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Experimental Study of The Influences of Inclination Angle and Heat Load on Loop Heat Pipe Thermal Performance

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A B S T R A C T

The utilization of nuclear power brings out a lot of benefits in fulfilling human needs for power. However, the thermal accident caused by the failure of an active cooling system due to an earthquake followed by a tsunami, such as in the Fukushima Dai-Ichi Nuclear Power Plant, Japan, could be taken as a lesson learned to keep improving the operation safety aspects of nuclear installation. Loop heat pipe (LHP), as an alternative cooling system technology, could be utilized to handle thermal problems on nuclear installations. This research aims to understand the influence of the inclination angle and heat load on the thermal performance of LHP. The experimental investigation was performed with varying inclination angles of 0°, 2.5°, and 5°, and hot water temperatures of 60°C, 70°C, 80°C, and 90°C. The LHP used demineralized water as the working fluid. The demineralized water was charged to the evaporator with a filling ratio of 100%. LHP was vacuumed on 2.666,4 Pa. Atmospheric air was used as a condenser coolant and blown with a velocity of 2.5 m/s. The result of this experiment showed that LHP has the best thermal performance with the lowest thermal resistance of 0.0043 °C/W. This result was obtained when the LHP operated with a 5° inclination angle and hot water at a temperature of 90 °C. The conclusion from this research shows that LHP thermal performance is better as the inclination angle increases on LHP because the steam velocity formed is bigger, and condensate flows back to the evaporator faster.

1. INTRODUCTION

Various human activities such as economic development, industrial construction, and population growth have led to an increase in energy consumption. Meanwhile, global energy sources are diminishing, with little sign of an increase. The use of alternative energy sources, such as nuclear energy, has become one of the options to meet the nearly depleted energy needs. The utilization of nuclear energy through Nuclear Power Plants (NPPs) is expected to be a solution to address the shortage of energy resources [1]. Nuclear technology brings numerous benefits to human life, including its use in cancer treatment facilities, power generation, disease diagnosis, and many other advantages [2].

Despite the tangible benefits, the utilization of nuclear technology also poses potential hazards. One potential hazard in NPP utilization is the release of radioactive in the event of accidents and operational

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failures [3, 4]. The severe accident at the Fukushima Dai-ichi NPP in Japan on March 11, 2011, serves as an example of the hazard related to nuclear industrial accidents. In that accident, the earthquake followed by a tsunami caused the generator, which was supposed to provide power to control the equipment needed to cool the reactor, to be submerged, leading to heat accumulation and a subsequent hydrogen explosion. Following this incident, researchers began searching for ways to prevent its recurrence, opening up fields for research in nuclear technology to implement passive cooling systems in reactors, which can operate without external driving energy sources in case of active safety system failures [5].

Nuclear reactor technology is considered high-tech in various aspects, such as its cooling system, safety system, environmental system, and more. However, sophisticated technology also has its weaknesses. Beyond design basis accidents, such as the thermal accident at Fukushima Dai-ichi, highlight the need for heat pipes to assist in heat removal from the reactor under both normal and abnormal conditions. The simultaneous use of active and passive cooling systems proves to be more efficient. Under normal conditions, the power required to operate the active cooling system is not significantly high because it is assisted by the passive cooling system, namely the heat pipe. In abnormal conditions or thermal accidents, the heat pipe is expected to efficiently dissipate heat and help the cooling process.

The heat pipe itself is a technology with a closed pipe of a specific size, containing a working fluid as a calor conductor from the evaporator to the condenser through the adiabatic region (an isolated part that does not release heat). The heat pipe consists of several parts, namely the adiabatic section as the vapor path, the condenser as the heat release location, and a tube as the wall, usually equipped with a capillary wick on the inside serving as a pathway and a capillary pump to return condensate from the condenser to the evaporator [6] [7].

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). As well known, an LHP is a passive heat dissipation technology with a two-phase heat transfer mechanism with capillary pumping of the working fluid [8–13]. Previous research by Kusuma et al. focused on the use of heat pipes for passive cooling systems, particularly in Small Modular Reactors using LHP with a capillary axis. It was concluded that the coolant flow rate significantly influences the temperature distribution of the LHP and the thermal resistance value decreases with increasing heat load and coolant velocity [14].

One of the factors affecting the thermal performance of the commercial heat pipe is the inclination angle. Despite placing the evaporator and condenser at the same height, the LHP can still operate vertically, horizontally, and/or at all inclination angles due to the capillary axis installed on one side of the pipe. Many studies have been conducted on the effect of inclination angle on the thermal performance of heat pipes [7, 15–19].

