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Experimental Investigation of Natural Circulation Stability Phenomena in a New Loop Heat Pipe Model

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A B S T R A C T

The severe accident at the Fukushima Dai-ichi Nuclear Power Plant in Japan in 2011 highlighted the critical need for a passive cooling system to dissipate residual decay heat following the failure of active cooling systems in the nuclear facility. The loop heat pipe (LHP) is a promising technology for such applications. The objective of this research is to understand the natural circulation stability phenomena of new LHP model under various conditions of filling ratio and heat load. The experimental methodology employed a laboratory-scale LHP model made of copper with an inner diameter of 0.104 m. The experiments were designed with filling ratios of 20%, 40%, 60%, 80%, and 100%, and hot water temperature as the evaporator heat source with variations of 60 °C, 70 °C, 80 °C, and 90 °C. The initial operating pressure was 10665.6 Pa, with a 5˚ inclination angle, demineralized water as the working fluid, and cooled by air at a velocity of 2.5 m/s. The results show that LHP natural circulation happens in two phases and stays stable. The best performance was seen at 90 °C and an 80% filling ratio. The conclusion of this research indicates that natural circulation stability in LHP operates well and occurs in two phases. This demonstrates that LHP effectively acts as a heat absorber and heat dissipator.

1. INTRODUCTION

Energy is a fundamental requirement in life. The demand for energy in every country is constantly increasing, in line with the rising population. Currently, oil and gas are the primary sources of energy across the globe. However, oil and gas reserves are finite and expected to deplete over time, while dependency on fossil fuel energy sources such as coal, petroleum, and gas is expected to continue increasing. Electricity consumed by the communities is primarily generated from coal-fired and oil-fired Steam Power Plants, which are categorized as non-renewable and environmentally

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unfriendly sources. According to the Presidential Decree of the Republic of Indonesia Number 22 Year 2017 regarding the National Energy Masterplan, there is a priority on transitioning to renewable energy with a target of at least 23% by the year 2025 and at least 31% by 2050 [1]. In addition, in the Bill on New and Renewable Energy (RUU EBT), Chapter IV includes nuclear energy as one of the new and renewable energy sources. The implications of this RUU EBT can be one of the alternatives to meet future energy demands. Globally, nuclear power is a well-established energy source, with over 440 reactors operating in 31 countries as of 2012, providing about 11% of the world's electricity [2]. The main advantages of nuclear power are the absence of greenhouse gas emissions, the waste produced has a negligible volume because the radiation risk is limited and monitored in such a way as not to cause pollution to the environment, and NPPs occupy a much smaller area compared to hydroelectric power plants, wind power plants, and photovoltaic cells. However, there are several disadvantages regarding nuclear energy, namely the high investment costs in reactor construction, and if operational failures occur, it can lead to the release of radioactive substances into the environment, which will have an impact on the surroundings [3].

One of the nuclear utilization accident cases occurred at Fukushima Dai-ichi, Japan, in 2011, triggered by a tsunami and earthquake. The earthquake damaged the power lines leading to the nuclear power plant, resulting in a station blackout. Subsequently, the tsunami flooded the area, submerging the diesel generators that were critical for supplying electricity to the cooling system. Without power, the cooling systems failed to dissipate the residual heat generated by the nuclear fuel in the reactor core and the spent fuel in the Spent Fuel Storage Pools (SFSP). The accumulated heat from the decay increased the water temperature in the SFSP, causing it to evaporate and lowering the water level below the fuel surface. The evaporation process produced hydrogen gas, which, when accumulated, contributed significantly to the failure of the nuclear power plant operation [4].

As a consequence of the accident, a passive cooling system is required to assist the active cooling system in dissipating residual heat generated by the reactor during a station blackout event. The passive cooling system aims to maintain the reactor system in a safe condition and ensure its normal operation. One technology capable of efficiently transferring heat is the heat pipe. Heat pipe, also known as heat transfer pipe, is a technology that utilizes a closed pipe of certain dimensions containing a working fluid, which functions as a conductor from the evaporator to the condenser. There are various types of heat pipes, and one of the most commonly used types in the electronics field is the loop heat pipe (LHP) [5].

