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Effective thermal conductivity of U-shaped heat pipe

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Abstract. The nuclear power station severe accident in Fukushima Daiichi became an important lesson learn to involve the passive cooling system in order to enhance the safety in a nuclear power station when prolonged station blackout occur. A U-shaped heat pipe is proposed as one of alternative passive cooling technology to absorb the decay heat generation in the cooling tank that connected to the reactor cavity cooling system. This research objective is to know the effective thermal conductivity of the U-shaped heat pipe. The effective thermal conductivity is an important factor to know the effect of the U-shaped heat pipe to remove the decay heat generation to the heat sink. An experiment was conducted to know the effective thermal conductivity of U-shaped heat pipe. The air cooling velocities on a bonded-fin heat sink in the condenser section were used as a parameter to obtain the effective thermal conductivity of U-shaped heat pipe. The air cooling velocities were varied at 0.65, 0.74, 1.02, and 1.21 m/s. The experiment results showed that the effective thermal conductivity of 35.37 was obtained at the highest variation of air cooling velocity on a bonded-fin heat sink in the condenser section. The result obtained shows that U-shaped heat pipe as a heat transfer device has thermal conductivity 35.37 times greater than the solid U-shaped Copper with the same geometry and dimension. This investigation results can be used to justify the use of heat pipes as a good passive cooling system in cooling tanks connected to Reaktor Daya Eksperimen reactor cavity cooling system.

Nomenclatures:

A	:	Surface area of U-shaped heat pipe (m^2)
C_p	:	Specific heat of coolant (J/kg. K)
k_{eff}	:	Effective thermal conductivity of U-shaped heat pipe (W/m.ºC)
La	:	Length of adiabatic section (m)
Lc	:	Length of condenser section (m)
Le	:	Length of evaporator section (m)
L_{eff}	:	Effective length of U-shaped heat pipe (m)
$\dot{m}$	:	Mass flow rate of coolant (kg/s)

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Q	:	Heat transfer rate (W)
Q_{out}	:	Amount of heat transport at condenser (W)
ρ	:	Density of water (kg/m^3)
R_T	:	Thermal resistance (°C/W)
T_i	:	Inlet temperature of coolant (°C)
T_o	:	Outlet temperature of coolant (°C)
ΔT	:	Temperature different between evaporator and condenser section (ºC)
$\bar{v}$	:	Volumetric flow rate of air coolant (L/min)

1. Introduction

Since the occurrence of severe accident at Japan's Fukuhisma Dai-ichi nuclear power plant, passive cooling systems (PCS) has begun to be highly considered as a heat dissipation systems of decay heat generation in a nuclear reactor. Although it has less effective cooling capability than an active cooling system, PCS can be relied on to remove the residual heat generation when an accident occurs in a nuclear reactor. Nuclear reactor accidents can be caused by loss of coolant accident that caused by station blackout (SBO), or caused by the failure of the active cooling system.

In the design of nuclear reactor, PCS will be implemented into the existing nuclear safety system. The PCS must be simple, increase the heat dissipation capability, and easy to operate in normal nuclear reactor conditions or when an accident occurs.

One of the passive safety system technologies commonly used in the electronics field is heat pipe. The heat absorbed by the heat pipe is discharged into the heat sink, thus there is no heat accumulation in the heat source chamber. Heat pipe is working in two phases, no electricity needed to operate and it has a simple geometry [1–3].

The investigation of heat pipe concept as a passive residual heat removal system in a nuclear reactor has also been carried out by the other researchers, for example in spent fuel storage pool [4–7], nuclear for space [8], nuclear core [9], control rod [10], etc. In addition, heat pipes can also be used for nuclear seawater desalination [11]. The investigation result stated that the heat pipe had good thermal performance, and it significantly dissipated the heat produced in normal nuclear reactor operating conditions or in accident conditions. The importance of decay heat generation dissipation in nuclear reactor result in many nuclear reactor designs that involve passive cooling systems in their safety systems. For generation 3 and 4 of NPP design, the concept of passive cooling system has to be implemented [12–14].

In the design concept of the Reaktor Daya Eksperimen (RDE) which is being developed by Indonesia, a U-shaped heat pipe is proposed as one of alternative passive cooling technology in order to absorb the decay heat generation in the cooling tank that connected to the reactor cavity cooling system (RCCS). The novelty of this research is the U-shaped heat pipe design that never used as passive cooling system in the cooling tank that connected to RCCS.

