

Analysis of Grashof Number in Large-Scale Passive Cooling Systems Based on Temperature Changes

Andrea Shevaladze¹, Deendarlianto^{1*}, Esa Putra¹, Putut Heri Setiawan², Hyundianto Arif Gunawan¹, Mulya Juarsa²

¹Department of Mechanical Engineering and Industry, Gadjah Mada University, Indonesia

²Nuclear Reactor Thermal-Fluids System (NRTFSys) Research Group, Research Center for Nuclear Reactor Technology, Research Organization of Nuclear Energy (ORTN), National Research and Innovation Agency of Indonesia (BRIN), Indonesia

*Corresponding Author: deendarlianto@ugm.ac.id

Abstract. *This study investigates the Grashof number calculation in large-scale passive cooling systems, focusing on temperature-induced changes. The research utilizes the FASSIP-02 test loop, a second-generation facility for passive cooling systems, to analyze natural circulation flow. Experiments were conducted by heating a Water Heating Tank (WHT) to various temperatures (50-90°C) and maintaining steady-state conditions for five hours. Flow rates and Reynolds numbers were measured and calculated, revealing a turbulent flow regime across all temperature settings. The Grashof number was then calculated and correlated with the Reynolds number to establish a relationship specific to the FASSIP-02 test loop. Results showed Grashof numbers ranging from 4.93×10^{12} to 1.64×10^{13} , confirming turbulent flow. The correlation between Reynolds and Grashof numbers was determined to be $Re = 0.1356(Gr_m/N_G)^{0.31}$, with $R^2 = 0.9952$. This correlation closely aligns with previous research on turbulent flow in natural circulation systems, with slight variations attributed to differences in measurement precision. The study contributes to understanding passive cooling system behavior in nuclear reactors, particularly for residual heat removal during accidents or shutdowns.*

Keywords: *natural circulation, grashof number, reynold number, large-scale, passive cooling system*

1. Introduction

The accident at the Fukushima Daiichi Nuclear Power Plant occurred due to a tsunami that caused the Station Black Out (SBO). This is caused by the failure of the active cooling function to prevent the melting of the reactor core due to residual heat from the reactor core. This situation highlights the importance of a cooling system that can operate independently of external power sources like electricity to run pumps. Natural circulation plays a crucial role in nuclear reactor safety, particularly in removing residual heat after an accident or during shutdown. The process works on a simple principle: as fluid heats up, its density decreases, causing it to rise. Conversely, when the fluid cools, its density increases, making it sink due to gravity. This temperature-induced density difference creates a natural flow cycle, allowing for circulation without mechanical assistance. In nuclear power plants, passive cooling systems are crucial for managing accidents by transferring heat from the reactor core to the steam generator without relying on active components. This process utilizes natural circulation (NC) flow, where the steam generator's heated section absorbs thermal energy and facilitates coolant movement through temperature-induced density differences. The system's design allows the heated coolant to rise naturally, while the cooler, denser fluid at higher elevations sinks due to gravity. This circulation continues as the upper, cooler component transfers heat to a

cooling tank, effectively removing thermal energy from the reactor core without the need for external power or mechanical pumps. This passive approach enhances the plant's safety by providing a reliable cooling mechanism during emergencies or shutdowns (Lai K, et al., 2018).