The two-phase operation of heat pipes facilitates the natural circulation of the condensate from the condenser section back to the evaporator section, thereby sustaining continuous fluid circulation within the system. Heat pipes exhibit two usage variations: those with a capillary structure and those that are wickless. Brushly et al. conducted research on heat pipes as passive cooling systems, employing biocarbon capillary pipes [6]. The working fluid in heat pipes can be varied, including options such as ammonia, graphene-water nanofluids [7], ethanol [8], and argon [9]. The findings of this research indicate that heat pipes demonstrate excellent heat transfer capabilities through natural circulation (NC).

The natural circulation stability in LHP is influenced by pressure, working fluid type, heat load, and filling ratio [9]. Hariyanto et al. conducted an experimental study on natural circulation in an irregular pentagon-shaped LHP finding that its performance in heating water using the bubble injection method was effective [10]. Singh et al. conducted a literature review on heat pipes that use nanofluids as working fluids, discovering that such heat pipes exhibit enhanced performance due to the superior good thermal conductivity of nanofluids. This review also highlighted that the natural circulation in heat pipes can be affected by various treatments such as sonication, stirring types, surfactant addition, surface modification, and pH variation [11]. Additionally, Masahiro Furuya et al. investigated the influence of different fluid densities on the stability of two-phase flow in a boiling water reactor. This study aimed to determine the effect of fluid density differences on local fluid temperature in thermal-hydraulic stability. Linear stability analysis was performed for boiling natural circulation loops with adiabatic risers. This study concluded that the temperature-dependent fluid density in stability analysis to accurately assess flow quality of NC [12]. Based on the literature study, the NC phenomena need to be understood in order to improve thermal performance, increase energy efficiency, and reduce reliance on active cooling.

Research Center for Nuclear Reactor Technology is currently focused on studying LHP for nuclear installations. The novelty of LHP in this research lies in the utilization of a wick composed of an array of capillary tubes without employing a compensation chamber. Generally, LHP employs wicks made of sintered copper powder and screen mesh, among others, and utilizes a compensation chamber. A key aspect of the study is examining the stability of natural circulation within the LHP. Understanding the stability of natural circulation is critical for assessing the thermal performance of LHP, particularly in terms of its ability to absorb and dissipate heat effectively.

The objective of this research is to investigate the phenomena of natural circulation stability in LHP. The experimental methodology employs various conditions including hot water temperature, filling ratio, air velocity, and inclination angle. Specifically, the study varies the pool water temperature, which serves as the heat source for the evaporator, and the FR, which pertains to the volume of demineralized water introduced into the evaporator relative to its capacity. The experiments are conducted with an air velocity of 2.5 m/s and an inclination angle of 5º. This forced convection air velocity is provided to simulate the airflow around the system and ensure a continuous airflow during the experiment, reflecting typical local conditions. The LHP is operated under sub-atmospheric conditions with an initial pressure of 10,665.6 Pa. To evaluate the stability of natural circulation in LHP, the Natural Circulation Flow Map (NCFM) calculation method is employed. This method considers two dimensionless parameters, namely the Phase Change Number (PCN) and Subcooled Number (SN), for different operational conditions within the LHP. By utilizing the analytical approach of the NCFM, the stability of natural circulation in LHP can be determined. Expanding on previous studies, this analysis focuses on assessing the stability of natural circulation by examining variations in PCN and SN. The evaluation encompasses diverse operational conditions, such as heat load and filling ratio. Furthermore, the stability of two-phase natural circulation is investigated based on the calculations derived from the LHP system.

Research on LHP is necessary to evaluate their potential before implementing them as passive cooling system in nuclear installations. A comprehensive study is conducted to understand the characteristics and natural circulation stability phenomena of LHPs, ensuring their effectiveness in heat dissipation when deployed in future applications.

2. METHODOLOGY

Experimental setup

The LHP experimental setup in this research can be seen in Fig. 1.