Testing the inclination angle in heat pipe experiments is necessary because the inclination angle can affect its performance. At low inclination angles, gravity affects fluid distribution, causing the fluid to accumulate at the bottom of the heat pipe. Meanwhile, at high inclination angles, the fluid tends to spread evenly along the pipe. Therefore, testing the inclination angle on heat pipes is essential to understand the performance of heat pipes under different inclination angle conditions, revealing how heat pipes operate in various usage scenarios [18].

Furthermore, testing the inclination angle on heat pipes can assist in optimizing heat pipe designs, such as wick placement or the use of better materials. In some cases, testing the inclination angle on heat pipes can also help identify issues or failures in heat pipes and contribute to the development of solutions to improve heat pipe performance [20].

The use of capillary pipes or wicks in passive cooling systems is the first and has not been previously found in research on heat pipes. The study of LHP is part of the research on the use of LHP as a passive cooling system being developed by the Research Center for Nuclear Reactor Technology, Research Organization for Nuclear Energy, National Research and Innovation Agency, funded by the Republic of Indonesia Endowment Fund for Education.

This research aims to investigate the influence of inclination angles and heat loads on various diameters on the thermal performance of LHP. The research was conducted experimentally by varying inclination angles of heat pipes at 0°, 2.5°, and 5°, and providing temperature on the evaporator at temperatures of 60°C, 70°C, 80°C, and 90°C. The working fluid used for LHP is demineralized water with a filling ratio of 100%. The initial pressure of LHP is 2666.4 Pa. The cooling air velocity in the condenser is 2.5 m/s; this value refers to the average air velocity outside Kartini Research Reactor, Indonesia. The expected outcome of this experimental study is to complement the investigation of LHP as a passive cooling system in nuclear installations.

Research on LHP is necessary to study the its potential before using it as a passive cooling system in nuclear installations. A comprehensive study was conducted to understand the characteristics, occurring phenomena, and thermal performance of LHP, ensuring that it can effectively dissipate heat when applied in the future.

2. METHODOLOGY

Experimental setup

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

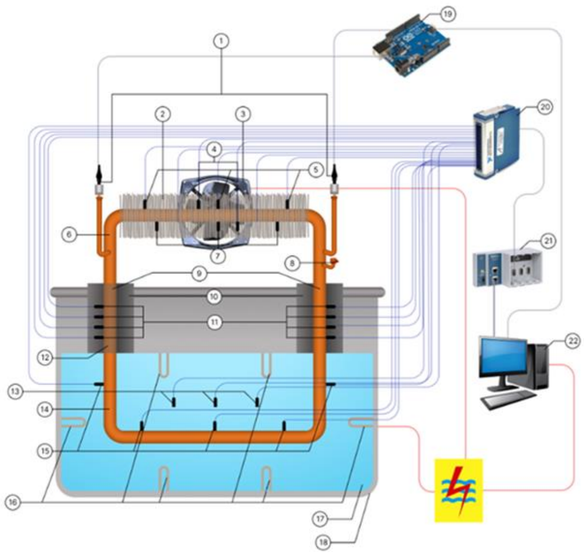

Fig. 1. Experimental setup of LHP

1.Pressure transmitter	12.Capillary wick
2.Fin	13.Water thermocouple
3.Blower	14.Evaporator
4.Air thermocouple	15.Evaporator thermocouple
5.Fin thermocouple	16.Heater
6.Condenser	17.Water
7.Condenser thermocouple	18.Water tub
8.Valve	19.Arduino uno R3
9.Adiabatic	20.Module NI 9213
10.Adiabatic isolation	21.NI chassis cDAQ 9185
11.Adiabatic thermocouple	22.Computer
12.Pressure transmitter	

The LHP is a passive heat transfer device divided into 1 evaporator section, 1 condenser section with fins, and 2 adiabatic sections. The evaporator section is the bottom part of the LHP immersed in a pool of heated water. Demineralized water is used as the working fluid inside the evaporator. The heat from the heated water causes the fluid in the evaporator to undergo boiling. Demineralized water was chosen as the working fluid due to its good compatibility with heat pipe materials, high merit number, and good thermal stability. Merit number is a number that expresses the magnitude of fluid transport ability in transferring heat. The evaporator and condenser sections each have a length of 1.4793 m with a diameter of 0.0508 m.