Some of the research on passive cooling systems that have been carried out include those that have been carried out by Swapnalee & Vijayan by using rectangular loops with variations in heating and cooling orientation (HHHC, HHVC, VHHC, VHVC) to observe the stability of the flow that occurs in the loop against various flow regimes (Swapnalee & Vijayan, 2011). A study by Rae-Joon Park and colleagues (2016) found that raising both the coolant injection temperature and the reactor cavity water level increased the circulating coolant's mass flow rate. This, in turn, enhanced the Critical Heat Flux (CHF) on the outer reactor vessel wall. CHF is a crucial factor in the effectiveness of In-Vessel Retention through External Reactor Vessel Cooling (IVR-ERV), an important safety strategy in nuclear reactors (Park et al., 2016). Jian Zhang and colleagues conducted a study in 2015 focusing on natural circulation cooling in nuclear reactors. They examined how the coolant flow velocity in the reactor core changes with increasing thermal power. To measure this, they used the temperature difference between the core's inlet and outlet. Their key finding was that as the reactor's thermal power goes up, the natural circulation flow speed in the core increases in a non-linear fashion. This means the coolant flows faster, but not in a straight-line relationship with power increase. This insight is important for understanding and designing effective passive cooling systems in nuclear power plants (Zhang et al., 2015). A further experiment was conducted utilizing a vertically oriented loop with fluctuating power supplied to the heater. Experiments demonstrate that the loop's behavior is perpetually unstable across all power levels, with the flow consistently reversing after a brief transitory period. At low power, temperature oscillations are consistent; but, as power grows, two distinct oscillatory modes emerge, characterized by recurrent flow reversals and oscillation periods fluctuating around the mean value, ultimately resulting in flow reversal. An increase in flow rate will result in heightened friction and a reduction in the overall buoyant force (Misale, 2016). Studies also utilize natural circulation loops constructed on an experimental platform with six degrees of freedom. A minor flow acceleration would not result in a substantial alteration in the flow rate in the natural circulation loop. The method by which rolling motion affects the natural circulation loop varies due to the shifting center axis of rotation. The supplementary rise in inertial force resulting from rotation in the direction of coolant flow induces greater flow fluctuations. The coefficient of periodic average friction indicates two flow fluctuations: one with a Reynolds number below 5000 and another in turbulent regions with a Reynolds number ranging from 5000 to 35000. This indicates that rolling motion can facilitate heat transmission at low flow rates. However, it mostly influences heat transfer characteristics by affecting flow rates at high flow circumstances (Lai Z, et al., 2022).

From 2016 to 2019, the Thermal-hydraulics experimental laboratory constructed a medium-scale experimental facility known as the FASSIP-01 Loop (FASSIP, Fasilitas Sirkulasi Sistem Pasif). The loop is rectangular, measuring 6 m in height and 3.5 m in width, constructed from SS304 pipe with a diameter of 1 inch and a total length of 19 m. An investigation was conducted on the impact of thermohydraulic factors on NC flow, considering fluctuations in cooling system flow and heating power, utilizing the FASSIP-01 loop to acquire NC flow rate data through magnetic flow meters (Tangkesalu et al., 2017). Experiments were conducted to analyze the flow rate and heat transfer in the pipe

by observing the phenomena during the experiment and making calculations based on the derivative of the natural circulation flow equation (Juarsa et al., 2016). One study on passive cooling systems referred to as BATAN, has developed and constructed a large-scale testing facility known as the FASSIP-02 test loop. It seeks to do analytical computations utilizing various relationships to estimate the natural circulation flow rate (Juarsa & Antariksawan, 2018). The FASSIP-02 test loop comprises two primary components: The Water Heating Tank (WHT) and the Water-Cooling Tank (WCT). WHT possesses four heaters that effectively elevate the temperature to the designated set point, while WCT functions to extract the heat from the fluid circulating through the heat exchanger pipe. The WHT is a tank equipped with four heaters, each rated at 5 kW, resulting in a total heating capacity of 20 kW. The energy retained in the water within the heating tank is supplied by the heater. It diminishes owing to thermal dissipation from the tank to the surrounding environment. Heat loss is a critical factor that must be addressed inside the system.

2. Methodology

2.1. Experimental Apparatus

The FASSIP-02 test loop is a second-generation facility for passive cooling systems constructed by the experimental Thermohydraulic research team. The components are WHT, WCT, a straight heat exchanger (HE), and an expansion tank (ET). Figure 1 is derived from the FASSIP-02 test loop, with geometric data presented in Table 1.

