

Simulation on Thermal and Flow Characteristics Investigation of Natural Circulation Under Different Heating Powers using FASSIP-06 Ver.03 Loop

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ABSTRACT

Natural circulation systems are passive cooling mechanisms that operate based on density differences caused by temperature variations. These systems play a crucial role in ensuring the safety and efficiency of nuclear reactors, particularly during transient cooling phases following total power loss, where active systems fail, and passive cooling becomes essential. This study aims to analyze the thermal and flow characteristics of single-phase natural circulation in the FASSIP-06 Ver.03 loop. The investigation was conducted using CFD simulations in ANSYS Fluent, with heater power variations from 750 W to 1050 W. A three-dimensional model of the loop geometry was developed and the RNG $k-\epsilon$ turbulence model with scalable wall functions. Boundary conditions included a constant cooling temperature of 10°C and adiabatic walls, with water as the working fluid. The analysis focused on transient and steady-state temperature distribution, flow velocity patterns, and the relationship between heater power and Reynolds number. The results show that increasing heater power enhances the temperature difference between the hot and cold legs, intensifies the circulation flow, and increases Reynolds numbers in the cold leg from 3414 to 4759, indicating a transition toward turbulent flow due to its smaller diameter. In contrast, the hot leg flow remains laminar, with Reynolds numbers below 1739. These findings confirm that CFD simulation effectively captures the thermohydraulic behavior of natural circulation and validates the FASSIP-06 Ver.03 loop as a reliable model for passive cooling system analysis.

Keywords: Passive Cooling System, Natural Circulation, Simulation, CFD, FASSIP-06 Ver.03.

1. INTRODUCTION

Natural Circulation Systems (NCS) are passive cooling mechanisms principle that operate based on density differences induced by temperature gradients without using mechanical pumps (IAEA TECDOC 1624, 2009). These systems are widely implemented in nuclear reactors, solar thermal systems, and heat exchangers due to their reliability in maintaining operational safety and efficiency (Vijayan et al., 2019). The importance of passive cooling systems significantly increased following the 2011 Fukushima Daiichi accident, which was caused by the failure of active cooling systems during a total station blackout (Gauntt et al., 2012; Labib & Harris, 2015; Visschers & Siegrist, 2013). This incident resulted in reactor core meltdown and large-scale release of radioactive materials. Consequently, the development and optimization of passive natural circulation-based cooling systems have become crucial for enhancing the safety of next-generation nuclear reactors (Kang et al., 2019).

The effectiveness of natural circulation is strongly influenced by thermal gradients, loop geometry, and flow dynamics. Therefore, a comprehensive thermohydraulic analysis is essential to understand the system's behavior and ensure operational reliability. In this context, the FASSIP (Fasilitas Simulasi Sistem Pasif) series has been developed by the Nuclear Energy Research Organization (ORTN-BRIN) as a staged experimental platform for investigating natural circulation under controlled conditions.

Research using FASSIP-01 and FASSIP-02 primarily focused on experimental evaluation of heater-cooler performance (Noufal et al., 2015), analysis of backward flow phenomena (Juarsa et al., 2018), coefficient of performance using Cycle-Tempo (Giarno et al., 2016), as well as CFD validation against experimental data (Juarsa et al., 2019). The FASSIP-02 system was extended to analyze temperature profile, mass flow rate, pressure, and the effect of insulation and valve operation on system performance (Antariksawan et al., 2018). RELAP5 simulations were used to validate steady-state thermal-hydraulic characteristics (Antariksawan et al., 2019). Studies on FASSIP-04 later incorporated nanofluid applications (Yuliaji et al., 2025), while FASSIP-05 served as a preliminary estimation tool for natural circulation flow rate prediction (Adrian et al., 2023).

Despite the extensive body of work across various FASSIP generations, a detailed CFD-based investigation of single-phase natural circulation behavior under variable heating powers in FASSIP-06 Ver.03 has not been conducted. The FASSIP-06 Ver.03 facility itself is a more advanced experimental loop, equipped with a Vertical Heater – Vertical Cooler (VHVC) configuration and Non-Uniform Diameter Loop (NDL) layout, specifically designed to simulate both single-phase and two-phase flow conditions. However, understanding single-phase system characteristics remains essential as a fundamental basis for evaluating passive cooling performance before progressing to two-phase studies (Jain et al., 1966; Krishnan & Gulshani, 1987; Manera & van der Hagen, 2003; Zvirin, 1982; Zvirin & Greif, 1979).

Computational Fluid Dynamics (CFD) simulations have become an essential tool in thermal-hydraulic studies as they enable detailed modeling of flow and heat transfer phenomena without requiring large-scale experiments (IAEA TECDOC 1379, 2002; Wahidi et al., 2021; Wang et al., 2013). In this study, CFD simulations were performed to analyze single-phase natural circulation in the FASSIP-06 Ver.03 loop with heater power variations of 750 W, 850 W, 950 W, and 1050 W. The analyzed parameters include temperature distribution during transient heating, steady-state temperature distribution, fluid flow patterns and velocity profiles, as well as the relationship between heater power and mass flow rate under steady-state conditions.

