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Study on Thermal Characteristics of U-Shaped Heat Pipe

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A B S T R A C T

The latest accident in Japan's nuclear power station became a valuable experience to start engaging passive cooling systems (PCS) more aggressively to improve safety aspects in nuclear power reactors being studied in Indonesia. This investigation is related to the U-shaped heat pipe (UHP) research as PCS of water in the cooling tank (CT). The objective of this research is to study the thermal characteristics of UHP as PCS in the CT. The experiment on small-scale UHP and simulation with RELAP5 code has been conducted to understand the performance of UHP. The experiment results of the small-scale UHP model will be used as a basic understanding of simulating and designing a UHP with big scaling. The study result showed the highest thermal performance of UHP was obtained when it operated on the higher temperature of heat load and higher air cooling velocity. The more UHPs inserted into the cooling pool, the more heat that can be discharged into the environment. This result also shows promising use of UHP for CT PCS. The use of UHP as PCS can enhance the safety aspect of the nuclear reactor, especially in station blackout event.

1. INTRODUCTION

The average electrification ratio in Indonesia was 91.60% in 2016. Many regions in Indonesia do not have a sufficient supply of electricity, especially in remote areas. To fulfill the electricity needs, the Indonesian government is interested to use nuclear power plants (NPP) with small power generation (usually called small modular reactor, SMR), i.e. NuScale or SMART NPP, as an alternative electrical energy supply in Indonesia.

On the other hand, the Fukushima Dai-ichi NPP severe accident has provided valuable experience and lessons learned that PCS is needed as a redundant system when the cooling performance from active system got malfunctioned from removing heat generation during station blackout (SBO) event. In the design concept of next-generation NPP, the PCS is implemented[1-4]. In an SMR during emergency, the core heat shall be absorbed by water in the cooling tank (CT) as a passive residual heat removal system. For the SBO accident, in which RPV heat and temperature increase, the water inside CT has to be able to remove that heat. As a consequence, if prolonged SBO happens, the water in the CT will evaporate to the environment and run out. If this condition remains continuously and heat generation continues to occur, the reactor will experience a severe accident.

To improve safety and to prevent radiation release to the environment in the SMR if any accident occurs, the passive system will be implemented. The heat pipes as PCS in the CT are

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considered to be implemented, so the heat absorbed by cooling water in the CT can be discharged into the environment quickly without massive cooling water evaporation in CT.

The heat pipe has an excellent ability to absorb heat and releasing it to the environment[5]. Another heat pipe type with U-geometry, UHP was commonly used to assist cooling in computer and server's central processing unit (CPU). The UHP could maintain the computer/server on its working temperature and prevent the electronic equipment from being overheated[6, 7]. The UHP was also investigated as a solution for energy savers in heating ventilation air conditioning systems. Based on its ability, the UHP could be used to provide a saving to the system[8]. The UHP also investigated as a technology which can improve the performance of solar cogeneration unit. The investigation results show that the use of UHP in solar cogeneration units can improve its performance significantly[9].

Based on the Fukushima Dai-ichi NPP accident, any kind of heat pipe has been investigated as PCS, especially if the active cooling system fails to work due to a long-term SBO condition that was caused by the tsunami. To keep the reactor remains in a safe condition, many researchers were proposed the loop heat pipe[10-13] and thermosyphon[14, 15]. It can be concluded from their investigations that heat pipes could be considered as PCS for nuclear installations if accidents occur due to their thermal performance.

There has been no research in the nuclear reactor using a UHP as PCS, especially the use of UHP as a PCS in CT. Therefore, the objective of this investigation was to study the UHP thermal characteristics of PCS in CT. Experiment method with small scale UHP and simulation with RELAP5 code were conducted to understand the influence of heat load and air cooling flow rate on the UHP performance. The assessment results on the small-scale UHP model could be used for designing and simulating the UHP with large geometry that will be proposed as a PCS in the CT. The heat loads on the evaporator section were varied in the experiment and simulation. Meanwhile, the effect of air coolant velocity was only varied in the experiment. The desired impact of this investigation results is to propose UHP as a PCS in nuclear installations.

2. METHODOLOGY

2.1. Experiment on small scale UHP

Figure 1 shows the experimental setup of UHP used in this study[16].