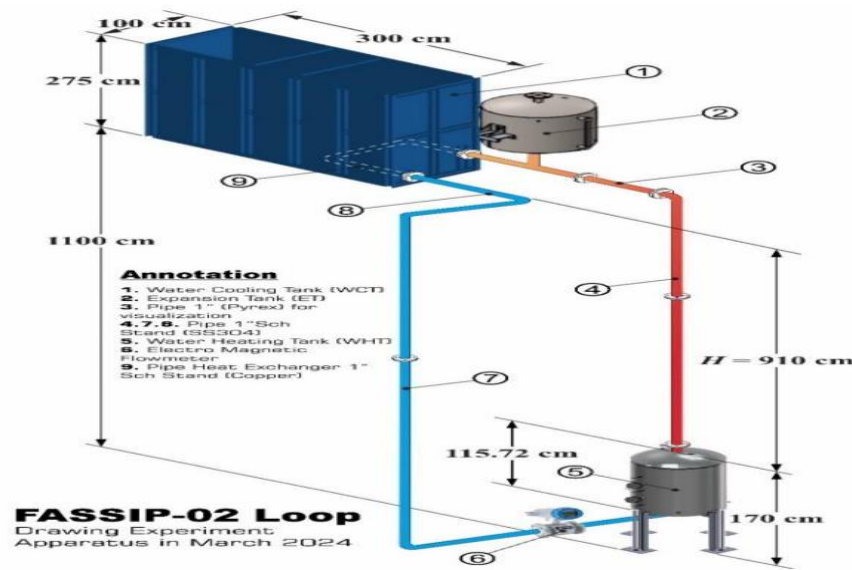


Figure 1. Experiment apparatus

Table 1. Geometrical Data

Components	Shape	Size and Materials
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

2.2. Experimental Setup

The measurement results of this research are in the form of temperature and mass flow rate, where measurement data acquisition is carried out using an NI cDAQ 9188 connected to a computer. Temperature measurement uses a thermocouple connected to the NI 9214 ear module, then the NI 9203 current module for reading data from the Electromagnetic Flowmeter. The experimental setup scheme can be seen in Figure 2.

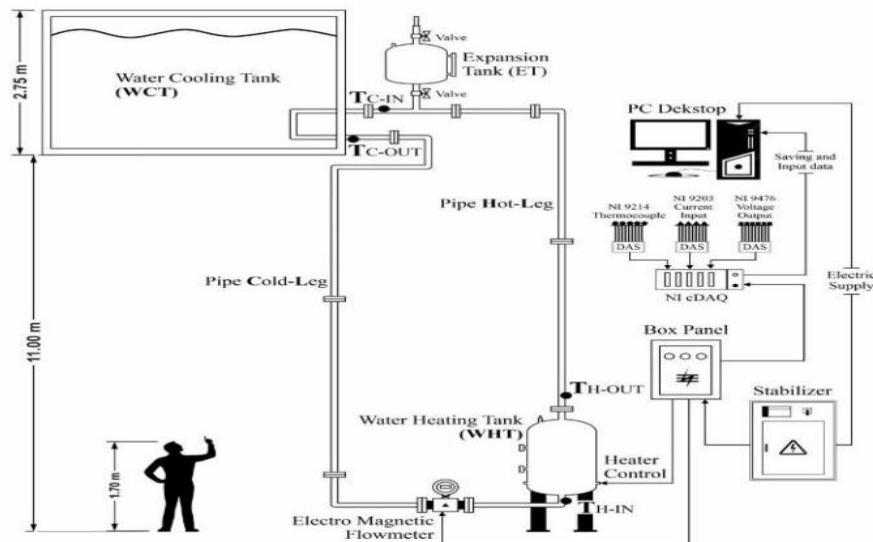


Figure 2. Experimental setup

The research also conducted the heater control to keep the fluid temperature in the tank the same as the temperature set. The heater was set using the NI 9476 connected to the Solid-State Relay (SSR) to turn on and off the heaters in the hole conditions.

2.3. Matrix Experiment

This experiment entailed heating the WHT with a heater until it attained the necessary temperature and sustaining it for five hours. Steady-state is achieved when the average temperature in the WHT tank attains the designated value. This can be achieved using an ON-OFF control mechanism for the heater to maintain the TWHT at the designated temperature. The heater control system executed is presented in Table 2. The number of heaters and the location of the operational heaters are established according to the commissioning outcomes before the experiment. Following five hours of steady-state conditions, the heater was deactivated to initiate the natural cooling process. Table 3 contains the experimental details.