The adiabatic section serves as the vapor path from the evaporator to the condenser and the path for the condensed fluid from the condenser to the evaporator. In this section, heat generated by the heat pipe must not escape to the environment, and vice versa. The adiabatic section was insulated with glass wool material to reduce heat loss to the environment. The glass wool used has a density of 64 kg/m^3 and a thermal conductivity of 0.03 W/m.K. One side of the adiabatic section was equipped with a vacuum system and channels for filling the working fluid, along with a pressure transmitter, while the other side has a wick made of a collection of capillary pipes, each 0.25 m long and 0.0018 m in diameter, with a total of 606 pieces, as seen in Fig. 2. The size of these capillary pipes was adapted to the geometry of the LHP adiabatic section.

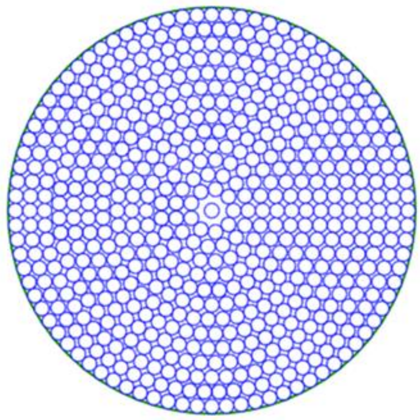

Fig. 2. Wick arrangement on the LHP used in this research

The upper section is the condenser, equipped with fins. Each fin has a length of 0.16 m, a width of 0.15 m, and a total of 120 fins with a thickness of 0.0000105 m each. There is a 0.005 mm gap between each fin. In this section, heat is released, and when the heat is dissipated, vapor does not escape but instead turns into water and returns to the evaporator. At the back of the LHP, specifically in the condenser and fin sections, there is a blower as a cooling source used to expel or dissipate heat to the environment.

There are variations in temperature at 60°C, 70°C, 80°C, and 90°C, and inclinations angle of 0°, 2.5°, and 5°. The condenser fin was blown with a constant air velocity of 2.5 m/s. The pipe diameter used was 2 inches. Experimental data collection will be carried out for approximately ± 40 minutes for each temperature increase and ± 60 minutes under steady conditions for each temperature. The obtained data will be read and processed into a series of tables using Ni LabVIEW software and stored on the computer. The subsequent data will be processed and graphed to determine the temperature distribution of the LHP.

In the case of a 0° inclination angle, the LHP tube will be in an upright position or parallel to the gravitational axis. For variations at 2.5° and 5° of inclination angles, the LHP tube is tilted at the given angle to the gravitational axis. Using Eq. 6, it can be determined that at a 2.5° inclination angle variation, the tube is tilted on the right side or the side without wick by 0.0473 m. At a 5° inclination angle, it is tilted by 0.0948 m. The inclination degree of freedom for the LHP apparatus is maximum in 7°. Theoretically, small differences in inclination angles can affect the thermal performance of LHP significantly [21]. The representation of how a rectangular-shaped LHP is tilted can be seen in Fig. 3.

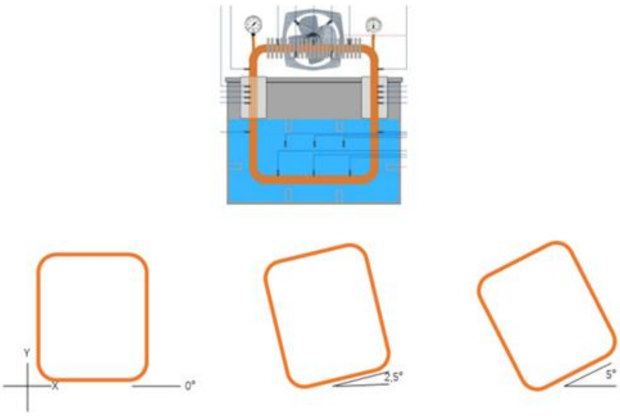

Fig. 3. LHP tilted at various angles

For hot water temperature variations, data collection started when the water temperature in the tank reaches 60°C 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 is the experimental characterization to determine the optimal time range needed 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 for steady conditions at each temperature is 1 hour.