The objective of this study is to analyze the characteristics of single-phase natural circulation in the FASSIP-06 Ver.03 loop through CFD simulations with varying heater power levels from 750 W to 1050 W. The investigation focuses on several key parameters including temperature distribution during transient heating processes, steady-state temperature distribution, fluid flow velocity patterns, and the relationship between heater power and Reynolds number. Compared to previous FASSIP studies, this research offers a novel computational approach in capturing detailed thermohydraulic dynamics and flow regime transition in a complex loop geometry under varying thermal loads. The findings are expected to establish a fundamental basis for

future experimental studies utilizing the FASSIP-06 Ver.03 facility, thereby contributing to the advancement of passive cooling system technology.

2. METHODS

FASSIP-06 Ver.03 (Fasilitas Sistem Pasif - 06 Version 03) is an experimental single-phase natural circulation loop facility developed by the (Organisasi Riset Tenaga Nuklir, ORTN) under the National Research and Innovation Agency (BRIN) of Indonesia. In this study, numerical simulation using CFD methodology was employed to model the flow behavior within the FASSIP-06 Ver.03 loop system. The CFD approach enables detailed analysis of thermal-hydraulic characteristics, providing valuable insights into the system's performance under various operational conditions while serving as a cost-effective alternative to full-scale experimental testing. This numerical investigation forms a crucial part of the facility's development process, allowing for comprehensive evaluation of design parameters before physical implementation.

2.1 Governing Equation

The FASSIP-06 Ver.03 loop is modeled using the three-dimensional Navier-Stokes equations, incorporating the following conservation principles Eqs. (1-3):

Continuity Equation Eq. (1):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad (1)$$

Momentum Equation Eq. (2):

$$\rho \cdot \left(\frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla P + \nabla \cdot (\mu \nabla u) + \rho g \quad (2)$$

Since the main driving force in natural circulation is the buoyancy force, the Boussinesq Approximation is applied using Eq. (3):

$$\rho = \rho_0 \{1 - \beta(T - T_0)\} \quad (3)$$

Energy Equation Eq. (4):

$$\rho c_p \left(\frac{\partial T}{\partial t} + u \cdot \nabla T \right) = \nabla \cdot (k \nabla T) \quad (4)$$

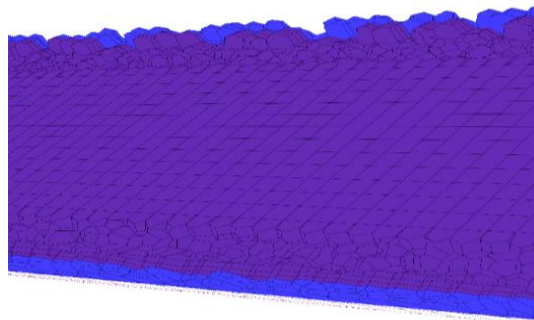
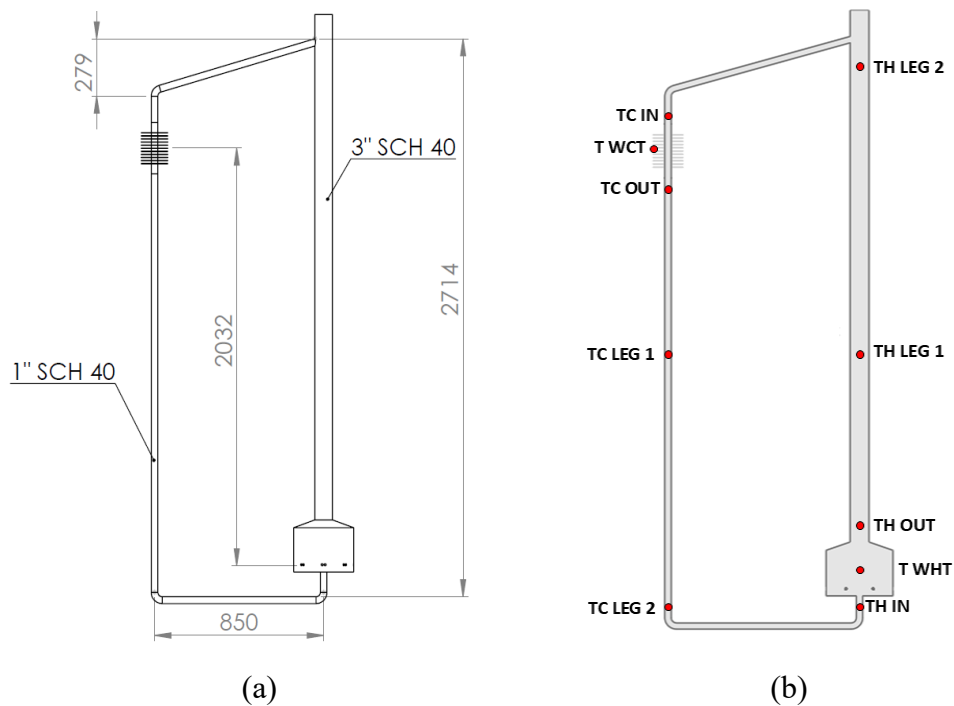
The single-phase, steady-state formulation assumes:

- Incompressible flow with temperature-dependent properties
- Negligible viscous dissipation
- No internal heat generation

2.2 Numerical Implementation

As shown in the Fig. 1, the system geometry consists of a rectangular natural circulation loop with a heater at the bottom and a cooler at the top, configured as a Vertical Heater Vertical Cooler (VHVC) and featuring a Non-Uniform Diameter Loop (NDL) design. The complete geometric specifications are provided in Fig. 1(a). Temperature measurement points are distributed across various locations to monitor thermal distribution during natural circulation, as illustrated in Fig. 1(b). The computational domain was discretized using the finite volume method, with numerical treatments following Fig. 1(c).