Table 2. Heater scenario

Temperature Setting	Transient Heating				Steady State							
					TWHT $\geq T_{set}$				TWHT $< T_{Set}$			
$\leq 60^{\circ}\text{C}$	H1	H2	H3	H4	H1	H2	H3	H4	H1	H2	H3	H4
$= 70^{\circ}\text{C}$	H1	H2	H3	H4	H1	H2	H3	H4	H1	H2	H3	H4
$\geq 80^{\circ}\text{C}$	H1	H2	H3	H4	H1	H2	H3	H4	H1	H2	H3	H4

= Heater ON

= Heater OFF

Table 3. Matrix experiment

Setting Temperature WHT [°C]	Time Steady- State	Loop Heating Type	Material Loop
40	5 Hour	Direct Heating	SS 304 Sch. 40 (Dia. 1 inch)
50			
60			
70			
80			
90			

2.4. Analytical Method

This experiment utilizes the Reynolds number to determine the flow regime within a pipe or loop. The range for laminar flows is 2000-3000, transitional flows are 3000-4000, and turbulent flows are characterized by $Re \geq 4000$. Reynolds numbers can be categorized as either global or local, contingent upon the scale. A global definition delineates the comprehensive constraints of the problem boundary, while locally, it elucidates the condition of the shear layer. The flow regime in this experiment influences temperature variations at the input and outlet heat exchangers in WCT without forced convection, where water viscosity does not inhibit the conversion of kinetic energy to thermal energy. The impact of regime flow on differential temperature can be characterized using Reynolds (Re) number values in Equation 1.

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

In this context, ρ represents the fluid density [kg/m^3], D denotes the pipe diameter [m], V indicates the fluid velocity within the pipe [m/s], and μ signifies the viscosity [Pa]. The fluid density can be determined using Equation 2 (Allen, 1993).

$$\rho = (A + BT_f + CT_f^2) \quad (2)$$

In this equation, ρ represents the density [kg/m^3], A equals 1004.789042, B is -0.046283, C is -7.9738×10^{-4} , and TF is defined as $1.8T + 32$. The determination of fluid viscosity is presented in Equation 3.

$$\mu = \exp[(A + CT) / (1 + BT + DT^2)] \quad (3)$$

Where μ represents dynamic viscosity [Pa.s], T denotes temperature [°C], and certain constants are present. A equal -6.325203964, B equals 8.705317×10^{-3} , C equals -0.088832314, and D equals -9.657×10^{-7} .

The next stage entails calculating the Grashof number within the loop, a dimensionless quantity essential for analyzing fluid dynamics, especially in contexts of natural convection. It functions as an estimate of the ratio of buoyant to viscous forces in a fluid. The Grashof number can be determined using Equation 4 (Vijayan et al., 2000)

$$Gr_m = \frac{D^3 \rho^2 Q \Delta H g \beta}{\mu^3 A C_p} \quad (4)$$

Gr_m denotes the modified Grashof number, D signifies the hydraulic diameter [m], β indicates the thermal expansion coefficient [K⁻¹], g represents gravitational acceleration [m/s²], Q denotes total heat input [W], ΔH signifies the height difference [m], A represents flow area [m²], and c_p indicates specific heat [J/kg·K], which can be calculated using Equation 5 (Allen, 1993).

$$c_p = \sqrt{\frac{A + CT}{1 + BT + DT^2}} \quad (5)$$

Where certain constants are present. A equal 17,48908904, B equals $-1,67507 \times 10^{-3}$, C equals -0.03189591 , and D equals $-2,8748 \times 10^{-6}$. Upon acquiring the two non-dimensional numbers Re and Gr/N_G , their correlation for turbulent flow can be articulated through Equation 6 (Vijayan, 2002).

$$Re = 1.9561 \left(\frac{Gr_m}{N_G} \right)^{0.36364} \quad (6)$$

3. Results and Discussions

Obtain the flow rate value present in the loop during the steady state from the measurement findings of this experiment. The flow meter measurements are recorded in Liters per Minute (LPM) and subsequently converted to cubic meters per second (m³/s). Figure 3 illustrates the flow rate values corresponding to variations in temperature settings within the WHT tank at steady state.