Data Calculation

- Filling ratio calculation

$$FR = \frac{V_{liq}}{V_{evaporator}} \tag{1}$$

- Evaporator volume calculation

$$R_{elbow} = tan\theta \times 1.5 \times D_{in} \tag{2}$$

$$L_{elbow} = \frac{R_{elbow} \times 1.5 \times \pi}{4} \tag{3}$$

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

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

- Inclination angle calculation

$$tan\theta = \frac{front\ side\ of\ evaporator}{side\ of\ evaporator} \tag{6}$$

- Average temperature calculation

$$\bar{T_e} = \frac{\Sigma Te}{amount\ of\ data} \tag{7}$$

$$\bar{T_c} = \frac{\Sigma Tc}{amount\ of\ data} \tag{8}$$

- Heat load calculation

$$Ra = Gr.Pr \tag{9}$$

$$Gr.\mathrm{Pr} = \frac{g.\beta.\rho^2.C_p}{\mu K}(T_w - T_\infty)\, d^3 \tag{10}$$

The ratio of convective to conductive at the boundary in a fluid (Nusselt number) was found as [22] :

$$Nu = (Ra_D \cos \emptyset)^{\frac{1}{4}}\left(0.48 + 0.555\left(\left(\frac{D}{L\cos\emptyset}\right)^{\frac{1}{4}} + \left(\frac{D}{L}\right)^{\frac{1}{4}}\right)\right) \tag{11}$$

$$h = \frac{Nu.K}{D} \tag{12}$$

$$Q_{in} = h\pi DL\,(T_w - T_\infty) \tag{13}$$

- Thermal resistance calculation

$$R_T = \frac{\bar{T_e} - \bar{T_c}}{Q_{in}} \tag{14}$$

- Heat flux calculation

$$Q'' = \frac{Q_{in}}{A_{HT}} \tag{15}$$

4. RESULTS AND DISCUSSION

Figures 4 to 6 show the graphs concerning the effect of inclination angle on the transient temperature distribution of the LHP when operated at inclination angles of 0°, 2.5°, and 5°, with hot water temperatures of 60, 70, 80, and 90°C, filling ratio of 100%, and air velocity of 2.5 m/s.

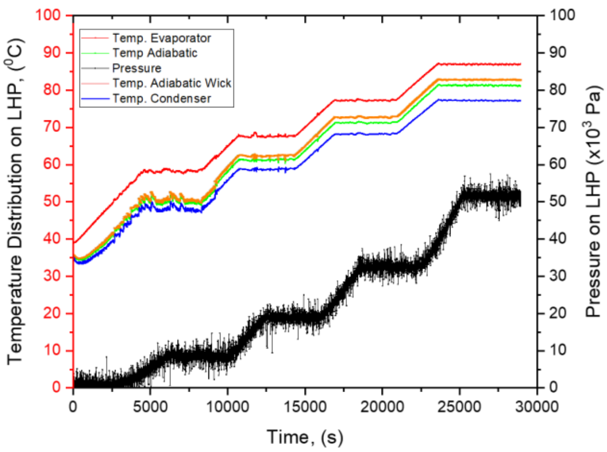

Fig. 4. LHP transient temperature distribution with an inclination angle of 0°

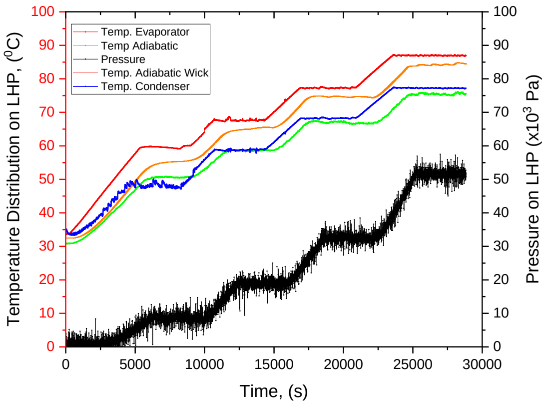

Fig. 5. LHP transient temperature distribution with an inclination angle of 2.5°

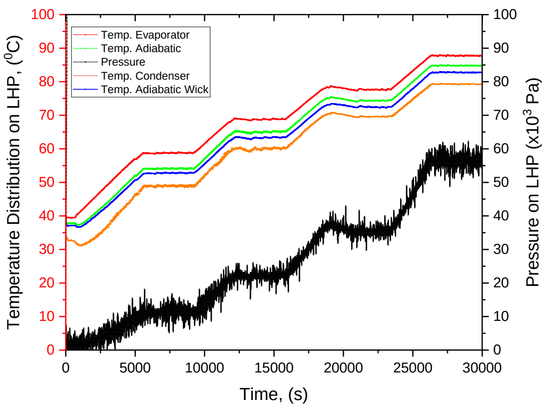

Fig. 6. LHP transient temperature distribution with an inclination angle of 5°

It can be seen from Figures 4 to 6 that common phenomena are occurring in the LHP, namely overshoot, zigzag, and stable behaviors for inclination angles of 0°, 2.5°, and 5°. The overshoot phenomenon in the LHP occurs because the evaporator wall directly contacts with high-temperature vapor without any condensate circulation inside the LHP. As a result, the evaporator wall temperature becomes high, creating a significant temperature difference between the evaporator and condenser, therefore increasing the thermal resistance of the LHP. Initially, the heat load is continuously received by the evaporator, causing the working fluid to quickly boil and turn into vapor. This vapor rises to the adiabatic and condenser regions, causing their temperatures to slowly increase due to heat absorption from the vapor. However, due to the high initial temperature difference, natural circulation within the LHP is hindered.

