Semesta Teknika
Vol. xx, No. x, xx-xx, Bulan yyyy
DOI: https://doi.org/10.18196/st.v26i1.16284

Thermal Resistance of the Loop Heat Pipe Prototype in Steady State Conditions

Dedy Haryanto, Giarno, Sumantri Hatmoko, Yoyok Dwi Setyo Pambudi, M. Hadi Kusuma

Nuclear Reactor Technology Research Center, National Research and Innovation Agency (BRIN), BJ Habibie, Science and Technology Area. South Tangerang, 15314, Indonesia.

*Corresponding author email: dedy004@brin.go.id

Check for updates

Kata Kunci:
Loop Heat Pipe, tahanan termal, *filling ratio*.

Abstrak
Kecelakaan PLTN Fukushima Daiichi pada Maret 2011 di Jepang mengakibatkan terjadinya tsunami dan merendam *emergency diesel generator* berakibat terjadinya *station blackout* (SBO). Berdasarkan kejadian kecelakaan tersebut maka dilakukan penelitian penggunaan sistem keselamatan pasif sebagai pendukung sistem keselamatan aktif pada sistem pendinginan reaktor nuklir. Prototipe *Loop Heat Pipe* (LHP) merupakan fasilitas penelitian LHP berskala kecil yang salah satunya digunakan untuk mengetahui karakteristik dan fenomena perpindahan kalor yang terjadi di dalam LHP. Perhitungan untuk mengetahui tahanan termal pada prototipe LHP perlu dilakukan untuk mengetahui tingkat kinerjanya. Penelitian dilakukan secara eksperimental untuk pengambilan data dilanjutkan dengan melakukan perhitungan berdasarkan data yang telah diperoleh. Hasil perhitungan memperoleh tahanan termal terkecil adalah 0,014 °C/w pada *filling ratio* 100% dengan kecepatan aliran udara 2,5 m/s. Sehingga pada *setting filling ratio* dan kecepatan aliran udara tersebut menghasilkan kinerja prototipe LHP yang terbaik. Semakin besar kecepatan udara, kalor yang dilepaskan oleh *condenser* semakin besar, akibatnya nilai tahanan termal prototipe LHP semakin kecil. Dengan demikian semakin besar kecepatan udara maka tahanan termal prototipe LHP semakin menurun hal ini menunjukkan bahwa kinerja prototipe LHP semakin meningkat.

Keywords:
Loop Heat Pipe, thermal resistance, filling ratio.

Abstract
The Fukushima Daiichi PLTN accident in March 2011 in Japan caused a tsunami and submerged the emergency diesel generator resulting in a station blackout (SBO). Based on the accident incident, a study was conducted on the use of passive safety systems as a support for active safety systems in nuclear reactor cooling systems. The Loop Heat Pipe (LHP) prototype is a small-scale LHP research facility, one of which is used to determine the characteristics and phenomena of heat transfer that occur in the LHP. Calculations to determine the thermal resistance of the LHP prototype need to be carried out to determine its performance level. The research was carried out experimentally for data collection followed by calculations based on the data that had been obtained. The calculation results obtained the smallest thermal resistance is 0.014 °C/w at 100% filling ratio with an air flow velocity of 2.5 m/s. So that the setting of filling ratio and air flow velocity produces the best LHP prototype performance. The greater the airspeed, the greater the heat released by the condenser, as a result the value of the thermal resistance of the LHP prototype is getting smaller. Thus the greater the airspeed, the lower the thermal resistance of the LHP prototype, this indicates that the performance of the LHP prototype is increasing..