This research objective is to know the effective thermal conductivity of the U-shaped heat pipe. The effective thermal conductivity is an important factor to know the effect of the U-shaped heat pipe to remove the decay heat generation to the heat sink. An experiment was conducted to know the effective thermal conductivity of U-shaped heat pipe. The air cooling velocities on a bonded-fin heat sink in the condenser section were used as a parameter to obtain the effective thermal conductivity of U-shaped heat pipe. The air cooling velocities were varied at 0.65, 0.74, 1.02, and 1.21 m/s.

2. Methodology

2.1. Experimental setup

The experimental setup of U-shaped heat pipe as a passive cooling technology to absorb the decay heat generation can be seen in figure 1.

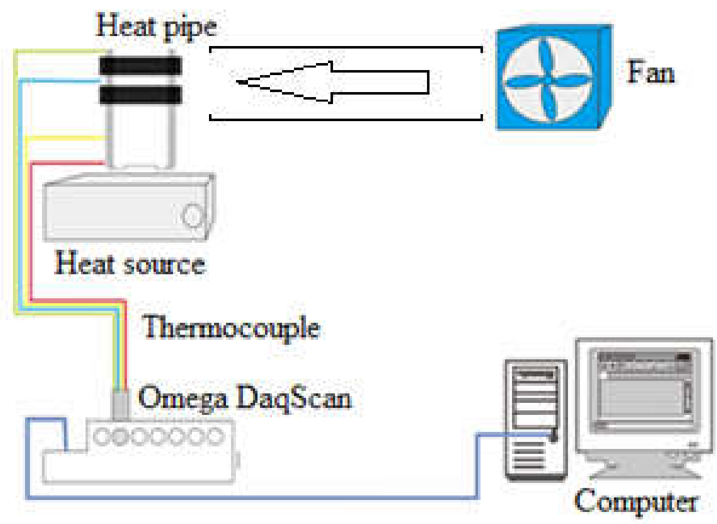

Figure 1. The experimental setup of U-shaped heat pipe.

U-shaped heat pipe consists of 4 copper tube with bonded-fin heat sink in the condenser section. Each heat pipe has outer diameter of 6 mm and inner diameter of 5.8 mm. Four of evaporator sections are placed on the bottom of heat pipe, and four of condenser sections are placed on the top of heat pipe. Evaporator and condenser section have length of 132.7 mm and 131 mm, respectively. On the outer side of the condenser section is placed 57 pieces of horizontal fins. Fins are made of Aluminum and have a rectangular shape. Each fin has a length, width, and thickness of 116.3 mm, 45.1 mm, and 0.4 mm, respectively. Fins are placed in a stacked horizontal position with a distance of 0.6 mm between the fins. The heat pipe is vacuumed for eliminate non-condensable gas and to decrease the boiling point of working fluid inside the heat pipe. De-mineral water is charged into the heat pipe with filling ratio of 100%. Filling ratio is the ratio between fluid volumes inside the evaporator compared with evaporator volume.

The function of evaporator is to absorb heat from the heat source, and the function of condenser is to release heat to heat sink. As a heat source, a heater with maximal power of 3000 W is placed on the evaporator section. Heat transfer by radiation from the heater is absorbed by the outer wall of the evaporator. The heat causes the working fluid in the heat pipe boils and change the phase of the working fluid from liquid to vapour. The heat provided by the heater to the evaporator is given at constant heat load of 900 W.

The steam then transfers the heat to the condenser. Latent heat is transferred to the outer walls of the condenser and fins. To accelerate the release of heat to the environment, air with ambient temperature of 29ºC is exhaled to the fin with variations in speed at 0.65, 0.74, 1.02, and 1.21 m/s. Air velocity measurement uses a digital anemometer which has an uncertainty of ± 0.005 m/s. A chimney is used to direct the air to the fins.

To measure the temperatures data, the ethernet-based Omega DaqScan/2000 series is used as data acquisition system. Sixteen K type thermocouples with uncertainty of ± 0.1ºC are placed in the test section. In the heat pipe, thermocouples are placed on the outside wall of Copper tube. Three thermocouples on evaporator section, 8 on condenser section, 1 thermocouple on heater room, 1 thermocouple on adiabatic section, 1 thermocouple for air inlet, 1 thermocouple for air outlet, and 1 thermocouple for measuring ambient temperature.