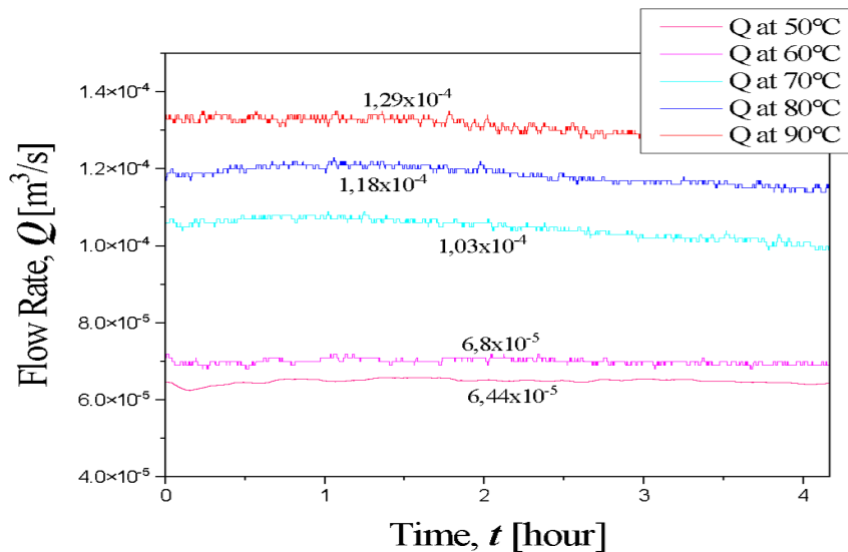


Figure 3. Graph of flow rate over time under steady-state conditions

Figure 3 illustrates that an increase in the setting temperature correlates with an elevated flow rate within the loop. At temperatures of 50, 60, 70, 80, and 90 degrees, the corresponding flow rates are 6.44×10^{-5} m³/s, 6.8×10^{-5} m³/s, 1.03×10^{-4} m³/s, 1.18×10^{-4} m³/s, and 1.29×10^{-4} m³/s, respectively. In natural circulation, the flow rate is generated by the temperature differential, which induces buoyant forces, aided by gravity. Additionally, the Reynolds number at steady state is derived from the flow rate using equations 1 to 3, as illustrated in Fig. 4.

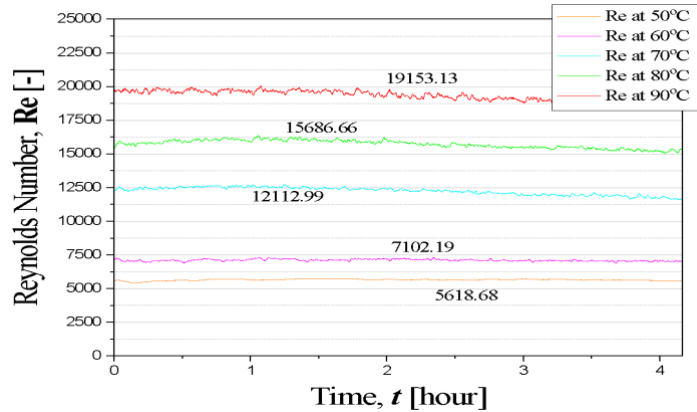


Figure 4. The value of the Reynolds number under steady-state conditions.

Figure 4 illustrates that the Reynolds number is directly related to the flow rate. The Reynolds number increases with the setting temperature, ranging from a minimum of 5618.68 at 50°C to a maximum of 19153.13 at 90°C. The Reynolds number serves to delineate the flow regime, and the numbers depicted in Fig. 2 indicate that the flow regime in the FASSIP-02 Test loop is turbulent. The flow regime can also be determined using the Grashof number. The flow regime delineation based on the Grashof number is as follows: $Gr < 10^8$ indicates a laminar regime, $10^8 < Gr < 10^9$ signifies a transitional regime, and $Gr > 10^9$ corresponds to a turbulent regime. Figure 5 displays the Grashof number values for the FASSIP-02 Test loop.

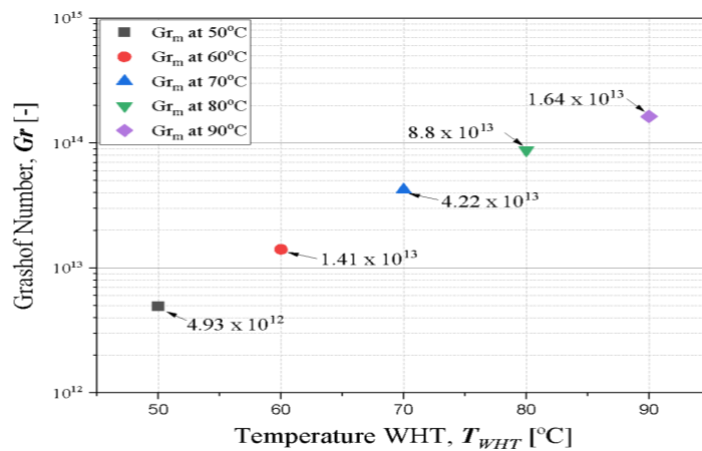


Figure 5. The Grashof number values are based on variations in temperature settings in WHT