The mesh was constructed using structured poly-hexcore elements, which are critical for accurately resolving viscous boundary layers. Mesh quality was rigorously evaluated by assessing skewness and orthogonality—key indicators of numerical stability and solution accuracy (Fertahi et al., 2018; Khan et al., 2020). The skewness check yielded an average value of 0.075, while the mean orthogonal quality was 0.919, confirming the mesh's suitability for high-fidelity simulations.



(c)

Figure 1. Geometrical FASSIP-06 Ver.03 loop set-up and meshing:
(a) geometrical dimension, (b) temperature measurement point and (c) volume mesh result

The ANSYS Fluent solver was configured using a pressure-based coupled solver with pseudo-transient formulation. The momentum and energy equations were discretized employing a second-order upwind scheme, while turbulence was modelled using the RNG k- ϵ approach augmented with scalable wall functions.

The boundary conditions were specified as follows:

- The heater was assigned a heat source corresponding to input power variations of 750 W, 850 W, 950 W, and 1050 W
- The cooler was maintained at a constant temperature of 10°C
- All walls were treated as adiabatic, except for the predefined heating and cooling sections

The working fluid in this simulation was water, whose well-documented thermal properties (available in literature) enable accurate prediction of its thermal behavior across temperature variations. These property variations were characterized using Allen Crabtree's correlations (Crabtree & Siman-Tov, 1993) Eq. (5), which provide specific equations and constants for precise thermophysical property calculations.

$$\rho_{water}(T) = A + BT_F + CT_F^2 \quad (5)$$

$$A = 1004.789042 \quad B = -0.046283 \quad C = -7.9738 \times 10^{-4} \quad T_F = 1.8T + 32$$

2.3 Analysis Framework

The comprehensive analysis process of the FASSIP-06 Ver.03 loop simulation results is illustrated in Fig. 2, beginning with the collection of temperature and flow velocity data obtained from the numerical simulations. These datasets were subsequently analyzed through multiple approaches to gain fundamental insights into system behavior, including qualitative flow visualization through contour plots and streamline patterns that reveal characteristic flow distributions. Simultaneously, quantitative analyses were performed by examining temperature temporal variations to assess thermal property changes (Juarsa, Antariksawan, Kusuma, Putra, et al., 2019).

For monitoring flow velocity evolution to evaluate circulation intensity, where velocity data was converted to volumetric flow rates using Eq. (6) for more practical engineering interpretation.

$$Q = v.A \quad (6)$$

Following the initial analysis, the subsequent step involves calculating the mass flow rate under steady-state conditions using Eq. (7).

$$\dot{m} = Q \cdot \rho \quad (7)$$

To determine the flow regime within the pipe, a dimensional analysis of the Reynolds Number (Re) was performed using Eq. (8).

$$Re = \frac{\dot{m}D}{A\mu} \quad (8)$$

The final stage of analysis for the FASSIP-06 Ver.03 loop simulation results demonstrated that both flow rate and flow regime intensify with increasing heater power. This indicates that natural circulation phenomena in the system can be effectively represented through CFD simulation. Furthermore, several critical characteristics of natural circulation systems, including temperature distribution and flow patterns were successfully identified and yielded consistent results. These findings support the validity of the obtained data and confirm the simulation's capability to accurately represent system behavior.

