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

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

Abstract
The nuclear accident at the Fukushima Daiichi nuclear power plant in March 2011 in Japan caused a tsunami and submerged the emergency diesel generator resulting in a station blackout (SBO). Based on the accident, 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 heat transfer events in 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 that the lowest thermal resistance is 0.014 °C/w with a 100% filling ratio and an airflow velocity of 2.5 m/s, so the setting of filling ratio and airflow velocity produces the best LHP prototype performance. The higher the airspeed, the greater the heat released by the condenser resulting in the value of the thermal resistance of the LHP prototype 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 during 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).

Heat pipe are a passive safety system that operates at pressures below atmospheric pressure. It is a heat exchange device that has high heat exchange capabilities. The heat pipe has three parts, namely the evaporator which functions to absorb heat and the fluid in the heat pipe turns into steam. The other two parts are the adiabatic part and the condenser which is located at the other end and functions to release heat. The fluid evaporates in the evaporator section, then the steam flows towards the condenser section. Next, the temperature in the condenser decreases so that the vapor turns into liquid. 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).

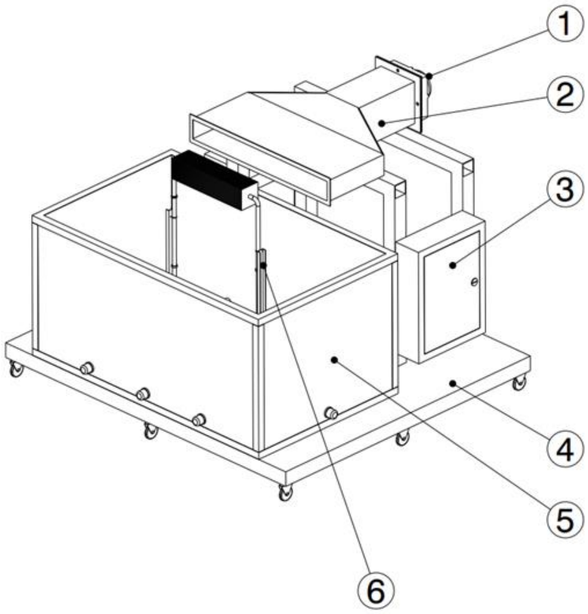
Several studies on heat pipes have been carried out by researchers, where the research activities aim to determine the thermal performance of heat pipes as heat exchangers with varying condenser lengths. This research found that the highest thermal resistance in a condenser with a length of 44 cm at a temperature of 400°C was 13.80 C/W and the lowest in a condenser length of 132 cm at a temperature of 1200°C was 0.80 C/W (Fachrudin, 2020). Another research is an analysis of the performance of a straight heat pipe using a 300 mesh screen capillary axis by varying the filling ratio. In this study, it was concluded that a filling ratio of 60% produced the best performance compared to a filling ratio of 80% and a filling ratio of 40% (Setyawan, 2020). This research was conducted to determine the heat transfer phenomena that occur in the Loop Heat Pipe (LHP) model and obtain results in the form of overshoot, zigzag, and stable phenomena such as the general phenomenon of heat transfer that occurs in LHP with the smallest thermal resistance value of 0.0017 ºC/W is operated at a heat load of 65°C. In this study, it was concluded that 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 an LHP are the evaporator section, the adiabatic section using a capillary axis (wick) or without a wick, and the condenser section which is filled with liquid working fluid with a certain filling ratio. Wick is a component of LHP that functions to optimize its performance in the heat transfer circulation process. The filling ratio is the ratio of the filling of the working fluid in the LHP as the ratio between the working fluid and the volume of the evaporator (Faghri, 2014). Vibration in the LHP model can occur if the filling ratio exceeds the maximum amount, this is caused by an explosion from the boiling of the working fluid in the evaporator. However, if the filling ratio is less than the minimum amount, it will result in the emergence of noncondensable gas which will reduce 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 a 1-inch diameter copper pipe. This prototype consists of several components including a pool unit that simulates a reactor cooling water pool, a Loop Heat Pipe unit, and a fan unit to exhale air which is equipped with an air duct. This research aims to determine the performance of the Loop Heat Pipe prototype through the calculation of thermal resistance based on temperature measurement data and airflow velocity when this prototype is operated. The measurement data has been 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.



Description:
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 is equipped with ducting functions to simulate the velocity of airflow 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 a 1-inch diameter copper pipe and is equipped with several fins on the condenser section. The LHP design is shown in Figure 2.