The zigzag phenomenon occurs as the initial step towards natural circulation. Vapor in the condenser raises the condenser temperature, and the latent heat of the vapor is absorbed by the condenser, transforming the vapor into condensate. This condensate descends by gravity through the adiabatic section until it reaches the evaporator. This process causes a drastic temperature change in the adiabatic and condenser, creating a zigzag pattern. Although this phenomenon occurs periodically, the temperature difference between the evaporator and condenser becomes low, reducing the thermal resistance of the LHP.

The “stable” phenomenon reaches a condition where natural circulation occurs consistently. The temperature profile across the entire LHP remains stable and no longer experiences significant fluctuations. This indicates that the natural circulation between vapor and condensate is running consistently and steadily. Although the addition of heat load after stable natural circulation causes a temperature increase, overshoot and zigzag no longer occur. The stable phenomenon indicates that the evaporation and condensation processes are taking place in thermodynamic equilibrium at every part of the LHP.

Before natural circulation occurs, the pressure increases in the evaporator chamber due to the heat load causing temperature differences at each point. This difference drives the flow of vapor from the evaporator to the condenser, initiating the natural circulation process inside the LHP. The overshoot, zigzag, and stable phenomena represent evolutionary steps in the natural circulation of the LHP, which can be optimized to enhance system performance and stability.

Steady-state temperature distribution in the heat pipe, when given variations in inclination angles of 0°, 2.5°, and 5° with a hot water temperature of 60˚C, 70˚C, 80˚C, 90˚C, filling ratio of 100%, and air velocity of 2.5 m/s, are shown in Figs. 7 –9.