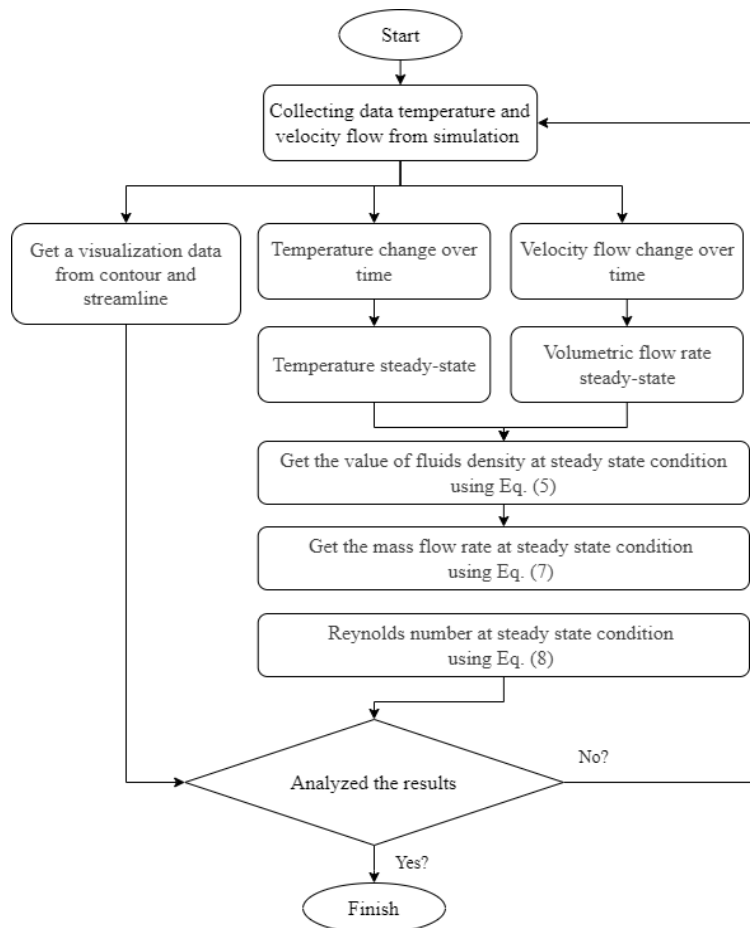


Figure 2. Collecting data and analysis flow diagram

3. RESULT AND DISCUSSION

3.1 Temperature Distribution Under Varying Heating Powers

The increase in heating power within the FASSIP-06 Ver.03 loop system led to temperature rises until steady-state conditions were achieved, as shown in Figs. 3-6. The simulations with power inputs of 750 W, 850 W, 950 W, and 1050 W demonstrated that higher heating power resulted in greater achieved temperatures. At 750 W, the TH OUT temperature reached 64.56°C, while at 850 W, 950 W, and 1050 W, this value increased to 70.07°C, 75.49°C, and 80.79°C, respectively.