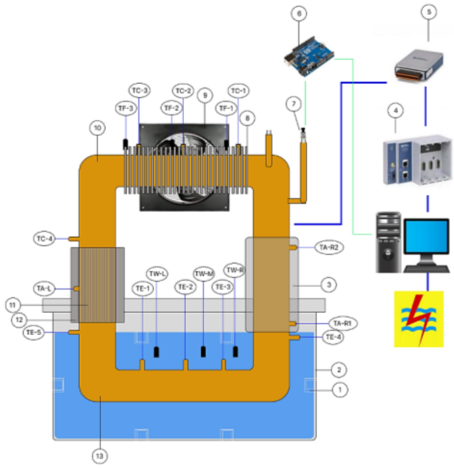

Fig. 1. Experimental setup of LHP (Courtesy by M. Hadi Kusuma).

1. Heater 1000 W
2. Water tub
3. Adiabatic
4. NI Chassis cDAQ 9185
5. Module NI 9213
6. Arduino R3
7. Pressure transducer
8. Fin
9. Fan
10. Condenser
11. Wick
12. Adiabatic with wick
13. Evaporator
14. TE: Evaporator thermocouple
15. TA-R: Adiabatic thermocouple
16. TC : Condenser thermocouple
17. TF: Fin thermocouple
18. TW: Water thermocouple
19. TA-L: Adiabatic wick thermocouple

In this experiment, copper was selected as the material for the LHP, due to its high thermal conductivity, which is approximately 400 W/m·°C, a density of 895.4 kg/m^3, and a specific heat capacity of 380 J/kg·°C [13]. The working fluid employed is demineralized water, chosen for its high merit number which facilitates efficient heat transfer and offers excellent thermal stability. Its vapor pressure maintains within an optimal range under operational temperatures, and it also possesses high latent heat and thermal conductivity. Additionally, demineralized water has low viscosity and high surface tension, enhancing its performance. The hydrophilic nature (contact angle $\theta < 90°$) ensures good wettability on the copper surface, allowing for uniform spreading across the entire surface of the copper walls. The operational temperature range of demineralized water, which is between 30–200 °C, aligns with the applied experimental conditions [14, 15].

The LHP utilized in this study has a length of 4.15 meters, an inner diameter of 0.1002 meters, and an outer diameter of 0.1008 meters. It comprises three main sections: an evaporator, spanning 1.828 meters in length and located at the bottom; an adiabatic section, measuring 0.7 meters in length and situated between the evaporator and condenser; and a condenser, extending 0.57 meters in length and positioned at the top. The condenser section uses fins to absorb heat. The evaporator, with a length of 1.828 meters, features horizontal and vertical lengths of 1.228 meters and 0.3 meters, respectively. This section is immersed in a tank containing hot water, where heat from the water is absorbed. The hot water tank, measuring 1.5 meters in length, 1 meter in width, and 1 meter in height, holds a volume of 375 L. To heat the water, six heaters were used in the hot water tank. The adiabatic section, consisting of two different sides installed vertically, is insulated with glass wool. The right adiabatic section spans 0.7 meters, while the left adiabatic section has 1220 copper capillary pipes, each measuring 0.25 meters in length, to prevent vapor rise, allowing the vapor to ascend through the right side, facilitating the natural circulation of the working fluid within the LHP to act as a capillary pump.

The wick arrangement used in this experiment can be seen in Fig. 2. The condenser, measuring 1.272 meters in length, serves as the heat absorber and is equipped with 120 aluminum fins. Each fin measures 0.2 meters in length, 0.2 meters in width, and 0.001 meters in thickness. Additionally, a blower installed in the condenser enhances heat dissipation.

Pressure transducers are connected to an Arduino Uno R3 device, which is further linked to a computer and utilizes PLX-DAQ software, and are employed to measure the fluid pressure entering the condenser. Thermocouples used as temperature measurement instruments, were connected to a NI c-DAQ series 9185 module. In the experimental setup, five thermocouples were placed in the evaporator, four in the condenser, three on the condenser fins, two in the adiabatic section without a wick, one in the adiabatic section with a wick, three in the water tank, one for measuring air inlet temperature, and one for air outlet temperature.

