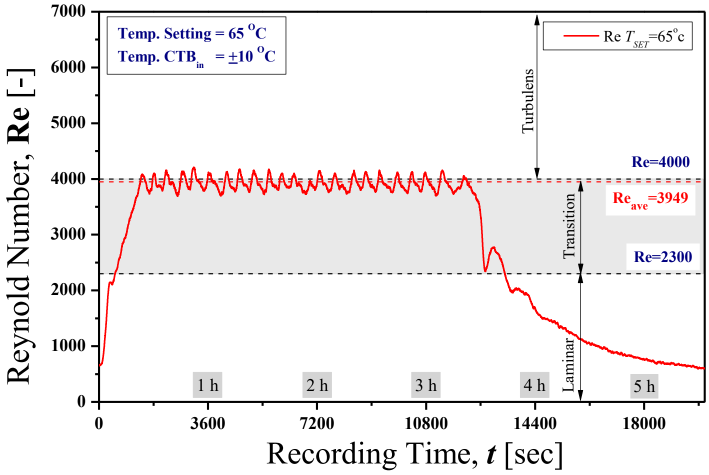


Fig. 6. Reynolds number at setting temperature of 65°C

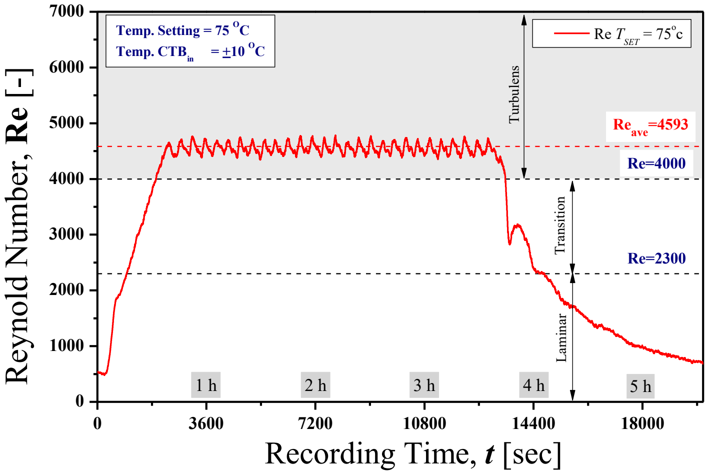


Fig. 7. Reynolds number at setting temperature of 75°C

. In this condition, the time to reach the steady-state is slower than in other temperature settings, around 2257 seconds. The Reynolds number obtained under this condition is 4593, which indicates a turbulent flow.

The results of the analysis and calculations are shown in fig. 4, fig. 5, fig. 6, and fig. 7 based on the water temperature in the WHT of 45°C, 55°C, 65°C, and 75°C, by maintaining the water temperature in the thermal cooling tank at 10°C. A comparison of the time required to reach steady state conditions in fig. 4 and fig. 7 shows that with a power of 4.2 kW at a temperature of 45°C, it takes less time, the buoyancy force is weaker. The flow tends to be laminar, while at a temperature of 75°C, the time required is faster, the buoyancy force is large, and the flow tends to be turbulent. The results show that the increase in water temperature causes the transition of laminar flow to turbulent flow, which significantly impacts the effectiveness of passive cooling. Another factor influencing changes in flow is changes in density and viscosity values, where density and viscosity values are inversely proportional as water temperature increases. As the Reynolds number increases, heat transfer through natural convection becomes more intensive, and increases heat release efficiency in the environment. Changes in fluid properties such as density and viscosity also affect the system's flow pattern and temperature distribution.

Fig. 8 shows the relationship between the average Reynolds number and the average water density-to- to viscosity ratio. The Reynolds number is influenced by various factors, especially the density and dynamic viscosity of water as the working fluid. It indicates the boundaries of the flow zone.

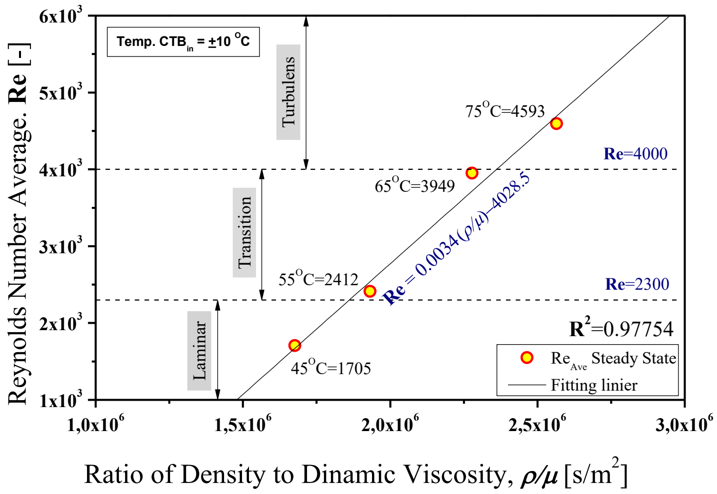


Fig. 8. Reynolds number versus ratio of thermal properties of water

Fig. 8 also shows that with the increase in the ratio of the thermal properties of water, the ratio between the density and dynamic viscosity of water, which are linearly related to the Reynolds number. The flow regime is divided into three regimes, namely the laminar regime for a temperature of 45ºC with a value of 1705, followed by the Reynolds number for the transition flow regime at temperatures of 55ºC and 65ºC, respectively 2412 and 3949, and finally, the turbulent flow regime of 4593 which occurs at a temperature of 75ºC. The linear fitting line on the graph in fig. 8 is shown with correlation (5).