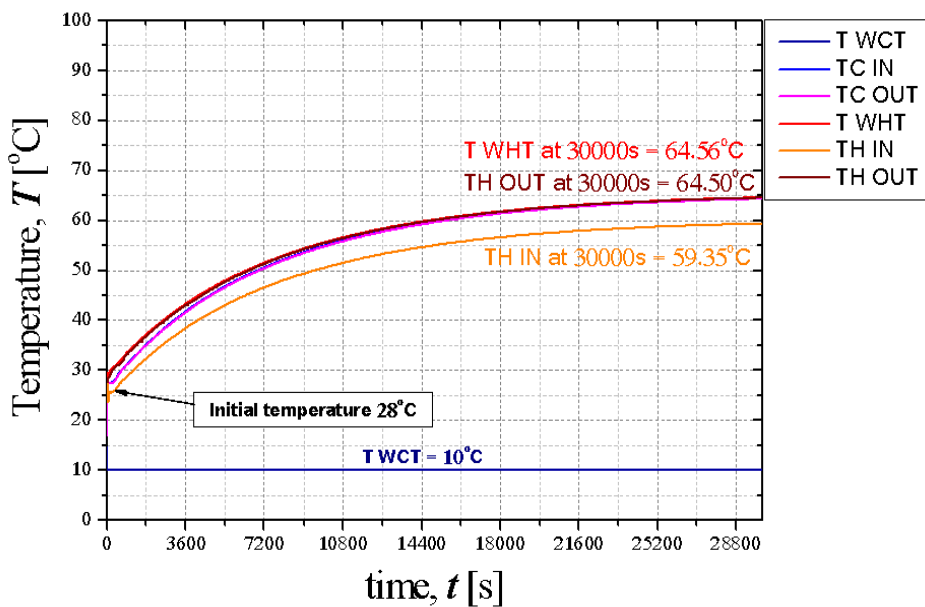


Figure 3. Transient heating temperature characteristic with heating power 750W

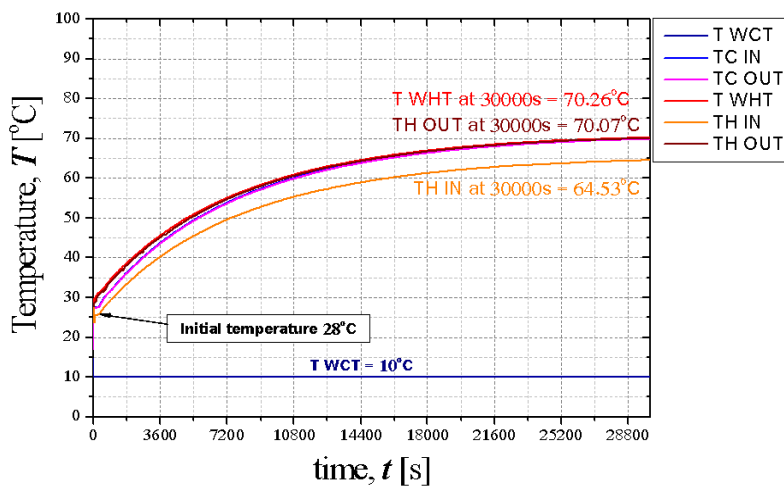


Figure 4. Transient heating temperature characteristic with heating power 850W

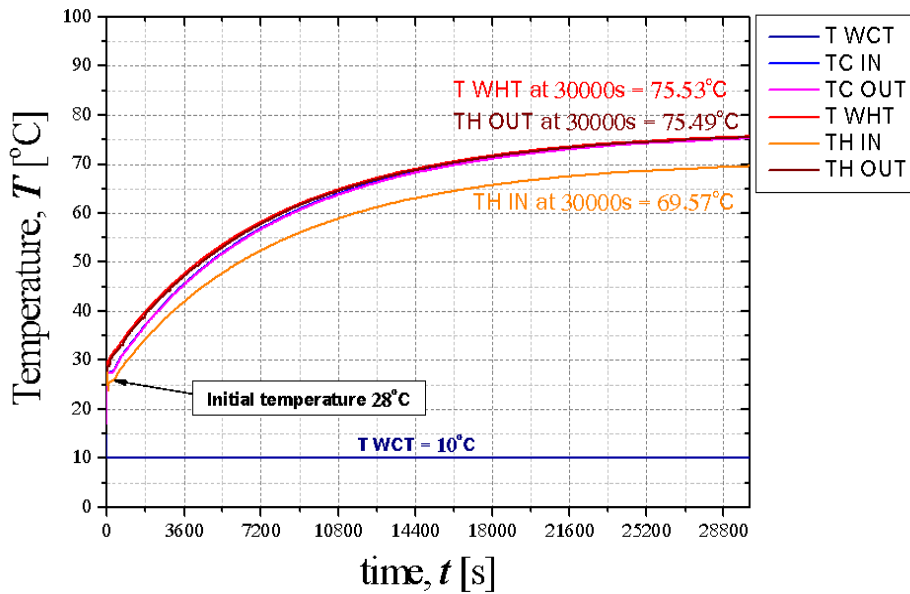


Figure 5. Transient heating temperature characteristic with heating power 950W

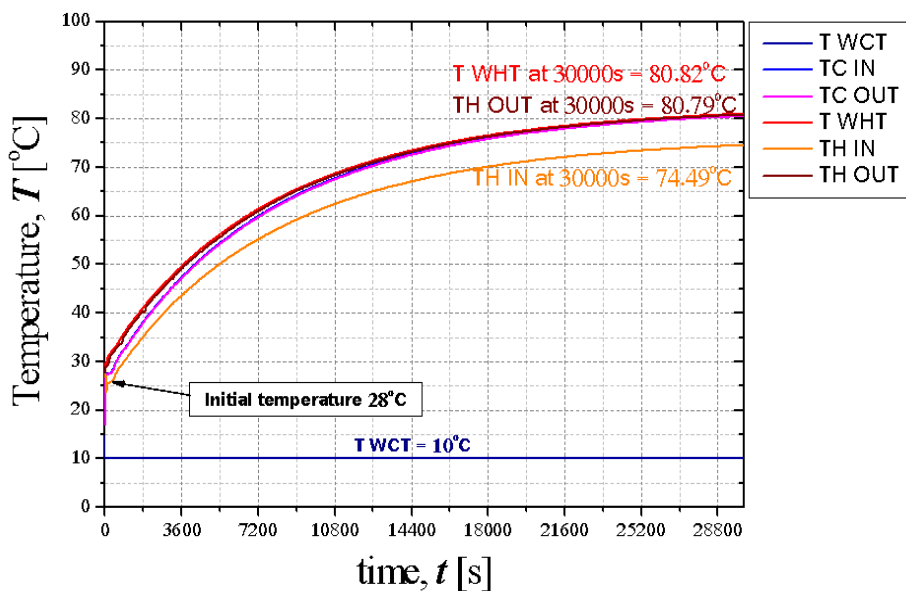


Figure 6. Transient heating temperature characteristic with heating power 1050W

Temperature increases were also observed at T WHT and TH IN, indicating enhanced heat transfer within the system corresponding to the applied energy input. Steady-state conditions were achieved after approximately 30,000 seconds in each simulation, with similar temperature

rise patterns observed across all cases. These results confirm that higher heating power directly leads to elevated temperatures in the natural circulation loop system.