INTRODUCTION

The need for electrical energy is increasing with the increase in population. Nuclear energy is one of the new and renewable energy sources, so nuclear energy is an alternative energy that can be used to meet electrical energy needs. The use of nuclear energy as an alternative energy source, in addition to bringing benefits, is also potentially dangerous if a radioactive substance is released due to an accident or failure in its operation. One of the nuclear accidents that resulted in the release of radioactive substances into the environment was the Fukushima Daiichi Nuclear Power Plant accident in March 2011 in Japan. The accident was caused by an earthquake which resulted in a tsunami and submerged the emergency diesel generator which became redundant when the power source was not available resulting in a station blackout (SBO) at the PLTN. Based on this accident, research was conducted on the use of passive safety systems as a support for active safety systems in nuclear reactor cooling systems (Putra et al., 2016) (Ramachandran et al., 2014) (Kusuma et al., 2017).

One of the passive safety systems is a heat pipe that operates at pressure below atmospheric pressure (vacuum), which is a heat transfer device that has a high heat transfer capability. The heat pipe has three parts, namely the evaporator, adiabatic and condenser. The evaporator at one end functions to absorb heat and the fluid in the heat pipe turns into steam. The adiabatic section, and the condenser which is located at the other end serves to release heat. After the fluid evaporates in the evaporator section, the steam flows towards the condenser section. Furthermore, the temperature decreases in the condenser so that the vapor turns into a liquid. Furthermore, this liquid or condensate will flow back to the hot side (evaporator) and the process will repeat continuously (Bumataria et al., 2019) (Setyawan,2018) (Setyawan et al, 2020).

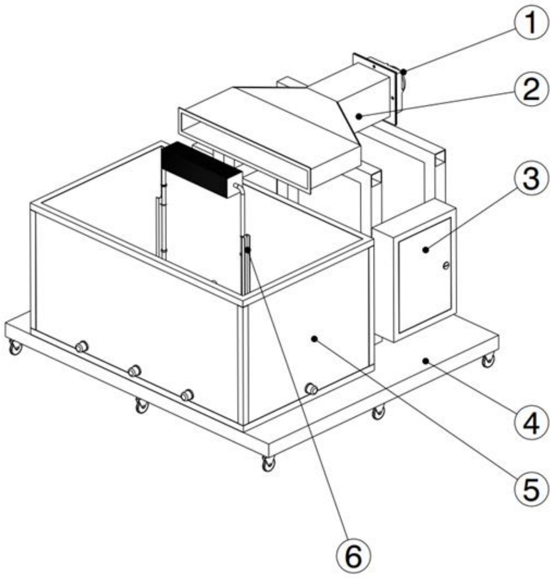
Several studies on heat pipes have been carried out by researchers, and the results of the research include research activities aimed at determining the thermal performance of heat pipes as heat exchangers with variations in the length of the condenser. The results showed that the highest thermal resistance was in a condenser with a length of 44cm at a temperature of 400°C was 13.80 C/W and the lowest was in a condenser with a length of 132 cm at a temperature of 1200°C was 0.80 C/W (Fachrudin, 2020). Research on performance analysis of straight heat pipes using screen mesh 300 capillary axis by varying the filling ratio. Research has found that a filling ratio of 60% produces the best performance compared to a filling ratio of 80% and a filling ratio of 40% (Setyawan, 2020). This research was conducted to find out the heat transfer phenomena that occur in the Loop Heat Pipe (LHP) model and the results areobtained overshoot, zigzag, and stable phenomena like the general heat transfer phenomena that occur in LHP with the smallest thermal resistance value of 0.0017 ºC/W, which is obtained when the LHP model is operated at a heat load of 65°C. And the higher the heat load received by the evaporator, the smaller the value of the thermal resistance of the LHP model (Nugraha, 2021).

Circular heat pipe (Loop heat pipe/LHP) is a type of heat pipe in the form of a circular pipe and works passively. In general, the main components of LHP are the evaporator section, the adiabatic section using a capillary axis (wick) or without a wick, the condenser section , and inside it is filled with liquid working fluid with a certain filling ratio . Wick is a component of LHP which functions to optimize its performance in the heat transfer circulation process. Filling ratio is the ratio of filling of working fluid in LHP as the ratio between working fluid and evaporator volume (Faghri, 2014). Giving a filling ratio above the maximum amount will cause vibrations in the LHP model due to an explosion from the boiling of the working fluid in the evaporator. However, if the filling ratio is below the minimum amount, it will result in the emergence of non-condensable gas which reduces the performance of LHP. LHP thermal performance is determined by thermal resistance, where the lower the value of thermal resistance, the better LHP performance (Jiao et al, 2008) (He et al, 2016).