$$\mathrm{Re} = 0.0034\left(\frac{\rho}{\mu}\right) - 4028.5 \tag{5}$$

Fig. 8 shows the confidence level of correlation (5) is linearly indicated by $R^2 = 0.97754$. In this case, the Reynolds number is a function of the ratio of density (ρ) to dynamic viscosity (μ), which exhibits a linear relationship. This shows that if the value of ρ/μ increases, the Reynolds number also increases and vice versa. The decrease in the density and viscosity of water due to an increase in water temperature explains how the relationship between density and viscosity affects fluid flow. Since the Reynolds number is directly proportional to the ratio ρ/μ, the decrease in the density and viscosity of water increases the Reynolds number. This shows that the increase in water temperature causes a decrease in the density and viscosity values, which will result in an increase in the Reynolds number and produce laminar, transitional, and turbulent flow. The results of the calculation of fluid density and viscosity based on variations in temperature settings are shown in Table 3.

Table 3. Calculation result for Reynolds number and regime flow

T Setting (°C)	Q (LPM)	ρ (kg/m³)	μ (kg/m·s)	ν (m/s)	Re (-)	uRe (-)	Flow Regime
45	1.12	989.23	0.00059	0.044	1705	16.9	Laminar
55	1.36	985.19	0.00051	0.053	2412	24.1	Transisi
65	1.89	979.73	0.00043	0.073	3949	33.4	Transisi
75	1.95	974.70	0.00038	0.076	4593	46.0	Turbulen

Table 3 shows the Reynolds number value and different types of flows, where at a temperature setting of 45ºC, the value of Re <2300 with type laminar flow, while at temperatures of 55ºC and 65ºC, the value of Reynolds number 2300 < Re < 4000, with type transition flow and at a temperature of 75°C the value of Re> 4000 with turbulent flow regime.

The change in flow characteristics from laminar to turbulent due to the increase in water temperature in the WHT affects the effectiveness of passive cooling. At low temperatures (45°C), the laminar flow with high viscosity causes a slower cooling rate. However, at high temperatures (75°C), turbulent flow due to decreased viscosity increases the cooling rate through stronger natural circulation. At transition conditions (55°C and 65°C), cooling begins to increase but is still influenced by changes in flow patterns that are not yet fully stable. The Reynolds number is critical in determining the flow pattern and cooling effectiveness. In laminar flow (Re<2300), heat transfer occurs mainly through conduction, which is less efficient than convection. As the temperature increases, the fluid's viscosity decreases, increasing the Reynolds number and a transition to turbulent flow (Re>4000). Passive cooling relies heavily on heat transfer to remove heat naturally. The more efficient the heat transfer mechanisms (conduction, convection, and radiation), the more effective the passive cooling system is at maintaining a stable temperature without requiring external energy. The limitation of this research is that it only considers single-phase flow, does not cover the dynamics of two-phase flow with laboratory-scale rectangular loop facilities and the CTB temperature variation is limited to ± 10°C. The weakness of this research is that the research was conducted with atmospheric pressure while, in reality, the pressure is above atmospheric pressure. Suggestions for further research require further studies with CTB temperature variations to compare the flow rate due to changes in water-cooled temperature.

3 Conclusions

Based on the results of experiments and analysis to obtain the relationship between changes in flow regime and variations in temperature changes as a thermal effect shows that the effect of increasing the water temperature setting in the WHT gives a linear relationship to the flow regime changes. The relationship between the Reynolds number changes due to thermal effects has been proven by a correlation with a high confidence value against experimental data. This proves that changes in the results of temperature measurement greatly affect the density and dynamics of the viscosity of water, affecting the results of measuring the natural circulation flow rate. Meanwhile, natural circulation flow regimes starting from the lowest water temperature setting in the WHT from 45ºC to the highest of 75ºC show changes in the flow regime from the laminar and transition regimes to the turbulent regimes. An increase in the temperature setting from 45ºC by 1.67

times to 75ºC contributed to an increase in the Reynolds Number of 169.38%. In addition, the observation results based on the flow rate graph against changes in time show unstable flow conditions due to the instability of frequency and non-uniform amplitude, which are characteristics of natural circulation phenomena.

Acknowledgement

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