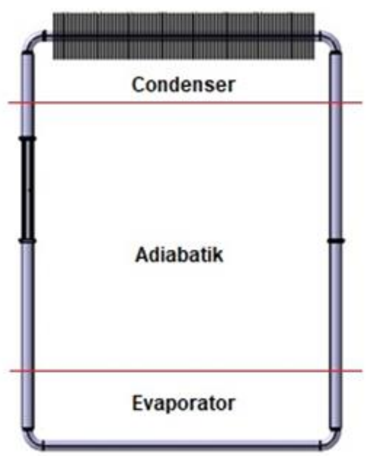


Figure 2. The Loop Heat Pipe prototype unit (Haryanto, 2022)

The Loop Heat Pipe prototype uses copper pipe material with a diameter of 1 inch (25.4 mm). The adiabatic section is 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

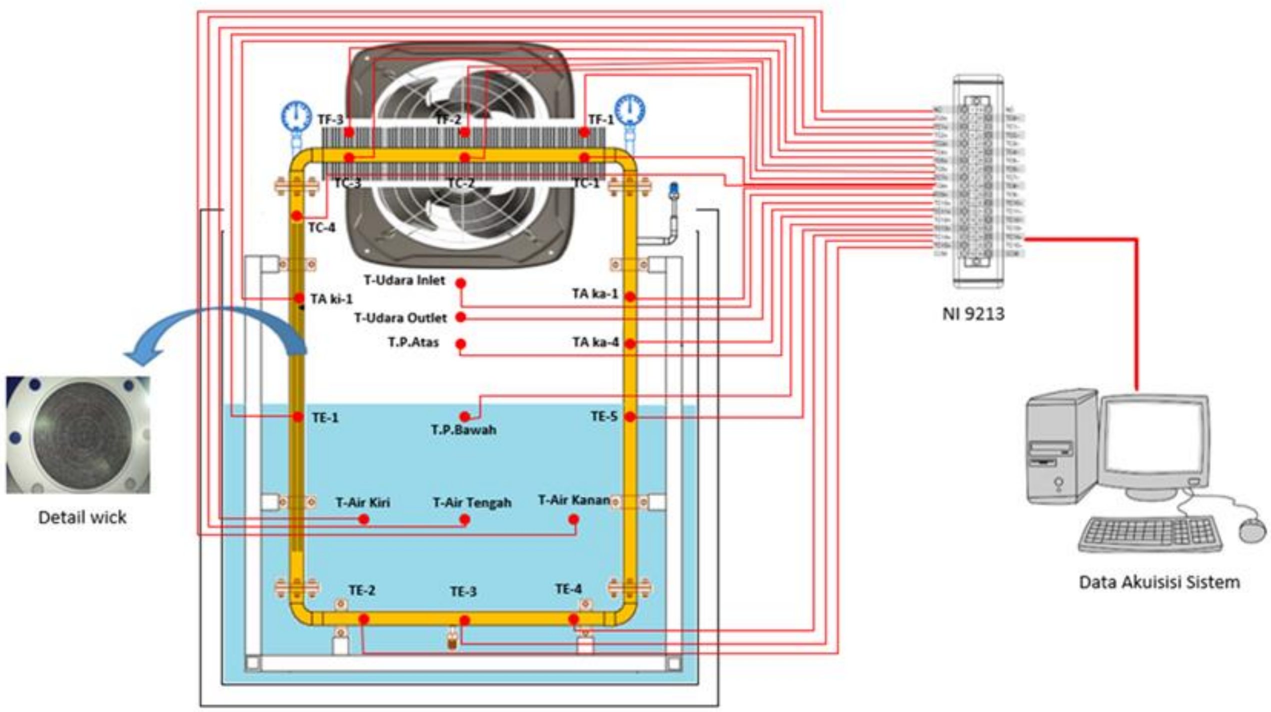


Figure 3. Data collection on the Loop Heat Pipe prototype

The thermal conductivity of the capillary axis (wick) used in a circular heat pipe (LHP) affects the thermal resistance of the heat pipe. So 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 begins by calculating the value of the air mass flow rate using Equation (1):

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

where

$\dot{m}$	=	The mass flow rate of air (kg/m^2 s)
ρ_{udara}	=	Air density (kg/m^3)
v_{udara}	=	Airspeed (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)
$\dot{m}$	=	The 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 can be found using Equation (3) (Hopkin et al, 1999):

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

where,

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

METHOD

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, airspeed, and filling ratio was carried out through research using LHP prototypes by varying air speed and filling ratio. The obtained data are 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 airspeed according to the time the research was conducted. (3) *Calculation of LHP output power*. The calculation was 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*. Calculations were performed using Equation (3) with the value of the LHP output power that has been generated from the previous calculation the evaporator temperature value and the condenser temperature value obtained from the results of research data recording. (5) *Analysis and conclusions*. Analysis was carried out after the calculation results were obtained and based on the results of the analysis, conclusions will be obtained from the research results.