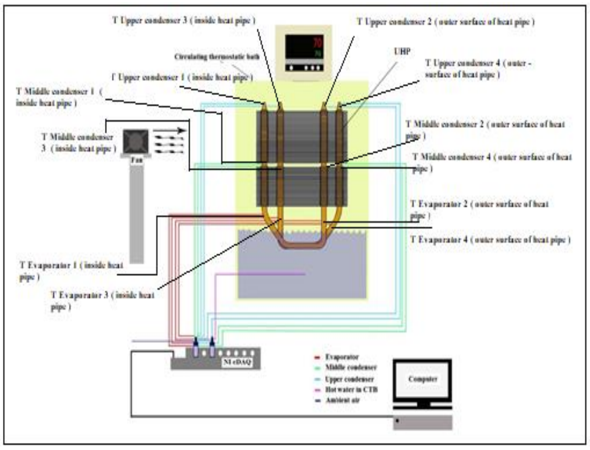

Fig. 1. UHP experimental setup[16]

Four heat pipes with U-shaped geometry were made from a copper tube and each one has the same inner and outer diameter, 5.8 mm and 6 mm. respectively. Each heat pipe has the same aspect ratio for evaporator and condenser sections. The evaporators are in the bottom part and condensers at the upper part, with a length of each condenser and evaporator of 131 mm and 132.7 mm, respectively.

To enhance its heat transport, 57 pieces of the fin are bonded on the condenser. Every piece of the fin has a rectangular shape with a length of 116.3 mm, a thickness of 0.4 mm, and a width of 45.1 mm. With a fins gap of 0.6 mm, it is placed horizontally. Air is blown to the fins with velocity variation of 1.06, 0.83, and 0.45 m/s (based on the spacing of fan with UHP, i.e. 75, 50, and 25 cm). The measurement of air velocity using a digital anemometer with the uncertainty of ± 0.03 m/s.

The evaporator section is submerged into hot water in a circulating thermostatic bath (CTB) with a water temperature of 40, 50, and 60°C.

A data acquisition system from National Instrument is used to record temperature data. The data recorded with a sampling rate of 1 data/s. A virtual instrument program of LabVIEW is built to connect the data acquisition system with a computer. Twenty thermocouples (type K, with an uncertainty of ± 0.1ºC) are pasted on outside wall UHP. One thermocouple in air, 1 thermocouple in water, 8 thermocouples in the condenser, and 4 thermocouples in the evaporator.

2.2. RELAP 5 simulatiom an large geometry

Figure 2 shows the proposed design of large geometry UHP as PCS in CT.

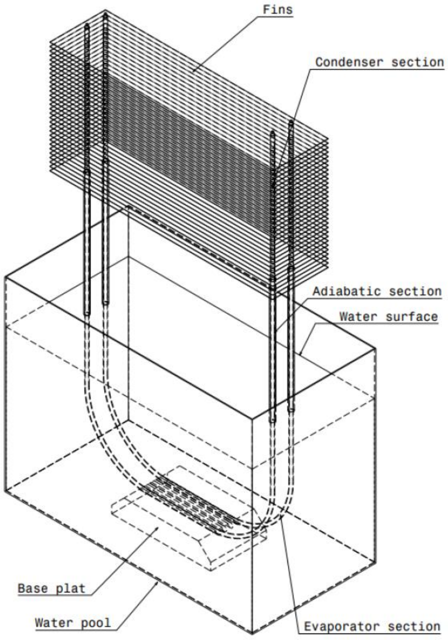

Fig. 2. Large geometry of UHP as PCS in CT

Based on the design above, the simulation with thermal-hydraulic code RELAP5 is carried out on large geometry of UHP as a PCS in the CT. In the case of long-term SBO, the temperature and pressure on the reactor core are increased because heat accumulation is not properly transferred into the environment. The heat generated then flowed through a heat exchanger in the CT. The increasing temperature of water in the CT then reduces the water level due to evaporation. The RELAP5 nodalization of large geometry of UHP as PCS in CT can be seen in Figure 3.

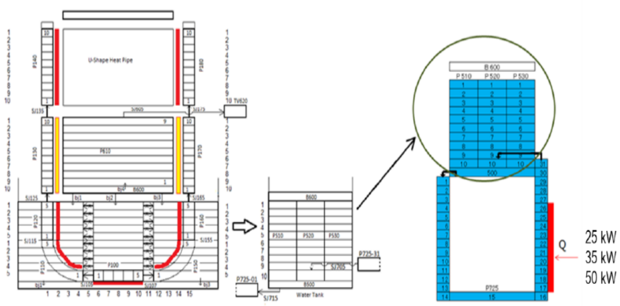

Fig. 3. Large geometry of UHP nodalization

The UHP in Figure 3 used pure copper material. The UHP consist of the evaporator placed on the bottom, the adiabatic on the middle, and the condenser on top. Each section has the same aspect ratio of 1 m. The UHP has an overall length of 3000 mm, the diameter of the outer tube of 28.4 mm, and the diameter of the inner tube of 25.4 mm. Each section of the UHP model is divided into 20 volumes. In this simulation, the heat from the core as a heat source for water in CT was varied at 25, 35, and 50 kW.

