Preliminary Experiment of U-Shaped Heat Pipe as Passive Cooling System in High Temperature Gas-Cooled Reactor Cooling Tank

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Abstract. When station blackout occurs on high temperature gas-cooled reactor, the decay heat will be absorbed by a residual heat dissipation system (known as cooling tank) which connected to the reactor cavity cooling system. The U-shaped heat pipe as passive cooling system is proposed as new feature of technology to absorb the decay heat in the high temperature gas-cooled reactor cooling tank, and to keep the water remains in its operating temperature and level. This research objective is to know thermal resistance of U-shaped heat pipe scale model based on variation of heat load and coolant velocity. The influence of water temperature in the circulating thermostatic bath as heat load on evaporator section and air velocity which flowed into the horizontal condenser fin were investigated experimentally. The heat loads were varied at water temperature of 45, 50, and 60°C. The air velocities were varied at 0.45, 0.83, and 1.06 m/s. The experiment result showed the lowest thermal resistance of 0.000027±0.000000593 °C/W when U-shaped heat pipe was operated at hot water temperature of 60°C and air velocity of 1.06 m/s. The investigation result can be used as a model and initial knowledge to design large scale of U-shaped heat pipe as a passive cooling system in cooling tanks connected to high temperature gas-cooled reactor cavity cooling system. This result is also useful regarding to the thermal management of passive cooling process in cooling tank and it can improve the nuclear safety and be able to overcome the thermal problems caused by station blackout in high temperature gas-cooled reactor.

Keywords: U-shaped heat pipe, Passive cooling system, High temperature gas-cooled reactor, Cooling tank, Reactor cavity cooling system.
1. Introduction
In the future, Indonesia will developed the High Temperature Gas cooled Reactor (HTGR) type as an alternative energy supply. As a starting point, a project is planned to built HTGR of 10 MWth, called Reaktor Daya Ekserimen-10 (RDE-10) [1]. In order for developed the HTGR to have a high level of safety, the Fukushima Dai-ichi nuclear power plant (NPP) severe accident became a lesson learns to involve the passive cooling system in order to enhance the safety aspect in HTGR. The advantage of a passive cooling system is that it can be operated without an external energy source driven if the active cooling system fails. In the application, the passive cooling system should be easy to operate and it can be applied to improve the safety of nuclear power plant.

The passive cooling system especially can be used to absorb the decay heat produced by reactor core when active cooling system became malfunctioning because of station blackout (SBO) or other causes. The decay heat should be removed to protect the safety of reactor system and radiation released to the environment. For generation 3 and 4 of NPP design, the concept of passive cooling system has to be implemented [2–4].

If SBO is occurred in HTGR, the decay heat will be removed with conduction from reactor core to a cavity cooling panel, reflector, and reactor vessel. The decay heat will be absorbed by reactor cavity cooling system (RCCS). The fluid inside the cavity cooling will be boiled. Because of density gradient, the fluid will flow in consequence of natural circulation into the water cooling tank in the top of reactor building. For prolonged SBO case, the water in the cooling tank will run out due to evaporation, then the reactor pressure vessel (RPV) concrete will absorb the decay. The increasing of RVP concrete temperature will decrease its strengthness.

To improve the HTGR safety, especially for RPV concrete strengthness, heat pipe technology can be used to remove the decay heat that absorbed by water in cooling tank to the environment. As a research and development in the design of HTGR in BATAN, this preliminary experiment is dealing with the research on application of the heat pipe technology in the RCCS design. It might be an interesting alternative design for RDE’s RCCS beside the current design that utilizes an air cooling.

Heat pipe uses evacuated closed pipe that charged with working fluid. The heat, which absorbed by evaporation section by conduction, will evaporate the fluid inside the evaporator section. With two-phased condition, the vapor from evaporation process will raise to the condenser section through an adiabatic section. In the condenser section, the latent heat of vapor will be absorbed by coolant and will change the vapor into condensate. The condensate will flow back into the evaporation section with gravity, and the natural circulation process will occur continuously inside the heat pipe.