The Loop Heat Pipe prototype is a small-scale Loop Heat Pipe research facility using 1 inch diameter copper pipes. This prototype consists of several components including a Pool unit that simulates a reactor cooling water pool, Loop Heat Pipe unit , and a fan unit to exhale air which is equipped with an air duct (ducting). To determine the performance of the Loop Heat Pipe prototype, it is necessary to calculate its thermal resistance based on temperature measurement data and airflow velocity when this prototype is operated. The measurement data recorded and stored in the Data Acquisition System (DAS) system at the Loop Heat Pipe prototype facility.

DESIGN AND THERMAL RESISTANCE OF THE LOOP HEAT PIPE PROTOTYPE

The Loop Heat Pipe prototype consists of cooling fan components, ducting, electrical and instrumentation panels, foundation, Pool Unit and Loop Heat Pipe prototype as shown in Figure 1.



Keterangan:
1. Cooling fan
2. *Ducting*
3. Electrical and instrumentation panels
4. Platform
5. Pool Unit
6. *Loop Heat Pipe*

Figure 1. Loop Heat Pipe Prototype (Haryanto, 2022)

The cooling fan which is equipped with ducting functions to simulate the velocity of air flow hitting the condenser which is equipped with fins. The fin functions to expand the condenser surface so that heat release in this section occurs more easily. The pool unit is equipped with 8 electric heaters with a power of 5 kW each. adjust the cooling water temperature. Meanwhile, LHP functions to take heat from cooling water, where LHP is made of 1 inch diameter copper pipe and is equipped with several fins on the condenser section. The LHP design is shown in Figure 2 below.

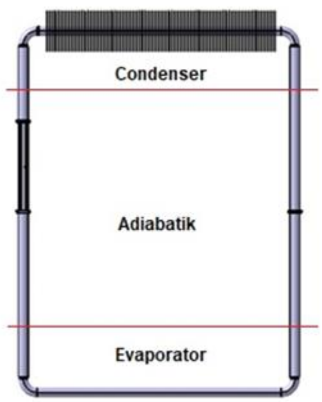


Figure 2. The Loop Heat Pipe prototype unit (Haryanto, 2022)

The Loop Heat Pipe prototype uses copper pipe material with a diameter of 1 inch (25.4 mm). The adiabatic section equipped with thermal isolators and wicks, while the condenser section is equipped with fins. Temperature measurements in several parts are carried out using a thermocouple connected to a DAS computer equipped with LabView software so that measurement results can be recorded and stored as shown in Figure 3