2.2. Data calculation

2.2.1. Thermal resistance calculation. The thermal resistance of U-shaped heat pipe is calculated using equation (1).

$$R_T = \frac{\overline{T}_e - \overline{T}_c}{Q_{out}} \tag{1}$$

The amount of heat removed across the U-shaped heat pipe to the environment is defined as:

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

Additionally, the mass flow rate of air coolant that absorbed the latent heat on condenser section can be obtained using:

$$\dot{m} = \rho.\tilde{v} \tag{3}$$

2.2.2. Effective thermal conductivity calculation. The effective thermal conductivity was used to compare the effectivity between heat pipe and a cylinderical copper with the same geometry. It assumed that the heat pipe as a cylindrical copper which absorb and transport the heat with conduction way.
The effective thermal conductivity calculation is used the Fourier heat conduction formulation as follow:

$$k_{eff} = Q\frac{L_{eff}}{A\,\Delta T} \tag{4}$$

Additionally, the effective length of U-shaped heat pipe can be obtained using:

$$L_{eff} = \left(\frac{L_e + L_c}{2}\right) + L_a \tag{5}$$

3. Results and discussion

3.1. Temperatures distribution
The experiment transient temperatures distribution obtained with variations on the air cooling flow rate and heat load of 900 W can be seen in figure 2.

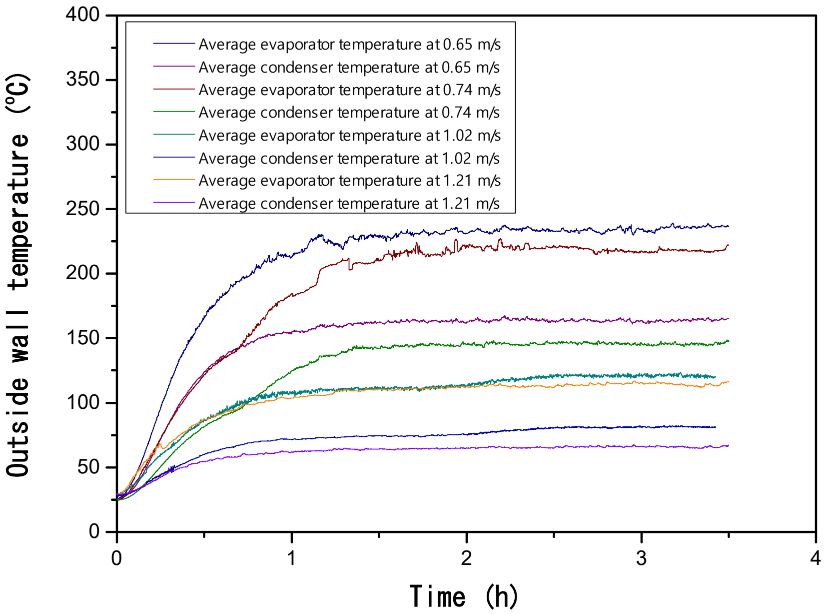

Figure 2. Transient temperature distributions at variation of air flow rate.

Figure 2 showed that the beginning of heating process on heat pipe, the evaporator temperatures were increase significantly because of heat absorbed continuously from heat source and it is effect on fluid to boil rapidly. The steam that resulted from the boiling process rises to the adiabatic and condenser section because it has lighter density than the fluid, thus affecting to increase the adiabatic and condenser temperature significantly. In this state, there has not been a natural circulation process in the heat pipe because the condensate has not formed enough in the condenser due to incomplete absorption of latent heat by the exhaled air into the condenser section. This heat pipe phenomenon is called overshoot.

The overshoot phenomenon is finished after the latent heat in the condenser section has been discharged into the environment and the condensate is formed. The condensate which has a heavier density than vapour then drops gravitationally through the adiabatic section and returns to the evaporator section. In this state, the vapour that rises to the condenser and condensate which drops to the evaporator does not occur smoothly because of the unstable vapour and condensate that produced in the evaporator and condenser. The amount of vapour rises to condenser is sometimes more than the condensate that drops to evaporator, and vice versa. The collisions between vapour and condensate cause the fluctuations in temperature distribution in overall of heat pipe. In this situation the natural circulation process has occurred, but it has not reached the steady state. This heat pipe phenomenon is called zigzag.

After the overshoot and zigzag phenomena occurred, the last phenomenon that occurs is stable. In this state, the overall temperature distributions in the heat pipe has a steady pattern continuously. This indicates that the natural circulation process has occurred perfectly in the heat pipe. The latent heat which generated in the condenser can be discharged properly into the environment through the fins.