Putra et al. conducted the investigation of heat pipe as passive cooling system for central processing unit (CPU). They used demineralized water and nanofluid as working fluid inside the heat pipe [5–8], and used wick i.e. screen mesh [9], sinter powder [8], and bio-material [6,10]. Vasiliev [11] investigated the heat pipe that applied as heat exchanger in industries, electronic cooling, heating ventilation air conditioning (HVAC) system, and air heater. They investigation result showed that heat pipe had good thermal performance in removing heat from heat source to the heat sink.

In nuclear fields, with experimental and simulation method, heat pipe had investigated as an alternative of passive residual heat removal system in reactor core and spent fuel storage pool (SFSP) in case of accident conditions. Alizadehdakhel et al. [12], Kafeel et al. [13], and Tung et al. [14], Ye et al. [15], and Fu et al. [16] had done the simulation of loop heat pipe (LHP) as passive residual heat removal system in reactor core when accident occurred. Their simulation results showed that heat pipe could be used as emergency passive residual heat removal system on accident condition and keep the temperature of water in reactor core and spent fuel pool not to boil. Kusuma et al. [17–20] had done the investigations on vertical straight wickless-heat pipe that would be proposed as passive cooling system on nuclear SFSP when SBO occurred. The investigations were conducted using experimental and simulation with RELAP5 thermal-hydraulic code. Their investigation results showed that vertical straight wickless-heat pipe had good thermal performance in removing the decay heat that generated from nuclear spent fuel when SBO occurred and could be proposed as alternative passive cooling system in SFSP. Xiong et al. [21] investigated experimentally the using of LHP to remove the decay
heat from SFSP of AP1000 reactor when SBO occurred. Their result showed that LHP had significant effect to remove the heat to the heat sink.

The use of other heat pipe type, U-shaped heat pipe, as alternative passive cooling system that will be used in HTGR will be investigated experimentally to know its thermal performance for removing the heat generation when nuclear reactor is on SBO accident. The U-shaped heat pipe will be placed in the water cooling tank which connected with RCCS. The investigation of U-shaped heat pipe as passive residual heat removal system on the water cooling tank is rarely done by previous researchers. The literature studies showed that U-shaped heat pipe is mostly used as passive cooling system for non-nuclear fields and is rarely used in the nuclear field. The U-shaped heat pipe with bonded-fin heat sink was chosen because it has very good thermal performance to remove heat from heat source to the heat sink. With low cost, passive work, and high thermal performance, U-shaped heat pipe is expected to be a solution to the existing thermal problems in nuclear reactors for SBO accident [22–24].

T. S. Liang and Y. M. Hung [23] conducted an experimental investigation of the thermal performance of U-shaped heat pipe with aluminum heat sink which was used as a cooler in a CPU that compatible for various high-frequency microprocessors. In their research, it had been characterized the optimum operating heat load range by analyzing the thermal resistance (thermal resistance) produced. The calculation of convection heat transfer coefficient between fin and environment air is estimated using Bessel's modified equation based on experimental results obtained. The heat sink thermal optimization involves the determining of the optimal L ratio (ratio between the length of the evaporator and the condenser section) of the U-shaped heat pipe, by evaluating the minimal thermal resistance function in which the empirical heat transfer coefficient obtained from the experiment is applied to the calculation. The U-shaped heat pipe is made of copper with diameter of 6 mm, total length of 373 mm, evaporator length of 120 mm, and condenser length of 38 mm. A total of 57 fins with 6 mm diameter and an outer diameter of 35 mm are placed on the condenser section. In their experiment, variations in the heat load from 10-75 W have been carried out. The results of their study showed that the lowest thermal resistance was 0.03 °C/W, and heat transfer from the heat pipes of 50 W to the environment. Their experimental results also showed that the optimal L-ratio of U-shaped heat pipe was depended on geometrical parameters such as the heat pipe diameter and the distance between fins at the condenser section.