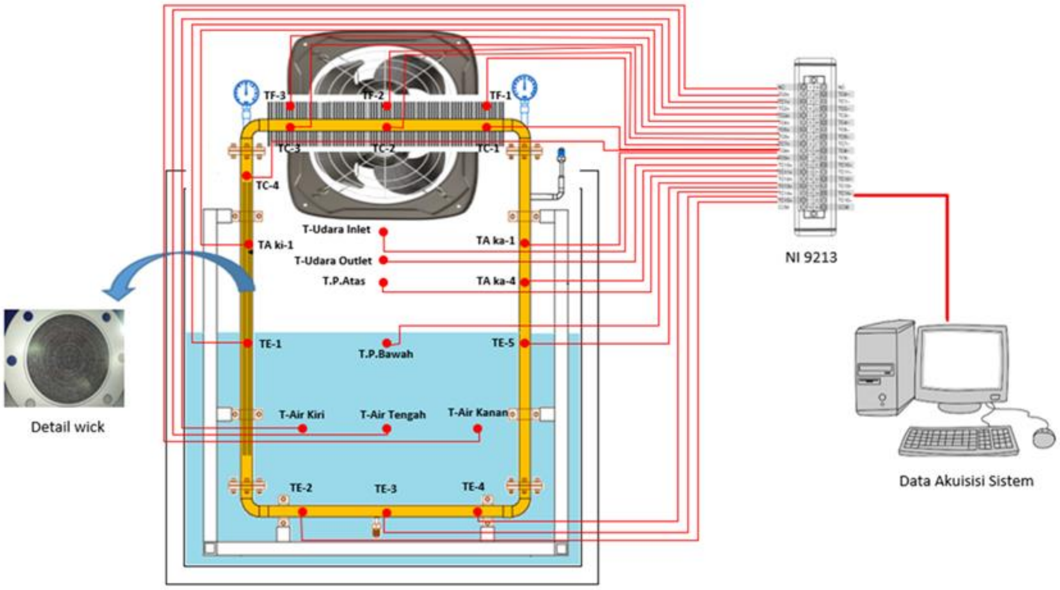


Figure 3. Data collection on the Loop Heat Pipe prototype

The thermal conductivity of the capillary axis (wick) used in a circular heat pipe (LHP) apparently affects the thermal resistance of the heat pipe. So that the thermal resistance of the heat pipe is a comparison between the temperature difference in the evaporator and condenser (dT) with the received heat load (Q) (Brautsch, 2002). The calculation to find out the value of the thermal resistance of the LHP begins by calculating the value of the air mass flow rate using Equation (1)::

$$\dot{m} = \rho_{air} \cdot v_{air} \tag{1}$$

where,,

$\dot{m}$	=	Mass flow rate of air (kg/m^2 s)
ρ_{udara}	=	Air density (kg/m^3)
v_{udara}	=	Air speed (m/s)

The calculation of the LHP output power can be found using Equation (2) (Holman, 1994):

$$Q_{out} = \dot{m}.c_p(T_o - T_i) \tag{2}$$

where,

Q_{out}	=	LHP output power (watt)
$\dot{m}$	=	Mass flow rate of air (kg/m^{2}s)
c_p	=	Specific heat of air (J/kg°C)
T_o	=	Air temperature leaving the fin (°C)
T_i	=	Air temperature entering the fin (°C)

so that the value of the thermal resistance of LHP can be found using Equation (3) (Hopkin et al, 1999):

$$R_{th} = \frac{T_E - T_C}{Q_{out}} \tag{3}$$

dimana,

R_{th}	=	Thermal resistance (°C/w)
T_E	=	Thermal resistance (°C)
T_C	=	Condenser temperature (°C)
Q_{out}	=	LHP output power (w)

METHODOLOGY

The stages of research to determine the value of LHP thermal resistance are as follows;

1. Data collection.

At this stage data collection on temperature, air speed and filling ratio was carried out through research using LHP prototypes by varying air speed and filling ratio. The data obtained is recorded and stored on the DAS computer.

2. Calculation of the air mass flow rate.

Calculations were made using Equation (1) with a large air density (ρ_{air}) value of 1.293 kg/m^3 and air speed according to the time the research was conducted.

3. Calculation of LHP output power.

The calculation is carried out using Equation (2) with the value of the air mass flow rate that has been obtained, the specific heat value of air (cp) of 1000 (J/kg°C) and the air temperature value coming out of the fins and the air temperature value entering the fins obtained from results of research data recording.

4. Calculation of the thermal resistance of the LHP.

Calculations are performed using Equation (3) with the value of the LHP output power that has been generated from the previous calculation and the evaporator temperature value and the condenser temperature value obtained from the results of research data recording.

5. Analysis and conclusions

Analysis is carried out after the calculation results are obtained and based on the results of the analysis, conclusions will be obtained from the research results.