Figure 2 also showed that the temperature at the evaporator and condenser can reach overshoot, zigzag, and stable conditions in a faster time due to the higher air velocity that blown to absorb heat in the condenser. Zigzag conditions are more dominant when the condenser is blown with a low air velocity, while the zigzag is not dominant if the air is blown at a high air velocity.

The distribution of average heat pipe surface temperature after reaching the stable condition is shown in figure 3.

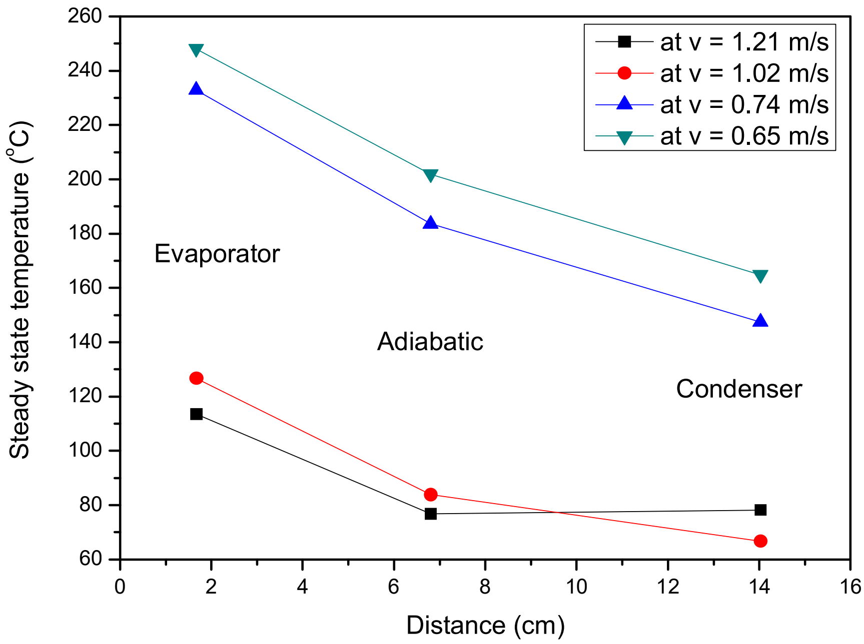

Figure 3. Steady state temperature distribution on U-shaped heat pipe.

Figure 3 showed that at a constant heat load, the lowest average temperatures of the evaporator and condenser were obtained when the condenser is cooled with air velocity of 1.21 m/s, and vice versa. The higher air velocity that used to absorb heat in the condenser causes the lower temperature of the evaporator and condenser, and the temperature difference between evaporator and condenser. The experiment showed that the highest air velocity of 1.21 m/s resulted in the smallest temperature difference between the evaporator and condenser. It can be seen that the air velocity has a significant effect on the temperature distribution in the U-shaped heat pipe. Increasing the air velocity is accelerate the steam condensation process in the condenser section, and it is resulted in the smallest temperature difference between the evaporator and condenser. Heat removal on the U-shaped heat pipe is strongly influenced by the air velocity that is used to take the heat in the condenser section.

3.2. Thermal resistance and effective thermal conductivity

3.2.1. Thermal resistance. The thermal resistance is an important parameter to know the heat pipe thermal performance. The heat pipe with the lowest thermal performance is indicated the best thermal performance of heat pipe to transport the heat to environment, and vice versa.
The thermal resistance of U-shaped heat pipe that obtained from experiment is shown in figure 4.

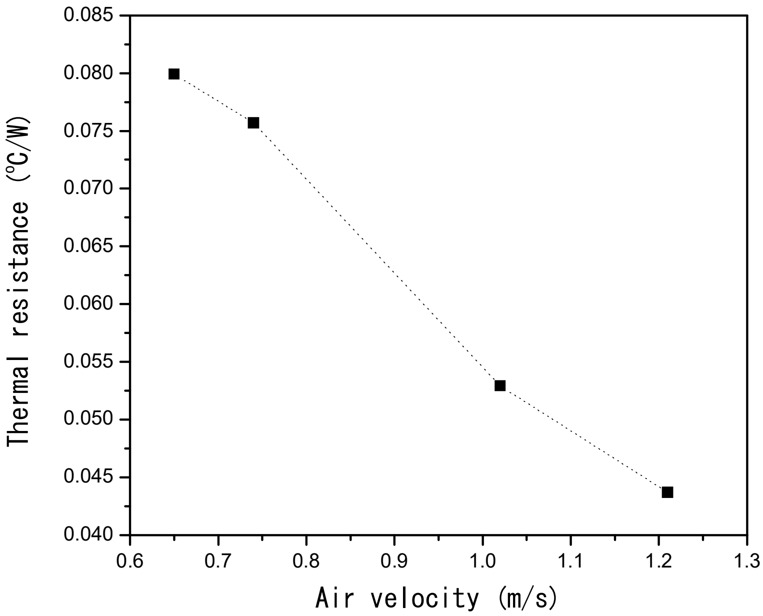

Figure 4. Thermal resistance of U-shaped heat pipe.