Figure 5 indicates that the flow regime within the loop has transitioned to a turbulent state. The lowest temperature setting of 50°C corresponds to a Grashof number of 4.93×10^{12} , while the highest temperature setting of 90°C has a Grashof number of 1.64×10^{13} . The Grashof number formula is generally applicable solely to specific domains, such as a flat plate or a pipe. Determining the Grashof number on a loop is distinct, as numerous factors might influence its value. The surface roughness, the number of turns, the number of joints in the loop, and the total length of the pipe can also have an impact. Consequently, the Grashof number's value must be split by these reduction factors, specifically written as N_G in this instance. The relationship between the two nondimensional numbers can be established by formulating Equation 7.

$$Re_{ss} = C \left[\frac{Gr_m}{N_G} \right]^r \quad (7)$$

This research employs data analysis through graph software to ascertain the values of the constants C and r. The correlation results are illustrated in Figure 6.

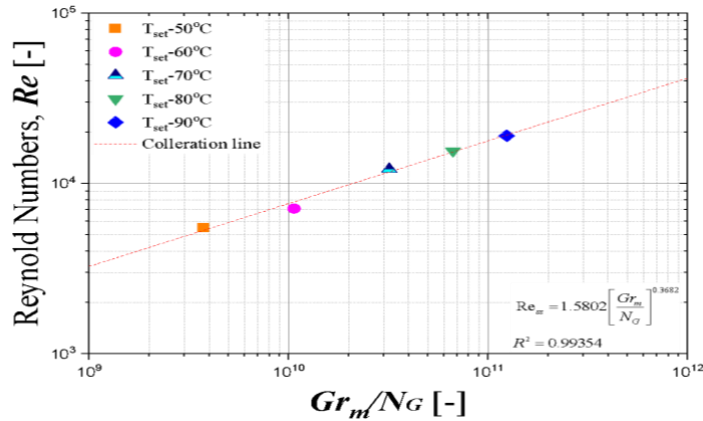


Figure 6. Graph of the relationship between the Reynolds number and Gr_m/N_G .

Figure 6 elucidates the relationship between the Reynolds number and Grashof number on the FASSIP-02 test loop, contingent upon fluctuations in temperature settings within the WHT tank. Allometric fitting is conducted on the generated data to ascertain the values of the C and r constants from Equation 7. The correlation results between the Reynolds number and the Grashof number are presented in equation 8, accompanied by the value of $R^2 = 0.99354$.

$$Re_{ss} = 1.5802 \left[\frac{Gr_m}{N_G} \right]^{0.3682} \quad (8)$$

The experimental data is compared with data from alternative investigations. The experiment's results closely approach the correlation line for turbulent flow. This indicates that the research data and the computed correlation exhibit a minor divergence from the correlation established by Vijayan et al (2000). The discrepancy may arise from variations in the precision of the measuring instruments employed in the experiment.

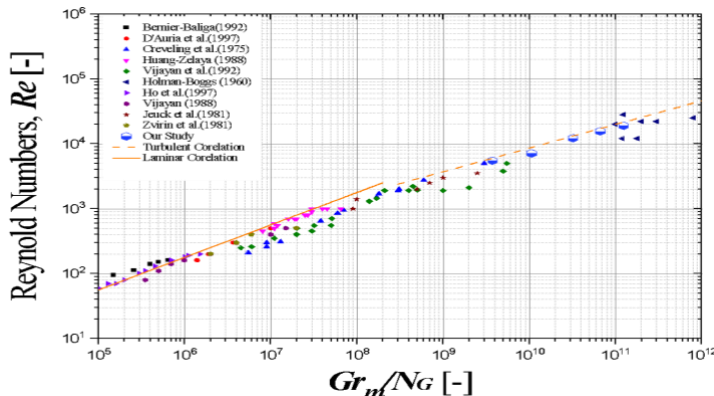


Figure 7. Comparison graph of the relationship between Reynolds number and Gr_m/N_G with other studies.