RESULTS AND DISCUSSION

Based on experiments using the LHP prototype, data on temperature, air velocity and filling ratio have been obtained . Processing and calculating experimental data using Equation (1), Equation (2) and Equation (3) to obtain results as shown in Table 1 below.

Tabel 1. The results of the calculation of the thermal resistance of the Loop Heat Pipe prototype at various filling ratio.

No	Filling ratio (%)	Air Speed (m/s)	T Evap (°C)	T Conden (°C)	Tair Input (°C)	Tair Output (°C)	ΔTair (°C)	T_{Evap}-T_{Cond} (°C)	Results	
									Q out (watt)	Rth (°C/w)
1	20	2,5	46,954	23,026	26,001	26,292	0,291	23,928	940,658	0,025
2	40	2,5	47,774	32,293	26,395	26,717	0,322	15,481	1040,865	0,015
3	60	2,5	47,953	28,152	27,877	28,220	0,343	19,802	1108,748	0,018
4	80	2,5	46,556	26,452	26,635	26,862	0,227	20,104	733,777	0,027
5	100	2,5	47,473	33,017	28,534	28,923	0,388	14,456	1004,216	**0,014**

The calculation results by varying the filling ratio setting in Table 1 also shows that with the increase in heat released by the condenser , it means that the heat load increases and the resulting thermal resistance decreases. The calculation results get the thermal resistance on the LHP prototype between 0.014 – 0.027 °C/w. The smallest thermal resistance of 0.014 °C/w occurs at a filling ratio of 100% with an air flow rate of 2.5 m/s, thus this setting produces the best LHP prototype performance compared to other filling ratio settings . The largest filling ratio given to the LHP prototype results in the best LHP prototype performance, because the more working fluid in the LHP prototype causes faster boiling to occur and the greater the heat transfer in the LHP prototype (Fadillah, 2021). To be more sure, calculations are made at a filling ratio of 100% with variations in air velocity with data as shown in Table 2

Table 2. The results of the calculation of the thermal resistance of the Loop Heat Pipe prototype at various air flow rates

No	Filling ratio (%)	Air Speed (m/s)	T Evap (°C)	T Conden (°C)	Tair Input (°C)	Tair Output (°C)	ΔTair (°C)	T_{Evap}-T_{Cond} (°C)	Results	
									Q out (watt)	Rth (°C/w)
1	100	1,0	58,837	39,626	27,238	27,544	0,306	19,211	395,658	0,049
2	100	1,5	48,194	33,877	28,367	28,626	0,259	14,318	502,331	0,029
3	100	2,0	46,607	32,471	27,633	27,900	0,267	14,136	863,077	0,016
4	100	2,5	47,473	33,017	28,534	28,923	0,388	14,456	1004,216	**0,014**

Table 2 is the data and the results of calculating the thermal resistance on the LHP prototype by varying the air flowvelocity. To make it easier to analyze the results of these calculations, the calculation results are displayed in graphical form as shown in Figure 4 and Figure 5 below.