RESULTS AND DISCUSSION

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

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

No	Filling ratio	Air Speed	T_{Evap}	T_{Conden}	$T_{air\ Input}$	$T_{air\ Output}$	ΔT_{air}	T_{Evap}-T_{Cond}	Results	
	(%)	(m/s)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	Q_{out} (watt)	R_{th} (°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 show 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 airflow rate of 2.5 m/s, thus this setting produces the best LHP prototype performance compared to other filling ratio settings. The greater the filling ratio on the LHP prototype, the better the performance of the LHP prototype, where the more working fluid in the LHP prototype causes faster boiling and easier heat transfer (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)	$T_{air\ Input}$ (°C)	$T_{air\ Output}$ (°C)	ΔT_{air} (°C)	T_{Evap}-T_{Cond} (°C)	Results	
									Q_{out} (watt)	R_{th} (°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 shows the data and the results of calculating the thermal resistance on the LHP prototype by varying the airflow velocity. 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.

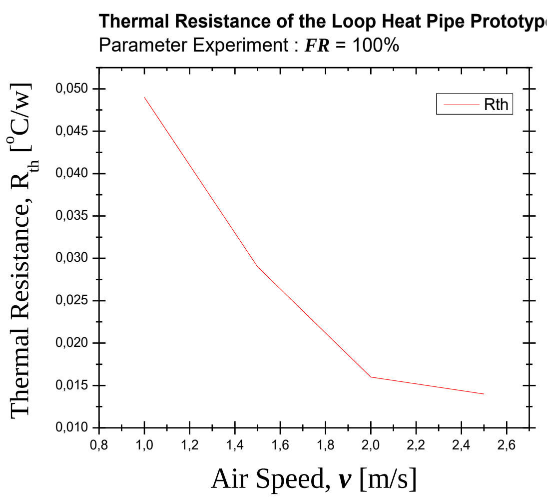


Figure 4. Graph of Thermal Resistance versus Airspeed

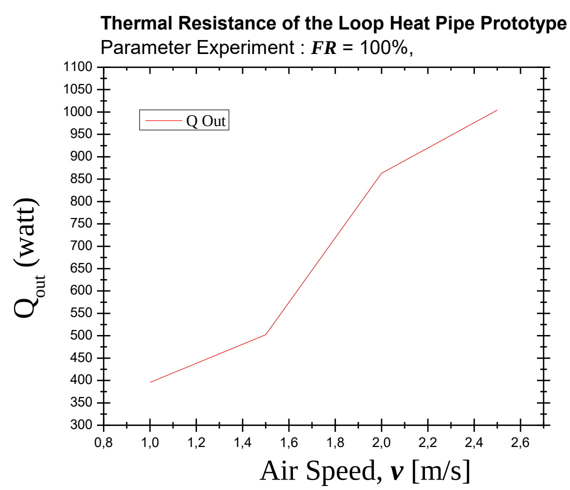


Figure 5. Graph of Thermal Resistance versus Heat in the condenser

Figures 4 and 5 show that the greater the value of the air velocity blown into the condenser, the smaller the thermal resistance. This is by 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, resulting in a smaller thermal resistance. Thus, the greater the airspeed, the thermal resistance decreases exponentially, this shows that the performance of the LHP prototype is increasing (Reynaldi, 2021). The increase in heat released by the condenser shows that the heat transfer cycle in the LHP prototype is getting faster so the performance of the LHP is getting better as shown by the decrease in thermal resistance (Nugraha, 2021). The thermal resistance value is also influenced by the difference in evaporator and condenser temperatures, the smaller the difference, the smaller the thermal resistance value, or vice versa, this is by Equation (3). The smaller the thermal resistance value on the LHP prototype, the better its performance, thus assessing the performance of the LHP can be done 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 airflow speed of 2.5 m/s. So setting the filling ratio and air flow speed produces the best LHP prototype performance. The greater the airspeed, the greater the heat released by the condenser, as a result, the thermal resistance value becomes smaller. Thus, air speed affects thermal resistance, where the greater the airspeed, the more thermal resistance decreases exponentially. This shows that the performance of the LHP prototype is increasing.

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