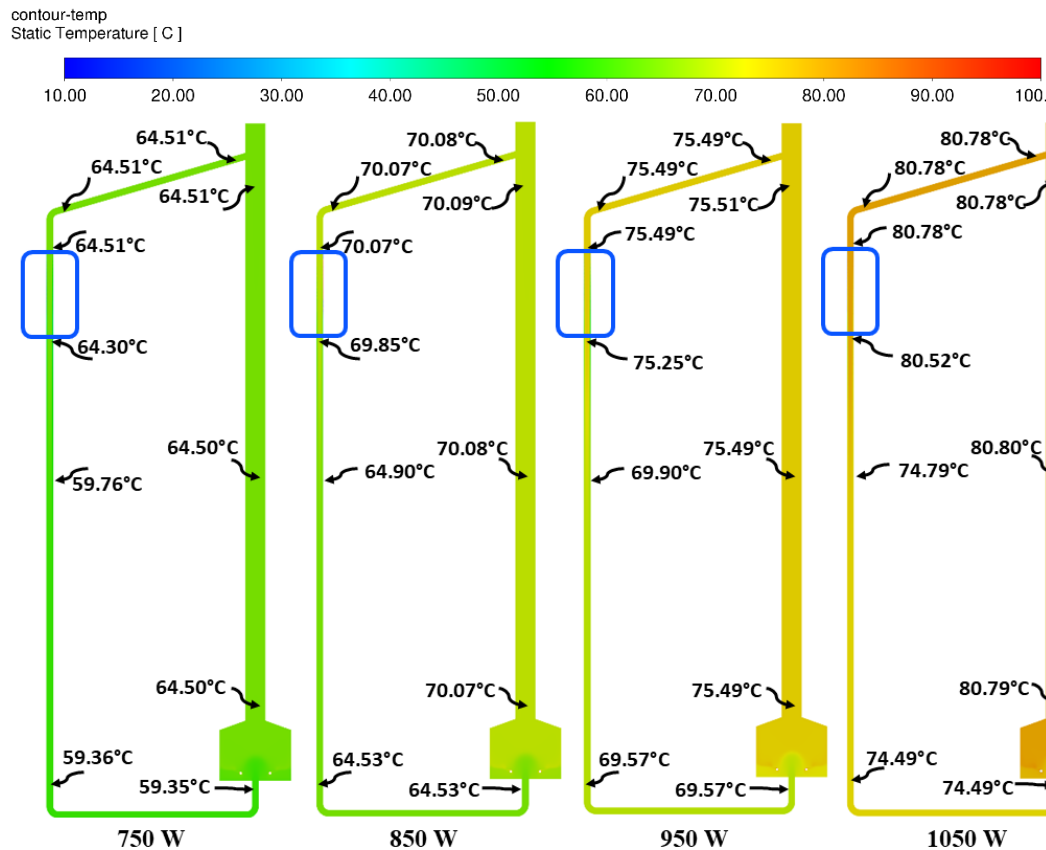


Figure 7. Visualization of temperature distribution

As illustrated in Fig. 7, the colour scale (ranging from 10°C to 100°C) shows low temperatures in blue and high temperatures in red. The four visualizations represent the temperature distributions for each power input. With increasing heating power, the fluid temperature throughout the loop rises, evident from the colour transitions from green to yellow-orange. The heater section consistently exhibited higher temperatures compared to other regions, while the temperature gradient along the loop clearly demonstrates the heat transfer occurring through natural circulation flow. The thermal stratification and circulation patterns visualized in these results validate the system's expected thermohydraulic behavior under varying operating conditions.

The increase in heater power in the NCS directly contributes to a greater temperature difference (ΔT_{leg}) between the hot leg and cold leg. As shown in Fig. 8, ΔT_{leg} consistently rises from 4.74°C at 750 W to 6.01°C at 1050 W. This growing temperature differential demonstrates that higher thermal energy input creates a steeper temperature gradient within the loop.

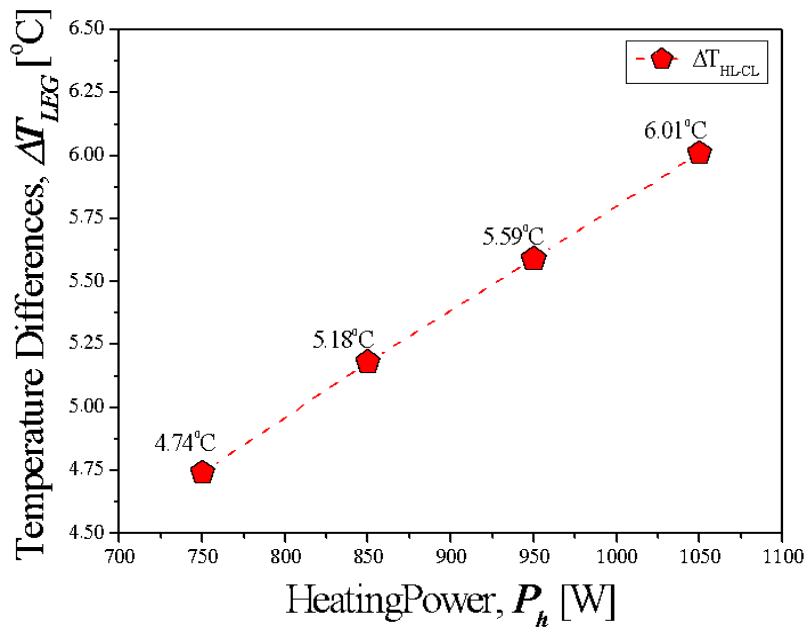


Figure 8. Temperature difference between hot leg and cold leg $\Delta T_{leg} = T_{hot\ leg} - T_{cold\ leg}$

The enhanced thermal gradient strengthens the buoyancy force due to increased fluid density variation, which in turn drives a higher fluid circulation rate. This mechanism clearly illustrates the fundamental thermo-hydraulic coupling in natural circulation systems, where greater heat input directly amplifies the driving potential for fluid motion through density-induced buoyancy effects.

3.2 Velocity and Flow Pattern Characteristic

The increase in heating power significantly affects the fluid flow characteristics in a thermal system. This is clearly shown in Fig. 9, which displays the transient response of the NC flow rate. It can be observed that the flow rate increases over time until reaching steady-state conditions, where the flow rate stabilizes. The higher the heating power, the greater the steady-state NC flow rate becomes. This demonstrates that increased heating power enhances the driving force of natural circulation within the system.

The increase in heating power in the natural circulation system strengthens the buoyancy force that serves as the primary driving mechanism for flow. This is demonstrated in Fig. 10, where the fluid velocity increases with rising power from 750 W to 1050 W. The maximum velocity was recorded in the 1-inch cold leg piping at the bottom section, with values increasing from 0.058053 m/s to 0.066013 m/s. In the 3-inch piping, the velocity decreased to between 0.005635 m/s and 0.006437 m/s due to the change in the loop's pipe cross-sectional area.