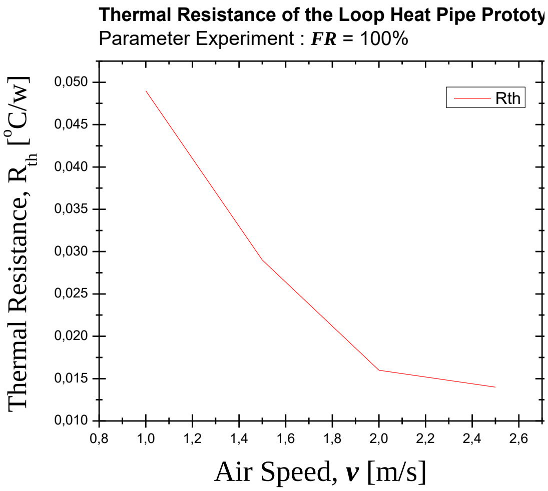


Figure 4. Graph of Thermal Resistance versus Airs peed

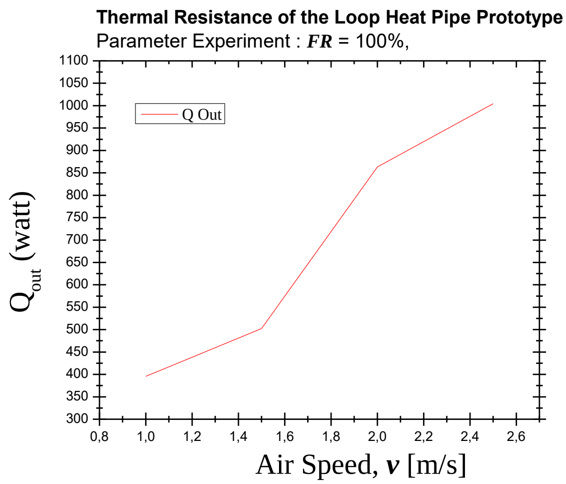


Figure 5. Graph of Thermal Resistance versus Heat in the condenser

In Figures 4 and 5 it can be seen that the greater the value of the air velocity exhaled into the LHP condenser , the lower the thermal resistance of LHP . This is in accordance with Equation (2) where the value of air velocity greatly affects the amount of heat released by the condenser. The greater the airspeed, the greater the heat released by the condenser , which results in the smaller the thermal resistance value of the LHP prototype. Thus the greater the airspeed, the thermal resistance of the LHP prototype decreases exponentially. This indicates that the performance of the LHP prototype is increasing (Reynaldi, 2021). The increased heat released by the condenser shows that the heat transfer cycle on the LHP prototype is getting faster so that the LHP performance is getting better by showing a decrease in the thermal resistance of the LHP prototype (Nugraha, 2021). The value of thermal resistance on the LHP prototype is also influenced by the temperature difference between the evaporator and condenser, the smaller the difference, the smaller the thermal resistance value or vice versa, this is in accordance with Equation (3). The smaller the value of the thermal resistance on the LHP prototype, the better the performance, thus to assess the performance of the LHP can be through the value of its thermal resistance (Putra, 2016).

CONCLUSION

The calculation results show that the smallest thermal resistance of 0.014 °C/w occurs at a filling ratio of 100% with an air flow velocity of 2.5 m/s, so that the setting of filling ratio and air flow velocity results in the best LHP prototype performance. At an air speed of 2.5 m/s the calculation results get the smallest thermal resistance as well. So that the greater the airspeed, the greater the heat released by the condenser , as a result the value of the thermal resistance of the LHP prototype is getting smaller. Thus the greater the air speed, the thermal resistance of the LHP prototype decreases exponentially. This indicates that the performance of the LHP prototype is increasing.

ACKNOWLEDGMENT

We thank you for the support provided by; Productive Innovative Research (RISPRO) Mandatory National Research Priority for Commercial NPP Products 2020-2025 with the title "Prototype Loop Heat Pipe as a Passive Cooling System in NuScale Reactor Pool Water" which has funded the research. Head of Research Center for Nuclear Reactor Technology, fellow researchers and Nuclear Institutions in the Sub-sector of Thermohydraulic Facilities for technical discussions.

REFERENSI

A. Brautsch and P. A. Kew, 2002, The Effect of Surface Conditions on Boiling Heat Transfer from Mesh Wick, Proceedings of 12th International Heat Transfer Conference, Elsevier SAS, Greenoble.

A. Faghri, 2014, Heat Pipes: review, Opportunities and Challenges. Frontiers in Heat Pipes (FHP), 5(1).

A. R. Fachrudin, 2020, Pengaruh Panjang Kondensor Terhadap Kinerja Termal Heat Pipe, Jurnal INTEKA, 20 (1), 47-52

A.Y. Nugraha, M. H. Kusuma, Giarno, Wardoyo, 2021, Studi Eksperimen Pengaruh Beban Kalor Terhadap Unjuk Kerja Termal Model Loop Heat Pipe, Majalah Ilmiah Sigma Epsilon, 25 (2), 84-91.