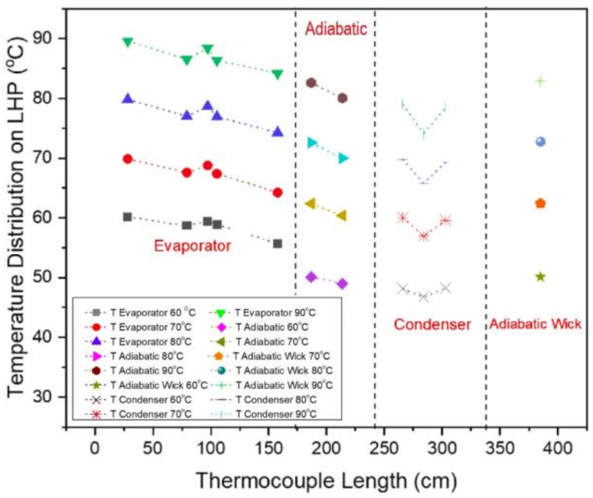

Fig. 7. LHP steady temperature distribution with an inclination angle of 0°

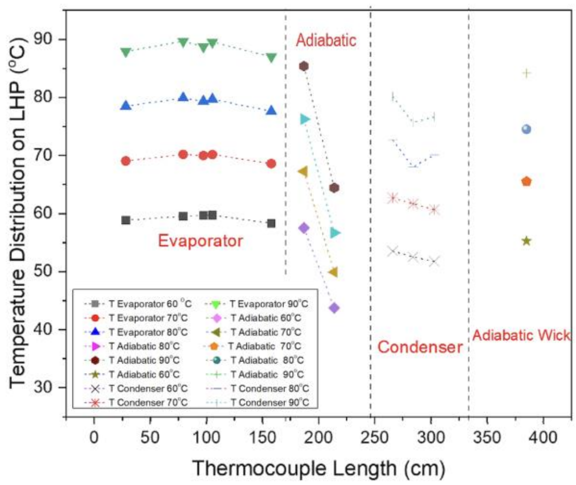

Fig. 8. LHP steady temperature distribution with an inclination angle of 2.5°

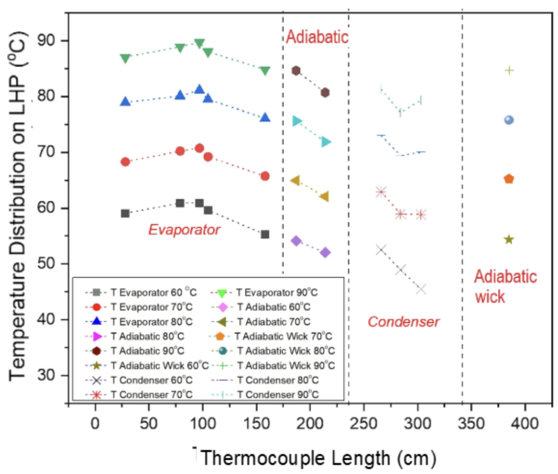

Fig. 9. LHP steady temperature distribution with an inclination angle of 5°

From Figs. 7-9, it can be observed that for the given conditions, the heat pipe with the highest heat load will result in higher evaporator and condenser temperatures, producing greater heat transfer from the evaporator wall to the working fluid, generating more vapor from the boiling process, increasing the evaporation rate, and raising the average temperature in the evaporator section. An increase in heat load will also elevate the temperature of the heat pipe until it reaches its isothermal condition. Once the isothermal condition is achieved, the temperature of the heat pipe will no longer increase due to the influence of the cooling water in the water jacket. When the steady-state temperature is reached, adding more heat load no longer leads to overshoot and zigzag phenomena in the heat pipe. The addition of heat load only affects the increase in the heat pipe temperature until it reaches a value above the stable temperature of the previous heat load. The steady-state condition obtained when applying a higher heat load has the same form as the lower heat load.

In Fig. 10, the distribution of thermal resistance of the LHP wall is shown when operated at inclination angles of 0°, 2.5°, 5°, hot water temperature 60°C, 70°C, 80°C, and 90°C and with air velocity of 2.5 m/s blown into condenser fin.

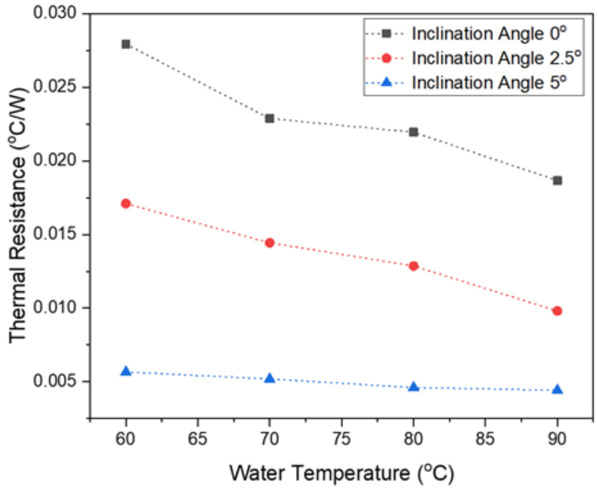

Fig. 10. Comparison of thermal resistance at inclination angles of 0°, 2.5°, and 5°, and hot water temperature of 60°C, 70°C, 80°C, and 90°C.

The thermal performance of LHP is usually measured by the thermal resistant formula (Eq. 14). Thermal resistance is highly influenced by the temperature difference between the evaporator and condenser sections, and the magnitude of the heat load applied to the LHP's evaporator. Thermal performance in the LHP is a crucial factor in assessing its overall performance. The thermal resistance affects the temperature difference between the evaporator and condenser and the amount of heat absorbed by the evaporator in the LHP. A smaller thermal resistance value indicates better thermal performance for the LHP. Increasing the heat load will accelerate the boiling process of the working fluid in the heat pipe, resulting in a rapid phase change process from liquid to vapor of the working fluid. This is consistent with the research conducted by N. Panyoyai et al., indicating that when the inclination angle increases, the vapor velocity also increases [23].

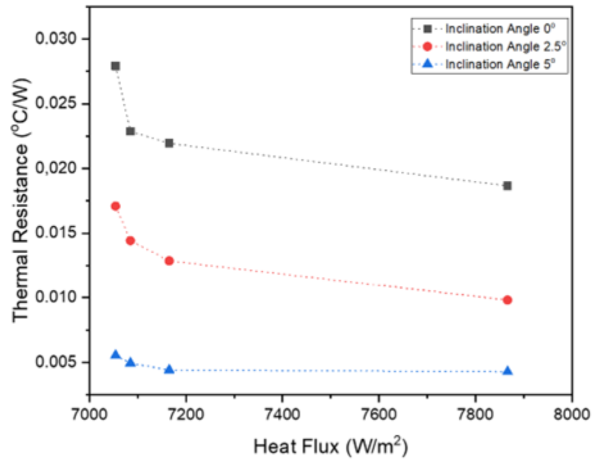

Fig. 11. Comparison of thermal resistance at variation of inclination angles of 0°, 2.5°, and 5°

From Fig. 11, it can be seen that higher heat load values and inclinations lead to a faster attainment of steady-state conditions. Increasing heat flux values will enhance evaporation and working fluid pressure, speeding up the saturation temperature of the working fluid. A higher heat load will cause greater heat transfer from the evaporator wall to the working fluid inside the LHP, increasing the evaporation rate, raising the average temperature in the evaporator, and producing more vapor. As a result of increased boiling, more condensate is generated, returning to the evaporator and adding to the amount of heat dissipated in the condenser.