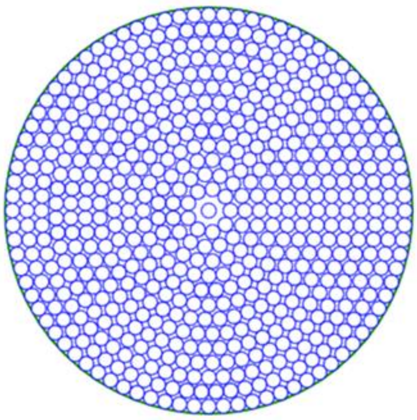

Fig. 2. Wick arrangement on the LHP.

The experimental matrix used in this experiment can be seen in Table 1.

Table 1. Experimental matrix

Hot Water Temperatures (°C)	Filling Ratio (%)	Inclination Angle (°)	Air Velocity (m/s)	Vacuum Pressure (Pa)	Pipe Diameter (m)
60 70 80 90	20% 40% 60% 80% 100%	5	2.5	10665.5	0.104

Experimental data collection was conducted for approximately ± 45 minutes for each temperature increase and ± 60 minutes under steady conditions for each temperature level. The obtained data were read and organized into a series of tables using Ni LabVIEW software and then stored on a computer. These data were processed and graphed to determine the temperature distribution within the LHP.

For hot water temperature variations, data collection began once the water temperature in the tank reached 60 °C and continued up to 90 °C. The air velocity used corresponds to the average air velocity in existing research reactors in Indonesia, which is 2.5 m/s.

After constructing the experimental matrix, the next step involves experimental characterization to determine the optimal time required to reach the specified temperature and the duration of steady conditions for each temperature. After the experimental characterization, it was found that the time required to achieve steady conditions at each temperature is 1 hour.

Data Calculation

- Filling ratio calculation

$$FR = \frac{V_{liq}}{V_{evaporator}} \quad (1)$$

- Evaporator volume calculation

$$R_{elbow} = tan\theta \times 1.5 \times D_{in} \quad (2)$$

$$L_{elbow} = \frac{R_{elbow} \times 1.5 \times \pi}{4} \quad (3)$$

$$L_{total} = (2 \times L_{elbow}) + (2 \times L_{vertical\ pipe}) + L_{horizontal\ pipe} \quad (4)$$

$$V = \pi \times \frac{D^2}{4} \times L_{total} \quad (5)$$

- Inclination angle calculation

$$tan\theta = \frac{front\ side\ of\ evaporator}{side\ of\ evaporator} \quad (6)$$

- Heat out calculation

$$\dot{m} = \rho_{air} \times \tilde{v}_{air} \quad (7)$$

$$A_{cross\ section} = h_{fin}\text{-}L_{fin\ installed} \quad (8)$$

$$Q_{out} = \dot{m}c_{p\ air}A_{cross\ section}\ (T_{outlet}\text{-}T_{inlet}) \quad (9)$$

- Phase change number calculation

Phase change number (PCN) is defined as the ratio between the heat flux changing phases (for example, condensation or evaporation) with the convection heat flux that occurs on the same surface. A higher PCN indicates a more stable natural circulation flow and better thermal performance of the LHP. The formula for calculating PCN is as follows [16, 17].

$$N_{PCH} = \frac{Q_{out}/(\rho_G \Delta h_{LG})}{M_L/(\rho_L\text{-}\rho_G)} \quad (10)$$

- Subcooling number calculation

The subcooling number (SN) is defined as the difference between the liquid temperature and the saturation temperature (boiling point) at the operating pressure, divided by the difference between the ambient temperature and the saturation temperature at the same pressure. A higher SN indicates a less stable natural circulation flow and poorer thermal performance of the LHP. The formula for calculating SN is as follows [16, 17].

$$N_{Sub} = \frac{\rho_L\text{-}\rho_G}{\rho_G}\frac{C_p\left(T_{sat}(p_{in})\text{-}T_{sat}(p_{out})\right)}{h_{LG}} \quad (11)$$

4. RESULTS AND DISCUSSION

Transient Distribution Temperature and Natural Circulation Stability on LHP

Figures 3-7 show the experimental results regarding the effect of the filling ratio on the LHP transient temperature distribution. The tendency that occurs when the LHP is operated at a filling ratio of 20%, 40%, 60%, 80%, and 100% with a hot water temperature of 60 °C, 70 °C, 80 °C, and 90 °C, air velocity of 2.5 m/s, and an inclination angle of 5°.