It was important for knowing water temperature distribution in CT with and without a UHP inserted, and the effect of the number of heat pipes that are inserted on the water temperature distribution in CT. The evaporator section that submerged in a CT absorbed the heat, And the working fluid inside the evaporator will then boil. The vapor generated in the evaporator will rise to the adiabatic part and condense into liquid in the condenser. The adiabatic part is well-insulated. The condensate was flowing gravitationally to the evaporator. Thus this cycle repeats continuously. The air cooling that flowed to the outer side of the condenser will remove the heat generated by the condenser.

Heat pipes, with vacuum pressure condition, contain demineralized water at room temperature. The ratio of water inserted to UHP is varied for determining an effective filling ratio to produce the best performance of UHP. The cooling tank is open to the outside air. The water in CT is used as a heat absorber derived from heat exchangers. A CT with a height of 1 m has 1 m of width and 5 m of length.

2.3. Resistance of Thermal of UHP

The resistance of thermal of UHP, R_T, is calculated using:

$$R_T = \frac{\bar{T}_e - \bar{T}_c}{Q_{in}} \quad (1)$$

Evaporator absorbing heat load, Q_{in}, with:

$$Q_{in} = k.A.\frac{dT}{dx} \quad (2)$$

where $\bar{T}_e$ is the average of evaporator wall temperature (°C), $\bar{T}_c$ is the average of condenser wall temperature (°C), k is copper tube thermal conductivity (W/m.K), A is evaporator cross-section area (m^2), dT is the difference of temperature for inside and outside evaporator wall (°C), and dx is the thickness of copper tube (m). In this calculation, it is assumed that the heat transfer by conduction is vastly dominant in the evaporator section, while the heat transfer by convection and radiation is considered not to affect the total heat load in the evaporator section.

2.4. U-shaped heat pipe experiment matrix

The UHP experiment matrix is shown in Table 1.

Table 1. UHP experiment matrix

UHP Working fluid	Filling ratio (%)	Air temperature (°C)	Temperature of water in CTB (°C)	Air velocity (m/s)
De-mineralized water	100	29	40 50 60	0.45 0.83 1.06

3. RESULTS AND DISCUSSION

3.1. The experiment of small scale UHP

a. The UHP wall temperature distribution

The UHP wall temperature distribution can be seen in Fig. 4.

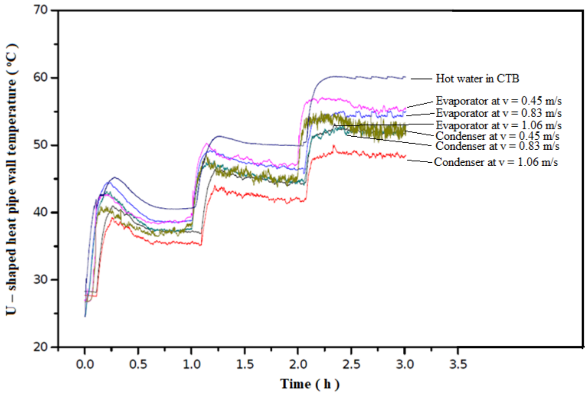

Fig. 4. The UHP wall temperature distribution at varied heat load and air coolant velocity

As observed from Figure 4, it was obtained for general phenomena of temperature distribution in heat pipes such as the overshoot, the zigzag, and the stable. For the overshoot phenomenon, the heat load absorbed significantly affect the increase of evaporator temperature. The water in the UHP then boils and transforms into vapor. Buoyancy force rises the vapor to the condenser and it significantly increase the temperature of condenser. Then vapor latent heat was absorbed by fins. At the beginning of the overshoot phenomenon, the condensate as a result of the condensation process has not been able to drop completely into the evaporator because the vapor were produced more than the condensate and preventing the condensate from falling gravitationally to the evaporator. For this state, the vapor and the condensate inside UHP were not circulated well.

The next distribution of temperature phenomena that were obtained in the UHP experiment was the zigzag phenomenon and the stable phenomenon. For the zigzag phenomenon, the UHP temperature distribution has a zigzag pattern. This phenomenon is the starting point of the natural circulation that occurs in the UHP. On the zigzag state, vapor comes and goes to/from the condenser and evaporator irregularly. The zigzag finished when a steady condition was achieved. The stable phenomenon, also called the steady condition of temperature distribution pattern, for a long period will occur continuously in the UHP. A stable phenomenon shows that natural circulation has occurred perfectly within the UHP.