Otherwise, applying a smaller heat load and a low inclination angle results in less latent heat transferred from the condenser to the cooling water. A smaller heat load will also yield a smaller condenser temperature, while the evaporator temperature is slightly above the saturation temperature of the working fluid. A sufficiently large difference between the evaporator and condenser temperatures will increase the thermal resistance of the heat pipe.

The best thermal performance is achieved with the smallest thermal resistance of 0.0043 °C/W, obtained when the LHP is operated with a 5° inclination angle and a hot water temperature of 90 °C. The increase in hot water temperature causes a higher heat load. The highest heat load will produce more vapor from the heating process of the liquid working fluid, accelerating the evaporation and working fluid circulation processes within it. Increasing the heat load will also raise the temperature of the heat pipe overall until it reaches its stable condition. This research shows that higher heat loads received by the evaporator lead to smaller thermal resistance values for the LHP, resulting in improved thermal performance.

5. CONCLUSION

An experimental study of heat transfer phenomena in an LHP model with capillary tubes regarding temperature distribution concludes that this LHP model exhibits characteristics and heat transfer phenomena in the form of temperature distribution patterns with overshoot, zigzag, and stable patterns. The experimental results show that the temperature distribution has patterns and shapes consistent with temperature distribution in various forms of normally operating LHPs. The best thermal performance is achieved with the smallest thermal resistance of 0.0043 °C/W, obtained when the LHP is operated at a 5° inclination angle with a hot water temperature of 90 °C. Heat dissipation in the LHP is significantly influenced by the inclination angle and heat load. A larger inclination angle of the LHP with capillary tubes leads to a faster condensate flow rate from the condenser to the evaporator due to gravity. A larger tilt angle allows the LHP to work more optimally, resulting in higher thermal performance compared to an LHP with a smaller inclination angle.

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AUTHOR CONTRIBUTION

Kusuma and Kiono equally contributed as the main contributors to this paper. All authors read and approved the final version of the paper.

NOMENCLATURE

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)

Gr = Grashof number

h = Heat transfer coefficient (W/m^2°C)

k = Thermal conductivity (W/m°C)

L	= Evaporator length (m)
L_{elbow}	= Elbow length (m)
L_{total}	= Total evaporator length(m)
Nu	= Nusselt number
Pr	= Prandtl number
ρ	= Density (Kg/m^3)
Q''	= Heat flux (W/m^2)
r	= Pipe radius (m)
Ra	= Rayleigh number
R_{elbow}	= Elbow pipe radius (m)
R_T	= Thermal resistance
$tan\theta$	= Inclination angle (°)
T_e	= Evaporator temperature ($°C$)
T_c	= Condenser temperature($°C$)
$\bar{T}_e$	= Average evaporator temperature ($°C$)