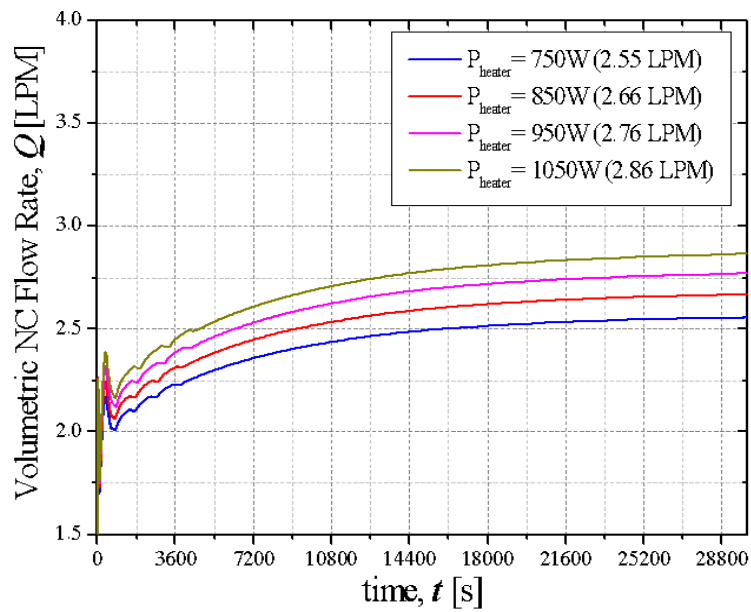


Figure 9. Transient heating volumetric flowrate characteristic with various heating power

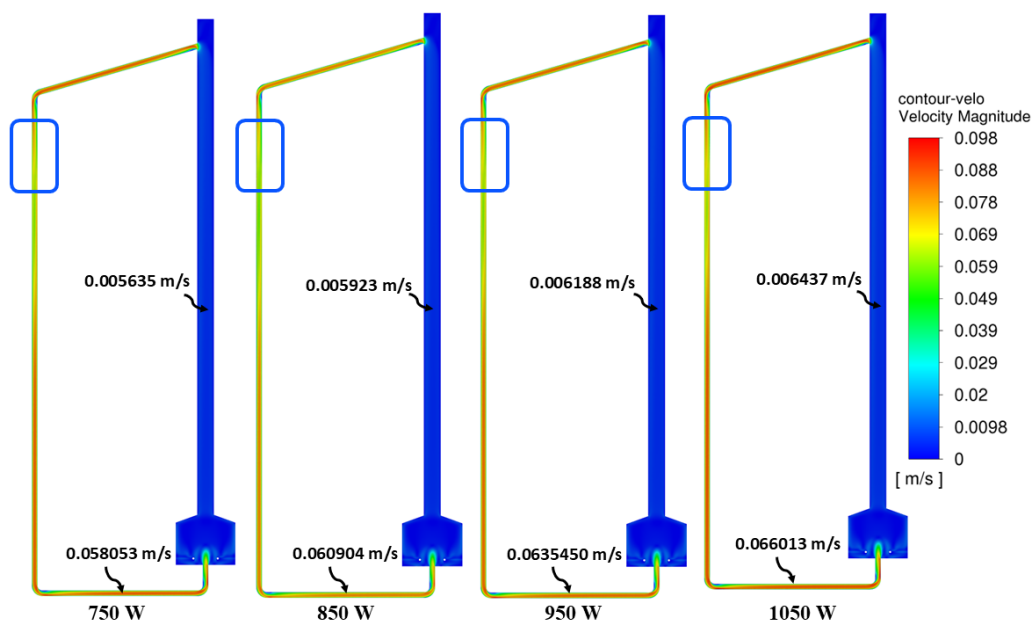
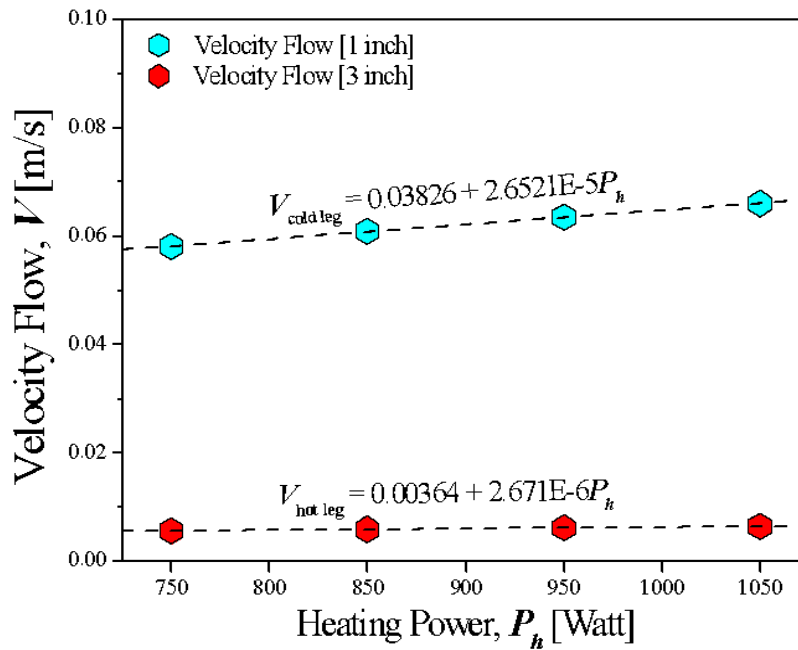
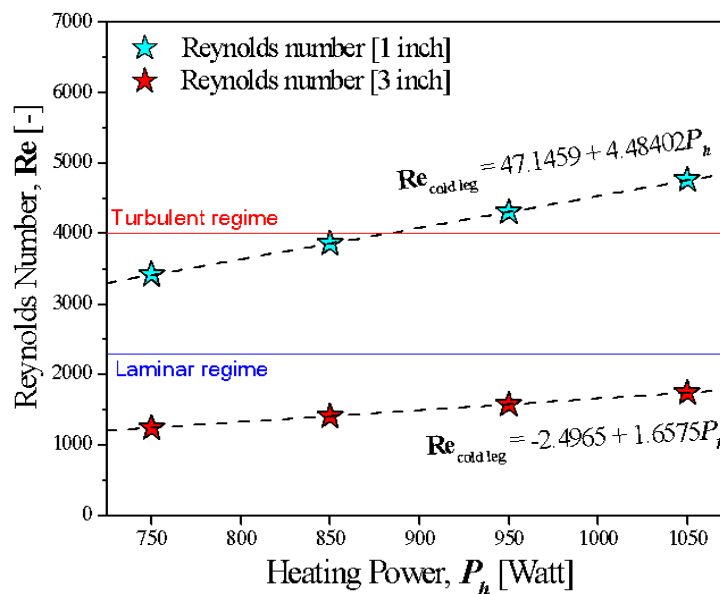