Wang [24] investigated experimentally the thermal performance of two U-shaped heat pipe. The experiment varied the air flow rates and heat sources. The determination of the thermal performance curves of each U-shaped heat pipe was performed using the superposition method and least-square estimators from the obtained experimental data. U-shaped heat pipe consists of two parallel copper pipe that charged with demineralized water, with diameter of 6 mm, total length of 265 mm, evaporator section length of 30 mm, and condenser section length of 117.5 mm. The evaporator section was directly connected to the heat source. A total of 35 pieces of fin were placed around the condenser, with fin distance of 2.4 mm. The fins, which made from aluminum with a thickness of 0.4 mm, have an area of 42 x 82 mm². The experiments were performed by varying the fan speeds at 1000, 2000, and 3000 rpm, and heat source area at 15 x 15 mm² and 30 x 30 mm². The experimental results obtained the lowest thermal resistance of 0.246 °C/W when two fans were operated at 3000 rpm and the heat source area is 30 x 30 mm². Thermal resistances of the U-shaped heat pipe were 0.04 °C/W and 1.7 °C/W when it was operated at heat loads of 78.85 W and 34 W. In other studies, Wang et al. [25] investigated the thermal performance of a U-shaped heat pipe with a horizontal heat sink as a heat absorber in the computer's CPU. The heat which was absorbed by the U-shaped heat pipe was discharged through the heat sink into the environment. The results showed that the heat pipe with horizontal fins could absorb and dispose 36% of the total heat in the CPU room, while 64% of total heat in the CPU room was absorbed by other CPU cooler in computer sourced from active cooling system.

Nazarimanesh et al. [22] investigated experimentally the influence of the heat load and working fluid concentration of silver nanoﬂuid to the thermal performance of U-shaped heat pipe. Test section of U-shaped heat pipe has a length of 135 mm in each branch. Parameters that became the reference
for the thermal performance to be generated were thermal resistance and overall heat transfer coefficient of U-shaped heat pipe. The working fluid used was a mixture of 70% Ethanol and 30% demineralize water. Various concentrations of 40 nm nanoparticles were dissolved into the fluid mixture. In the study, they varied the working fluid concentration of nanofluid at 0.001, 0.005, and 0.1 % (50, 200, 600 ppm) to the overall percentage of nanofluid volume in the heat pipe, the evaporator heat load of 10-40 W, and the temperature of coolant in the condenser of 20-40 °C. The results showed that the increase of heat load would increase the temperature on the evaporator, condenser, and working fluid. The increasing of heat load had resulted in a decrease of thermal resistance value and increase in the U-shaped heat pipe overall heat transfer coefficient. A comparison of tested concentrations showed that the concentration of nanofluid of 0.001 % would decrease the thermal resistance up to 42.26 %, and would increase the U-shaped heat pipe overall heat transfer coefficient up to 1883 W/m²·°K.

The severe accident of the Fukushima Dai-ichi nuclear power plant can be used as a lesson learned for better design of HTGR safety. As a preliminary step of continuous investigation, preliminary experiments from U-shaped heat pipes as passive residual heat removal system in HTGR cooling tank are required. The cooling tank continuously operates to extract the heat generates from the normal operation of RCCS. The U-shaped heat pipe used in this study is usually used for cooling system on computer servers. The research objective is to know thermal resistance of U-shaped heat pipe scale based on variations of heat load and coolant velocities. The influences of water temperature in the circulating thermostatic bath as heat load on evaporator section and air velocity which flowed into the horizontal condenser fin were investigated experimentally. The heat loads are varied at the water temperature of 45, 50, and 60°C. The air velocities were varied at 0.45, 0.83, and 1.06 m/s. The results obtained will be used as a preliminary knowledge to design U-shaped heat pipe which will be designed as a passive residual heat removal system in HTGR cooling tank.