REFERENCES

1. Kusuma M.H., Putra N., Ismarwanti S., Widodo S. Simulation of the Wickless-heat Pipe as a Passive Cooling System in Nuclear-spent Fuel Pool using RELAP5/MOD3.2. Int. J. Adv. Sci. Eng. Inf. Technol. 2017. **7**(3):836–42.
2. Kusuma M.H. Sistem Pendingin Pasif di Kolam Penyimpanan Bahan Bakar Bekas Nuklir dengan Menggunakan Pipa Kalor = Passive Cooling System in Nuclear-spent Fuel Storage Pool using Heat Pipe. 2017.
3. Pambudi Y.D.S. Particle Swarm Optimization Based Probabilistic Neural Network for Classification of Severe Accident of Nuclear Reactor. J. Teknol. Reakt. Nukl. Tri Dasa Mega. 2021. **23**(3):99–104.
4. Kusuma M.H. Universitas Indonesia Sistem Pendingin Pasif. 2017.
5. Kusuma M.H. Laporan Teknis Hasil Penelitian Tahun 2019 Lembaran Kontrol Laporan Teknis Hasil Penelitian Studi Eksperimental Model Loop Heat Pipe sebagai Sistem Pendingin Pasif di Kolam. 2019.
6. Putra N., Septiadi W.N. Teknologi Pipa Kalor Teori, Desain, dan Aplikasi. Jakarta Univ. Indones. 2014.
7. Hadi Kusuma M. *Sistem Pendingin Pasif di Kolam Penyimpanan Bahan Bakar Bekas Nuklir dengan Menggunakan Pipa Kalor*.Universitas Indonesia; 2017.
8. Htoo K.Z., Huynh P.H., Kariya K., Miyara A. Experimental Study on Thermal Performance of a Loop Heat Pipe with Different Working Wick Materials. Energies. 2021. **14**(9):2453.
9. He X., Yan W., Wang S. Study on Heat Transfer Characteristics of a Dual-evaporator Ultra-thin Loop Heat Pipe for Laptop Cooling. Appl. Therm. Eng. 2024.:122395.
10. Liu C., Xie R., Li N., Lu D., Hong F., Wu Y. Experimental Study of Loop Heat Pipes with Different Working Fluids in 190–260 K. Appl. Therm. Eng. 2020. **178**:115530.
11. Rosidi A., Giarno G., Haryanto D., Pambudi Y.D.S., Kusuma M.H. The Simulation of Heat Transfers and Flow Characterization on Wickless Loop Heat pipe. J. Polimesin. 2022. **20**(1):29–35.
12. He S., Zhou P., Liu W., Liu Z. Experimental Study on the Thermal Performance of Loop Heat Pipe with a Composite-material Evaporator for Cooling of Electronics. Appl. Therm. Eng. 2020. **168**:114897.
13. Xiao B., Deng W., Ma Z., He S., He L., Li X., et al. Experimental Investigation of Loop Heat Pipe with a Large Squared Evaporator for Multi-heat Sources Cooling. Renew. Energy. 2020. **147**:239–48.
14. Kusuma M.H., Putra N., Antariksawan A.R., Koestoer R.A., Widodo S., Ismarwanti S., et al. The Passive Cooling System in a Nuclear-spent Fuel Pool using a Vertical Straight Wickless-heat Pipe. Int. J. Therm. Sci. 2018. **126**:162–71.
15. Markal B., Aksoy K. The Combined Effects of Filling Ratio and Inclination Angle on the Thermal Performance of a Closed Loop Pulsating Heat Pipe. Heat Mass Transf. 2021. **57**:751–63.
16. Li H., Ren J., Yin D., Lu G., Du C., Jin X., et al. Effects of Inclination Angle and Heat Power on Heat Transfer Behavior of Flat Heat Pipe with Bionic Grading Microchannels. Appl. Therm. Eng. 2022. **206**:118079.
17. Wang C., Zhang L., Liu X., Tang S., Qiu S., Su G.H. Experimental Study on Startup Performance of High-temperature Potassium Heat Pipe at Different Inclination Angles and Input Powers for Nuclear Rreactor Application. Ann. Nucl. energy. 2020. **136**:107051.
18. Zhang B., He Z., Wang W., Wang J., Mikulčić H., Klemeš J.J. Investigation on the Thermal Performance of Flat-plate Heat Pipes with Various Working Fluids under Different Inclination Angles. Energy Reports. 2022. **8**:8017–26.
19. Wang Z., Diao Y., Zhao Y., Chen C., Wang T., Liang L. Effect of Inclination Angle on the Charging Process of Flat Heat Pipe-assisted Latent Heat Storage Unit. J. Energy Storage. 2022. **51**:104402.
20. Goshayeshi H.R., Goodarzi M., Safaei M.R., Dahari M. Experimental Study on the Effect of Inclination Angle on Heat Transfer Enhancement of a Ferrofluid in a Closed Loop Oscillating Heat Pipe under Magnetic Field. Exp. Therm. Fluid Sci. 2016. **74**:265–70.
21. Jouhara H., Chauhan A., Nannou T., Almahmoud S., Delpech B., Wrobel L.C. Heat Pipe Based Systems-Advances and Applications. Energy. 2017. **128**:729–54.
22. Akbari A., Mohammadian E., Alavi Fazel S.A., Shanbedi M., Bahreini M., Heidari M., et al. Natural Convection from the Outside Surface of an Inclined Cylinder in Pure Liquids at Low Flux. ACS Omega. 2019. **4**(4):7038–46.
23. Panyoyai N., Kammuang-lue N., Terdtoon P., Sakulchangsatjatai P. Effect of Inclination Angles on Internal Flow Pattern of Closed-Loop Oscillating

Heat Pipe at Maximum Heat Flux State. in: *Proceedings*. 2014. pp. 57–62.