4. Conclusions

The conclusions of this investigation indicate that the flow regime in the FASSIP-02 Test Loop is turbulent. The Reynolds number is seen within the range of $5500 < Re < 18983$, while the Grashof number indicates that the experimental results are within the range of $4.93 \times 10^{12} < Gr_m < 1.64 \times 10^{14}$. The connection between the two non-dimensional integers yielded the equation.

$$Re_{ss} = 1.5802 \left[\frac{Gr_m}{N_G} \right]^{0.3682} \quad (9)$$

The correlation results, when matched with those of other researchers, exhibit a marginally lower value, attributed to the type and precision of the measurement instrument employed in the experiment.

5. Acknowledgments

Research Grant funded this research for “Riset Inovasi untuk Indonesia Maju” (RIIM) batch 1 the year 2022-2025 with contract number B-811/II.7.5/FR/6/2022 and B-103/III.2/HK.04.03/7/2022. Thank you to the Head of the Research Centre for Nuclear Reactor Technology, the Research Organization for Nuclear Energy (BATAN), and the National Research and Innovation Agency (BRIN). Also, special thanks to all members of the Nuclear Reactor Thermal-Fluids System (NRTFSys.) research group.

6. References

- Allen, C. (1993). Thermophysical Properties of Saturated Light and Heavy Water for Advanced Neutron Source Applications. 25–29.
- Juarsa, M., Girano, Heru, G. B., Haryanto, D., & Prasetyo, J. (2016). Passive Safety Sistem Simulation (FASSIP) Loop for Natural Circulation Study. *Prosiding Seminar Nasional Teknologi Energi Nuklir*, 673–682.
- Juarsa, Mulya., & Antariksawan, A. R. (2018). Estimation of natural circulation flow based on temperature in the FASSIP-02 large-scale test loop facility. *IOP Conference Series: Earth and Environmental Science*, 105(1), 0–7. <https://doi.org/10.1088/1755-1315/105/1/012091>
- Lai, K., Wang, W., Yi, C., Kuang, Y., & Ye, C. (2018). The study of passive cooling system assisted with a separate heat pipe for decay heat removal in spent fuel pool. *Annals of Nuclear Energy*, 111, 523–535. <https://doi.org/10.1016/j.anucene.2017.08.062>
- Lai, Z., Tian, W., Chen, C., Wang, M., Zhang, K., Qiu, S., & Su, G. (2022). Experimental study on thermal-hydraulic characteristics of natural circulation loop under motion condition. *Applied Thermal Engineering*, 207(October 2021), 118122. <https://doi.org/10.1016/j.applthermaleng.2022.118122>
- Misale, M. (2016). Experimental study on the influence of power steps on the thermohydraulic behavior of a natural circulation loop. *International Journal of Heat and Mass Transfer*, 99, 782–791. <https://doi.org/10.1016/j.ijheatmasstransfer.2016.04.036>

- Park, R. J., Ha, K. S., & Kim, H. Y. (2016). Detailed evaluation of natural circulation mass flow rate in the annular gap between the outer reactor vessel wall and insulation under IVR-ERVC. *Annals of Nuclear Energy*, 89, 50–55. <https://doi.org/10.1016/j.anucene.2015.11.022>
- Swapnalee, B. T., & Vijayan, P. K. (2011). A generalized flow equation for single-phase natural circulation loops obeying multiple friction laws. *International Journal of Heat and Mass Transfer*, 54(11–12), 2618–2629. <https://doi.org/10.1016/j.ijheatmasstransfer.2011.01.023>
- Tangkesalu, A., Kusuma, I., & Suarnadwipa, I. N. (2017). Analisis Perpindahan Panas Pada Cooler Tank FASSIP-01. *Jurnal METTEK*, 3(1), 11–20.
- Vijayan, P. K. (2002). Experimental observations on the general trends of the steady state and stability behavior of single-phase natural circulation loops. *Nuclear Engineering and Design*, 215(1–2), 139–152. [https://doi.org/10.1016/S0029-5493\(02\)00047-X](https://doi.org/10.1016/S0029-5493(02)00047-X)
- Vijayan, P. K., Bade, M. H., Saha, D., Sinha, R. K., & Raj, V. V. (2000). *A generalised correlation for the steady state flow in single-phase natural circulation loops by.*
- Zhang, J., Shen, X., Fujihara, Y., Sano, T., Yamamoto, T., & Nakajima, K. (2015). Experimental study on the safety of Kyoto University Research Reactor at natural circulation cooling mode. *Annals of Nuclear Energy*, 76, 410–420. <https://doi.org/10.1016/j.anucene.2014.10.010>