2. Methodology

2.1. Experimental setup

The experimental setup of U-shaped heat pipe model can be seen in Figure 1. U-shaped heat pipe consists of 4 U-shaped heat pipe with bonded-fin heat sink in condenser section.
Each of the U-shaped heat pipe is made from a copper tube with inner diameter of 5.8 mm, and outer diameter of 6 mm. Evaporator section with total length of 132.7 mm is placed on the bottom of heat pipe, and two of condenser section with length of each section of 131 mm is placed on the top of heat pipe. The U-shaped heat pipe is vacuumed and charged with demineralized water with filling ratio of 100%.

The evaporator section as heat absorber is submerged in circulating thermostatic batch (CTB) which contains hot water. The heat from hot water will boil the working fluid in the heat pipe. Hot water temperatures are maintained at constant values for each experiment performed (heat load under steady conditions). In this experiment, hot water as a heat load in the evaporator varied at 45, 50, and 60°C.

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. As a heat releaser in the condenser section, the fins will be blown by air as coolant at a constant velocity. To measure the air velocity, a digital anemometer with uncertainty of 0.03 m/s is used. In this experiment, the air velocity of the fan is varied at 0.45, 0.83, and 1.06 m/s (according to the arrangement of fan spacing to U-shaped heat pipe, i.e. 25, 50, and 75 cm).

The experimental temperature data are recorded using the temperature module of a National Instrument data acquisition system which is connected to a Lab VIEW virtual instrument program. Twenty thermocouples, with each uncertainty of ± 0.1ºC, are placed on outside wall of U-shaped heat pipe, 4 thermocouples on evaporator section, 8 on condenser section, 1 thermocouple on hot water in CTB, and 1 thermocouple for measuring ambient temperature.

2.2. Calculation of thermal resistance

The thermal resistance in U-shaped heat pipe, $R_T$, is calculated using:

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

The amount of heat that absorbed in the evaporator, $Q_{in}$, is defined as:

$$ Q_{in} = k \cdot A \cdot \frac{dT}{dx} $$

Where $T_e$ is average wall temperature of evaporator (°C), $T_c$ is average wall temperature of condenser (°C), $k$ is thermal conductivity of copper tube (W/m.K), $A$ is surface area of evaporator section (m²), $dT$ is temperature difference between outside and inner wall of evaporator (°C), and $dx$ is thickness of copper tube (m).

2.3. Experiment matrix

The experiment matrix of U-shaped heat pipe as passive cooling system in HTGR cooling tank is shown in Table 1.

| Working fluid  | Filling ratio (%) | Air temperature [°C] | Water temperature in CTB [°C] | Velocity of air [m/s] |
|----------------|-------------------|----------------------|-------------------------------|----------------------|
| Demineralized water | 100  | 29         | 45                  | 0.45               |
|                 |       |            | 50                  | 0.83               |
|                 |       |            | 60                  | 1.06               |

3. Results and discussion

3.1. Transient temperature
The transient temperature of U-shaped heat pipe, which is obtained from experiment with variations of heat loads on evaporator section and velocities of air coolant, can be seen on Figure 2, 3, and 4.

Figure 2 shows the transient temperature which is obtained from experiment with variation of hot water temperatures at 45, 50, and 60°C for air coolant velocity of 0.45 m/s.

![Figure 2. Transient temperatures at air velocity of 0.45 m/s and variation of CTB hot water](image)

It can be seen from Figure 2 that for air velocity of 0.45 m/s and variations of CTB hot water, the evaporator temperature increase significantly when the heat load is supplied to the U-shaped heat pipe. The increase of evaporator temperature occurs since the working fluid inside the evaporator section boils and transforms the fluid to vapour phase. The vapour will rise to the condenser section since it has lighter density than the fluid phase. The condenser section temperature gradually increase in consequence of the heat received from the vapor. This phenomenon is usually called an overshoot, i.e. a phenomenon where temperature is still rising and condensate has not circulated yet from the condenser to the evaporator section. In overshoot condition, the natural circulation in the heat pipe will not occurred. Temperature in the evaporator and condenser will continue to rise until its peak for 550 seconds. The overshoot temperature was obtained at an average evaporator temperature of 44.39°C and an average condenser temperature of 43.07°C.