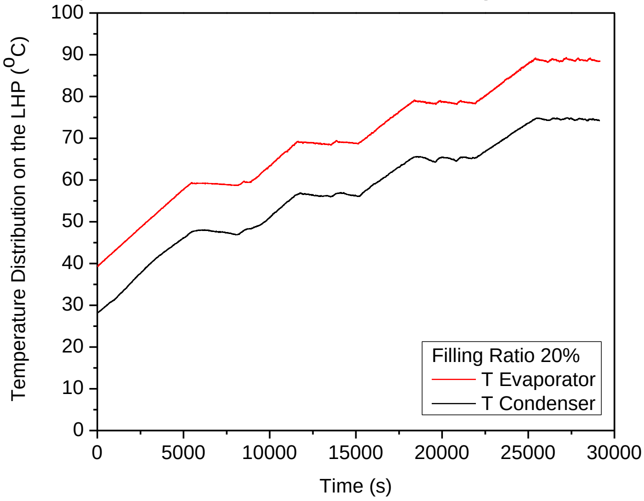

Fig. 3. Transient temperature distribution at filling ratio 20%.

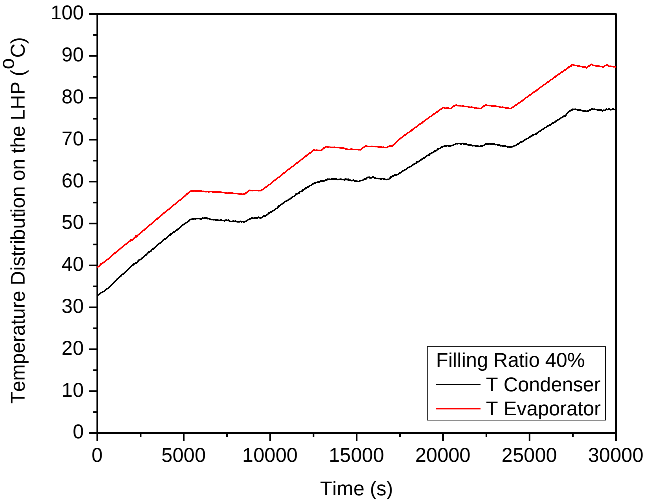

Fig. 4. Transient temperature distribution at filling ratio 40%.

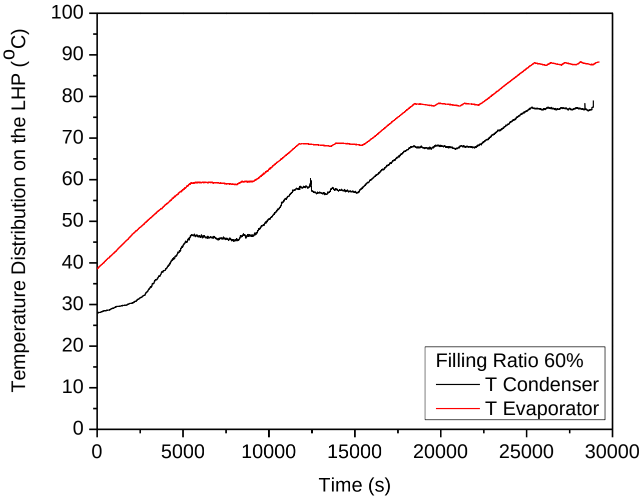

Fig. 5. Transient temperature distribution at filling ratio 60%.