B. Jiao, L. M. Qiu, X. B. Zhang, Y. Zhang, 2008, Investigation on The Effect of Filling Ratio on The Steady State Heat Transfer Performance of A Vertical Two-Phase Closed Thermosyphon, Appl. Therm. Eng., 28 (11), 1417-1426.

D. Haryanto, Giarno, G.B.H. Kusnugroho, A. Rosidi, N.A. Wahanani, M.H. Kusuma, 2022, The Mechanical Strength Analysis on The Pool Tub of Loop Heat Pipe Prototype using CATIA Software, Jurnal Polimesin, 20 (1), 13-17.

I. Setyawan, 2018, Pengembangan Hybrid Loop Heat Pipe Untuk Aplikasi Pendingin Device Berfluks Kalor Tinggi, Disertasi, Fakultas Teknik Universitas Indonesia.

I. Setyawan, S. R. Riawan, S. P. Sari, Ridwan, 2020, Analisis Kinerja Pipa Kalor Lurus Menggunakan Sumbu Kapiler Screen Mesh 300 dengan Memvariasikan Filling Ratio, Jurnal ASIIMETRIK: Jurnal Ilmiah Rekayasa & Inovasi, 2 (2), 133-138.

J. He, J. Miao, L. Bai, G. Lin, H. Zhang, D. Wen, 2016, Effect of Noncondensable Gas On The Startup of A Loop Heat Pipe, Appl. Therm. Eng., 15 (4).

J. P. Holman, 2010, Heat Transfer, 10th ed. New York: McGraw-Hill, a business unit of The McGraw-Hill Companies, Inc., 1221 Avenue of the Americas, New York.

M. H. Kusuma, N. Putra, S. Ismarwanti, and S. Widodo, 2017, "Simulation of Wickless-Heat Pipe as Passive Cooling System in Nuclear Spent Fuel Pool Using RELAP5/MOD3. 2," International Journal on Advanced Science, Engineering and Information Technology, vol. 7, pp. 836-842.

N. Putra, M. H. Kusumas, A. R. Antariksawan, R. A. Koestoer, B. T. Verlambang, S. Ismarwanti, 2016, Unjuk Kerja Heat Pipe pada Sistem Pendingin Pasif di Kolam Bahan Bakar Nuklir Bekas, Prosiding Seminar Nasional Teknologi dan Rekayasa (SENTRA), pp. 297-304.

R. Fadillah, M.H. Kusuma, Giarno, A. Kholil, 2021, Studi Pengaruh Filling Ratio Terhadap Unjuk Kerja Termal Model Loop Heat Pipe, Majalah Ilmiah Sigma Epsilon, 25 (2), 65-73.

R. Hopkins, A. Faghri, D. Khrustalev, 1999, Flat Mniature Thermosyphons with Micro Capillary Grooves, Journal of Heat Transfer, 121 (1), 102-109.

R. K. Bumataria, N.K. Chavda, H. Panchal, 2019, Current Research Aspects in Mono and Hybrid Nanofluid Based Heat Pipe Technologies., Heliyon, 5(5), p.e01627.

R. Ramachandran, K. Ganesan, M.R. Rajkumar, L.G. Asirvatham, S. Wongwises, 2016, Comparative Study of The Effect of Hybrid nanoparticle on The Thermal Performance of Cylindrical Screen Mesh Heat Pipe, International Communications in Heat and Mass Transfer, 76, 294-300.

R. Reynaldi, M. H. Kusuma, Giarno, Dyah Arum Wulandari, 2021, Studi Pengaruh Laju Aliran Udara Pendingin pada Kondensator Terhadap Distribusi Suhu Model Loop Heat Pipe, Majalah Ilmiah Sigma Epsilon, 25 (2), 84-91.