After overshoot phenomenon occurred, a zigzag and stable temperature distribution are then observed. Zigzag and stable phenomena occur when the vapour arrive in the condenser, and increase the condenser temperature. The latent heat of vapour is absorbed by the air being blown by the fan. The fins which are bonded-fin heat sink in the condenser increase the condenser heat transfer area. The vapour will then turn into condensate, and then fall down gravitationally to the evaporator. The temperature of the evaporator and condenser section decrease due to the absorption of the latent heat. This phenomena occur until it reach steady conditions, which is indicated by a stable temperature profile that does not change significantly for long periods. This condition occurs continuously because the natural circulation is established in the U-shaped heat pipe.

Figure 3 and 4 show the transient temperatures which are obtained from the experiment with variation of hot water temperatures at 45, 50, and 60°C for air coolant velocities of 0.83 and 1.06 m/s.
It can be seen from Figure 3 and 4 that the distribution of transient temperature for variation of air coolant velocities of 0.83 and 1.06 m/s have similar phenomena with the result in Figure 2. The result we obtained for average overshoot temperature of evaporator and condenser section for air velocity of 0.83 m/s are 42.56°C and 40.84°C, meanwhile average overshoot temperature of evaporator and condenser section for air velocity of 1.06 m/s are 40.83°C and 39.11°C. The temperature distributions in Figure 2, 3, and 4 show that the influence of evaporator heat load and air velocity have the same effect on the transient temperature profile. While a higher applied evaporator heat load will increase the temperatures of evaporator and condenser section, a higher air velocity decrease the temperatures of evaporator and condenser section.

3.2. Thermal resistance
Figure 5 shows the thermal resistance that was obtained from the U-shaped heat pipe experiment in CTB hot water at 45, 50, and 60°C, and air coolant velocities at 0.45, 0.83, and 1.06 m/s.
Figure 5. Thermal resistances of U-shaped heat pipe

It can be seen from Figure 5 that the lowest thermal resistance of U-shaped heat pipe is 0.000027 ± 0.000000593 °C/W when U-shaped heat pipe is operated at hot water temperature of 60°C and air coolant velocity of 1.06 m/s. The experiment results show that the thermal resistance of U-shaped heat pipe will decrease by increasing air coolant velocity in the condenser and temperature of CTB hot water applied to the evaporator. The higher hot water temperature is applied to the evaporator will result in the more steam/vapour rises to the condenser. If the air coolant in the fins has sufficient velocity to absorb heat from the condenser, then it will lead to a rapid return of condensate to the evaporator.

Thermal resistance is a very significant factor for determining the thermal performance of U-shaped heat pipe. The lowest thermal resistance obtained from a heat pipe operation indicates more rapid natural circulation to occur in the U-shaped heat pipe and lowest resistance to remove the heat from condenser section to the environment. The thermal resistance results show that the U-shaped heat pipe has good thermal performance and can be used as a model and initial knowledge to design large scale of U-shaped heat pipe as a passive cooling system in cooling tanks connected to high temperature gas-cooled reactor cavity cooling system.

4. Conclusion

The thermal resistance of U-shaped heat pipe, which will be used as a model and initial knowledge to design large scale of U-shaped heat pipe as a passive cooling system in cooling tanks which is connected to HTRG cavity cooling system, was investigated experimentally. The preliminary experiment showed that the lowest thermal resistance of U-shaped heat pipe was 0.000027 ± 0.0000000593 °C/W when it was operated at higher hot water temperature and air coolant velocity. Based on the U-shaped heat pipe thermal resistance results, it will be used as a knowledge to design large scale U-shaped heat pipe which will be proposed as a passive cooling system in HTGR cooling tank.

5. Acknowledgments

The authors would like to thank the PTKRN BATAN and Program Flagship INSINAS 2018 Kemenristekdikti for funding this research. We would also like to thank Mr. Ari Nugroho for his
advice and assistance during the work. Our grateful thanks are also extended to Mr. Kukuh Prayogo, Ms. Desy Wulandari and Mr. David Febraldo for their support in the experiment.

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