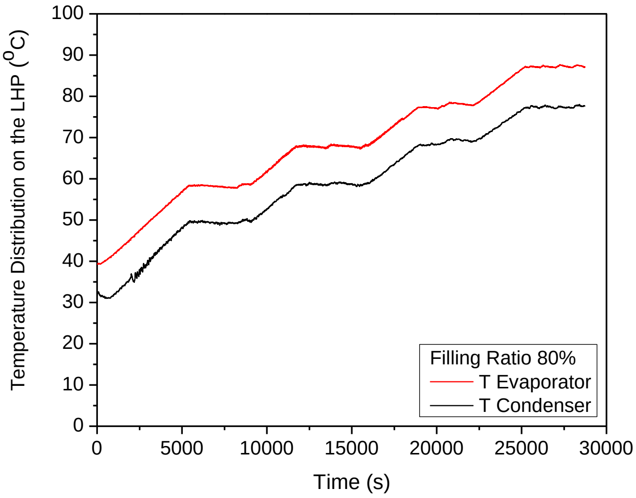

Fig. 6. Transient temperature distribution at filling ratio 80%.

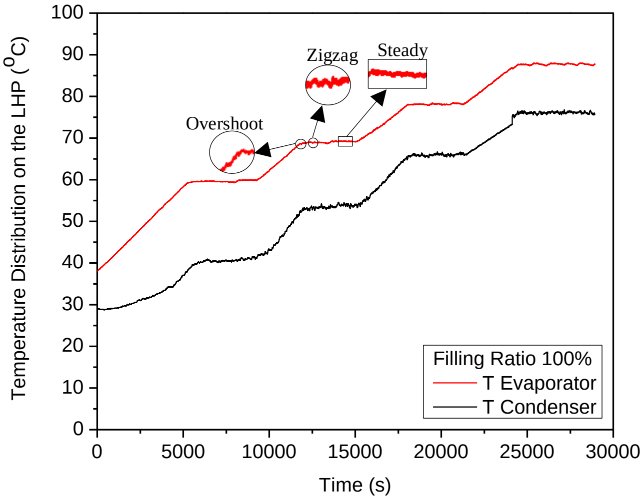

Fig. 7. Transient temperature distribution at filling ratio 100%.

Based on Figs. 3–7, the natural circulation in LHP significantly influences operational stability and thermal performance. At initial stages, when natural circulation is not yet established smoothly, vapor begins to rise towards the adiabatic section, progressing towards the condenser section. The absence of condensate descending from the condenser through the LHP walls towards the evaporator leads to a drastic increase in temperature at the evaporator section. Specifically, the phenomena of overshoot, zigzag, and steady state are indicated in Fig. 7. This elevated temperature at the evaporator section is referred to as an overshoot. Overshoot occurs because the inner walls of the LHP come into direct contact with the boiling vapor. During the overshoot phase, condensate from vapor cooling has not yet formed. Following the overshoot phase, the temperature distribution profile undergoes a zigzag pattern. The zigzag phase is characterized by the approaching steady state of fluid circulation resulting from condensation towards the evaporator. During the zigzag phase, overshoot does not occur during LHP operation. As vapor reaches the condenser section, the condenser temperature increases. The fins absorb the latent heat present in the condenser section, which is then aided by air cooling, transforming vapor into condensate. Subsequent to the zigzag phase is the stable stage (steady condition). The stable stage is identified by the steady temperature across all LHP sections. In this condition, overshoot and zigzag phase cease to exist. This indicates that the vapor and condensate formation circulation within the LHP has been continuous. This condition is expected to persist due to the LHP established natural circulation stability, which ensures efficient heat dissipation in the condenser. The higher the filling ratio, the more steam will be formed, and the higher hot water temperatures, the faster the natural circulation in the LHP will be stable.

From the transient temperature distribution data that has been obtained, it is then obtained the map of natural circulation flow from this experiment as shown in Fig. 8.

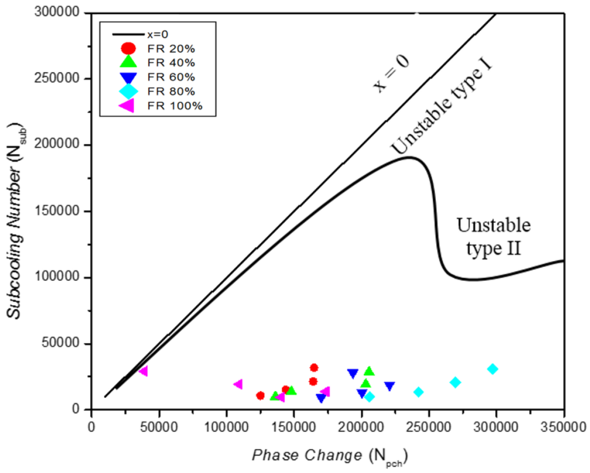

Fig. 8. Stability map of PCN and SN with variations in filling ratio and hot water temperatures.