Figure 10. Visualization of velocity flow characteristics

3.3 Influence of Heating Power on Velocity and Reynolds Number



(a)



(b)

Figure 12. Effect of heating power variation on flow velocity (a) and Reynolds number (b) in the single-phase natural circulation loop of FASSIP-06 Ver.03 loop.

The increase in heating power directly impacts the enhancement of fluid flow velocity and Reynolds number in the single-phase natural circulation system. This occurs because higher heating power amplifies the temperature gradient between the hot leg and cold leg, thereby generating greater buoyancy force to drive the fluid.

In the flow velocity graph (Fig. 12a), the cold leg (1-inch diameter) shows significantly greater velocity increase compared to the hot leg (3-inch diameter). The cold leg velocity follows the linear equation shown in the graph, reaching approximately 0.058 m/s at 750 W and increasing to about 0.066 m/s at 1050 W. Conversely, hot leg velocities remain much lower, with only about 0.0064 m/s at maximum power.

The Reynolds number graph (Fig. 12b) reveals similar behavior, with the cold leg demonstrating substantial growth from $Re=3414$ at 750 W to $Re=4759$ at 1050 W. These values indicate transition from transient to turbulent flow regime, as marked by the $Re=4000$ threshold line. The relationship between Re and Ph in the cold leg follows the equation displayed in the graph. Meanwhile, the hot leg maintains laminar flow conditions ($Re < 2300$), showing a much slower increasing trend and reaching a maximum value of approximately 1739 at 1050 W.

Collectively, the data demonstrate that heating power is the dominant factor governing fluid circulation rates, particularly in smaller-diameter piping which shows greater sensitivity to temperature and density gradients. Larger-diameter sections exhibit more stable, slower flow characteristics. These findings provide crucial fundamentals for passive cooling system design, especially in optimizing pipe diameter distribution to achieve maximum heat transfer efficiency.

4. CONCLUSION

Based on the results of CFD simulation on the FASSIP-06 Ver.03 loop system, it can be concluded that an increase in heater power directly causes an increase in temperature between the hot leg and the cold leg. The fluid flow visualization through velocity contours and streamlines also confirms the formation of a stable circulation pattern, with increased velocity in the heater region.

The Reynolds number in the cold leg also shows a significant increase from 3414 to 4759, indicating a transition from transient to turbulent flow (exceeding the threshold of $Re = 4000$). In contrast, the Reynolds number in the hot leg remains within the laminar regime, with a maximum value of approximately 1739. These results show that the cold leg, with a smaller diameter (1 inch), tends to have a more turbulent flow pattern due to the reduced pipe diameter, which leads to higher flow velocity. Meanwhile, the larger-diameter hot leg (3 inches) tends to produce a slower and more stable flow.

This proves that the FASSIP-06 Ver.03 loop system and the CFD simulation approach used are capable of accurately representing thermo-hydrodynamic phenomena in passive cooling systems. The simulation also demonstrates the potential of FASSIP-06 Ver.03 as a reliable experimental and predictive platform in the study of single-phase natural circulation systems.

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6. AUTHORS CONTRIBUTION

Sunandi Kharisma conducted the design and methodology of this research, providing a structured data collection and analysis framework. **Mulya Juarsa** provided conceptualization, framed the overarching ideas and objectives, and conducted a solution to the problems and research funding. **Deendarlianto** with a keen eye for detail, conducted a thorough review and contributed to the editing process, enhancing the overall quality of the manuscript and financial support for publication. **Shendy Akbar Maryadi** provided assistance to the first author during the data collection process.

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