Effective thermal conductivity of U-shaped heat pipe

M H Kusuma¹, U Setiorini², T A R Putri², G, A R Antariksawan³ and M Juarsa¹

¹Centre for Nuclear Reactor Technology and Safety, National Nuclear Energy Agency of Indonesia (BATAN), Kawasan Puspiptek Serpong, Tangerang Selatan 15314, Indonesia
²Department of Physics, Padjadjaran University, Jatinangor, Bandung, Indonesia
³Center for Science and Accelerator Technology, National Nuclear Energy Agency of Indonesia (BATAN), Jl. Babarsari Kotak Pos 6101 ykbb Yogyakarta 55281, Indonesia

E-mail: luluikal@batan.go.id

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)
\( L_a \) : Length of adiabatic section (m)
\( L_c \) : Length of condenser section (m)
\( L_e \) : Length of evaporator section (m)
\( L_{eff} \) : Effective length of U-shaped heat pipe (m)
\( \dot{m} \) : Mass flow rate of coolant (kg/s)
\[ Q \] : Heat transfer rate (W)
\[ Q_{out} \] : Amount of heat transport at condenser (W)
\[ \rho \] : Density of water (kg/m³)
\[ R_{T} \] : Thermal resistance (°C/W)
\[ T_{i} \] : Inlet temperature of coolant (°C)
\[ T_{o} \] : Outlet temperature of coolant (°C)
\[ \Delta T \] : Temperature different between evaporator and condenser section (°C)
\[ \bar{v} \] : Volumetric flow rate of air coolant (L/min)

1. Introduction
Since the occurrence of severe accident at Japan's Fukushima 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.
2.2.1. **Thermocouple section.**

To direct measurement of condenser the fluid evaporator. The working fluid 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 29°C 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 ± 0.1°C 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).
The amount of heat removed across the U-shaped heat pipe to the environment is defined as:

\[ Q_{out} = \dot{m} \cdot c_p \cdot (T_o - T_i) \]  

(2)

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

\[ \dot{m} = \rho \cdot \dot{V} \]  

(3)

2.2.2. Effective thermal conductivity calculation. The effective thermal conductivity was used to compare the effectivity between heat pipe and a cylindrical 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:

\[ k_{eff} = \frac{Q \cdot L_{eff}}{A \cdot \Delta T} \]  

(4)

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

\[ L_{eff} = \frac{L_e + L_c}{2} + L_a \]  

(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.](image-url)
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.](image)

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.](image)

Figure 4 showed that the lowest thermal resistance of 0.044 °C/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 °C/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 conductivity, 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.

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