Figure 4 showed that the lowest thermal resistance of 0.044 ºC/W is obtained when air was blown the condenser section at the velocity of 1.21 m/s. It is shown that the trend of thermal resistance decrease with the increase of air velocity because higher air velocity is absorb more latent heat in the condenser section and affected to decrease the condensate temperature produced in the condenser section. The low-temperature condensate that drop into the evaporator result in lower evaporator temperature than the condensate which drop at high temperature. Thus at the highest air velocity, the U-shaped heat pipe is resulting lower temperatures difference between evaporator and condenser section.
The experimental results show that the U-shaped heat pipe has the best thermal performance when it is operated at higher air velocity. The results obtained indicate the compatibility with t research that has been done before [4, 15].

3.2.2. Effective thermal conductivity. The highest effective thermal conductivity of the U-shaped heat pipe is 35.37, obtained when U-shaped heat pipe is operated with the largest air velocity of 1.21 m/s. The experimental results show that the effective thermal conductivity is increase with the increase of air velocity which used to take latent heat in the condenser section. The effective thermal conductivity obtained shows that the U-shaped heat pipe made from copper used in the experiment has the heat transport ability of 35.37 times greater than the copper solid rod with the same geometry.

4. Conclusion

The effective thermal conductivity of U-shaped heat pipe, which will be proposed as a passive cooling system technology to absorb the decay heat generation in the cooling tank that connected to the reactor cavity cooling system, was investigated experimentally. It was concluded that U-shaped heat pipe have an overshoot, zigzag, and stable temperature distribution. The lower thermal resistance of 0.044 ºC/W and effective thermal conductivity of 35.37 was obtained when the condenser section of the U-shaped heat pipe was blown with the highest variation of air velocity of 1.21 m/s. The U-shaped heat pipe has the heat transport ability of 35.37 times greater than the copper solid rod with the same geometry. Based on the thermal resistance and effective thermal conductivy, the U-shaped heat pipe can be proposed as an alternative for passive cooling system technology to absorb the decay heat generation in the cooling tank that connected to the reactor cavity cooling system.

References

[1] Wang J-C 2014 Microelectron Reliab **54** 1344–54
[2] Kumar K R S, R Dinesh, Roseline A A, Kalaiselvam S 2017 *Microelectron Reliab* **73** 1–13
[3] Wang Y, Wang B, Zhu K, Li H, He W and Liu S 2018 *Appl Therm Eng* **143** 630–38
[4] Kusuma M H, Putra N, Antariksawan A R, Koestoer R A, Widodo S, Ismarwanti S and Verlambang B T 2018 *Int. J. Therm. Sci.* **126** 162–71
[5] Kim I G and Bang I C 2018 *Energy Convers Manag* **173** 233–43
[6] Lai K, Wang W, Yi C, Kuang Y and Ye C 2018 *Ann. Nucl. Energy* **111** 523–35
[7] Ye C, Zheng M G, Wang M L, Zhang R H and Xiong Z Q 2013 *Ann. Nucl. Energy* **58** 124–31
[8] Wang C, Chen J, Qiu S, Tian W, Zhang D and Su G H 2017 *Ann. Nucl. Energy* **103** 74–84
[9] Panda K K, Dulera I V and Basak A 2017 *Nucl. Eng. Des.* **323** 376–85
[10] Kim K M, Bang I C 2018 *Int. J. Heat Mass Transf.* **119** 472–83
[11] Jouhara H, Anastasov V and Khamis I 2009 *Desalination* **249** 1055–61
[12] Wang Y 2013 *Energy Procedia* **39** 240–47
[13] IAEA 2009 *IAEA-TECDOC*-1624
[14] Yu X-G, Park H-S, Kim Y-S, Kang K-H, Cho S and Choi K-Y 2015 *Nucl. Eng. Des.* **259** 205–20
[15] Kusuma M H, Putra N, Antariksawan A R, Imawan F A 2017 *Nucl. Eng. Technol.* **49** 476–83

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