According to the results shown in Fig. 8, curves and lines are used as boundaries to determine the stability of natural circulation within the LHP. It is observed that both the PCN and SN values lie below these boundary lines and curves. The optimal performance is attained when the LHP is operated at an 80% filling ratio with 90 °C hot water temperature, due to its significant PCN and minimal SN values. The greater the PCN, the more stable the natural circulation flow and the higher the thermal performance of the LHP. Conversely, instability in the natural circulation flow results in reduced thermal performance of the LHP. This is attributed to the existence of three filling ratio categories for LHP operation: minimum, optimal, and maximum. Operating the LHP below the minimum filling ratio can lead to dryout, while operation above the maximum filling ratio can result in upper flooding due to an imbalance in the steam generation and cooling rates [18].

Figure 8 also demonstrates the stable natural circulation operation of the LHP. Two-phase natural circulation stability occurs across all variations of filling ratio with heat loads ranging from 60-90 °C. Heat absorbed by the evaporator section is effectively dissipated at the condenser section. Furthermore, increasing the hot water temperatures at the evaporator leads to a more stable circulation within the LHP. Under stable conditions for all heat loads and filling ratios, the working fluid continuously absorbs and dissipates heat. PCN values exceeding SN values indicate the LHP's stable natural circulation and operation in a two-phase manner [19–21]. This finding aligns with Kusuma's research, which suggests that when $N_{Sub} < N_{PCh}$, two-phase circulation occurs within the LHP [16]. Understanding the phenomena of natural circulation stability in LHP is crucial for safety and serves as an indicator of the LHP heat dissipation capability [22].

5. CONCLUSION

In this experimental investigation, an 80% filling ratio with 90 °C hot water temperatures emerges as the most effective for LHP operation. Optimal results are achieved at an 80% filling ratio at 90 °C hot water temperatures due to its significant PCN and minimal SN. These phenomena are attributed to the three distinct categories of filling ratio in LHP operation: minimum, optimal, and maximum. Running the LHP below the minimal filling threshold may cause dry-out, whereas operating beyond the maximum filling threshold can cause operational breakdown due to an imbalance in steam generation and cooling rates.

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AUTHOR CONTRIBUTION

Wirza, Kusuma, Rozi, and Yunus contributed as the main contributors to this paper. All authors read and approved the final version of the paper.

NOMENCLATURE

$A_{Cross\ Section}$ =Cross section area in the condenser (m^2)
C_p = Specific heat (kJ/kg·°C)
D = Pipe diameter (m)
D_{in} = Pipe inner diameter (m)
FR = Filling ratio (%)
g = Gravity (m/s^2)
h_{fin} = Fin height (m)
h_{LG} = Specific enthalpy liquid-gas (kJ/kg)
k = Thermal conductivity (W/m·°C)
L = Evaporator length (m)
L_{elbow} = Elbow length (m)
L_{total} = Total evaporator length (m)
$L_{Installed\ fin}$ = Installed fin length (m)
N_{pch} = Phase change number
N_{sub} = Subcooling number
$\dot{m}$ = Mass flow rate (kg/s)
M_L = Liquid mass flow rate (kg/s)
ρ = Density (kg/m^3)
ρ_L = Liquid density (kg/m^3)
ρ_G = Gas density (kg/m^3)
r = Pipe radius (m)
R_{elbow} = Elbow pipe radius (m)
$tan\theta$ = Inclination angle (°)
T_e = Evaporator temperature (°C)
T_c = Condenser temperature (°C)
T_{sat} = Saturated temperature (°C)
T_{inlet} = Air inlet temperature (°C)
T_{outlet} = Air outlet temperature (°C)
$\tilde{v}_{air}$ = Air velocity (m/s)

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