Figure 4. shows the temperature distribution pattern caused by air velocity to fins and heat absorbed by the evaporator. Increasing the velocity of air decrease the temperature of the condenser and evaporator, and vice versa.

b. The thermal resistance of UHP

Thermal resistance is used as an indicator of the thermal performance of UHP. Higher thermal resistance indicates lower UHP thermal performance to dissipate heat to heat sink.

Figure 5. shows experiment resistances of thermal obtained from the varied velocity of air and heat load[16].

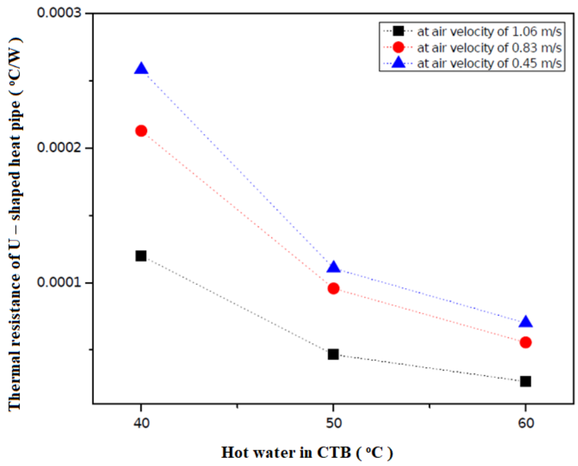

Fig. 5. The resistances of thermal of UHP[16]

Fig. 5 shows the lowest resistance of thermal of the UHP is 0.000027 ± 0.0000000593 °C/W. It is found when UHP is at a higher velocity of air and heat load. Higher heat load given resulted in aggressive vapor and steam comes to condenser section. The higher air velocity perfectly absorbs condenser latent heat and causes condensate to fall gravitational to evaporator rapidly.

The UHP resistance of thermal obtained in this study was compared with other thermal resistances obtained from other researchers' results. The investigation results show that their thermal resistances were 0.12-0.28 °C/W[15, 17, 18]. The obtained experimental thermal resistance of UHP show that this UHP has an exceptionally lower thermal resistance compared with other researchers' results. It is indicated that resistance of thermal depends on the experiments performed, heat pipe geometry, the amount of fluid charging inside heat pipe, heat load absorbed by an evaporator, velocity of coolant into the condenser, etc. Resistance of thermal value obtained in this study shows that the UHP has excellent thermal performance in dissipating heat.

3.2. Simulation of large scale UHP

Figs. 6-8 show the water temperature distributions in CT with and without UHP inserted.

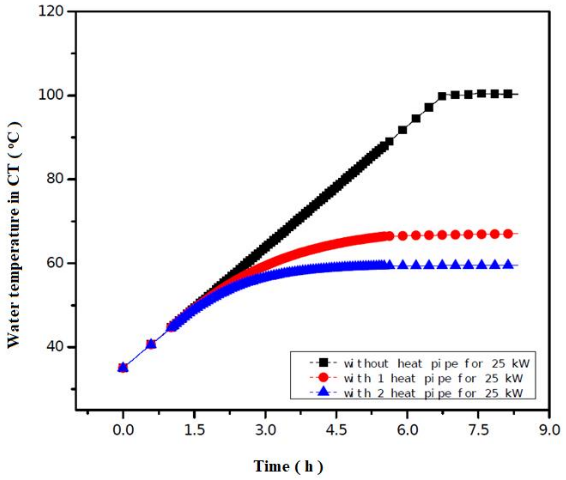

Fig. 6. Water temperature distribution in the CT for the heat of 25 kW

Figure 6 indicated in a case for heat load of 25 kW, there was a significant water temperature difference when the CT is not inserted with UHP than when1 UHP and 2 UHPs are inserted. The steady-state temperature of the water is 100ºC in the case without UHP inserted, 68.2 ºC in case 1 UHP inserted, and 59.67ºC in case 2 UHPs inserted. These results indicated the UHP insertion is very helpful to reduce water temperature compared to water temperature without UHP insertion. When 1 UHP is inserted, the temperature of the water could decrease for 31.8ºC. When 2 UHPs are inserted, resulting temperature of the water is 40.33ºC lower compared to without UHP inserted, and 8.53ºC lower when compared to 1 UHP inserted.

Figure 7 shows the water temperature in CT with and without UHP inserted for a heat load of 35 kW.

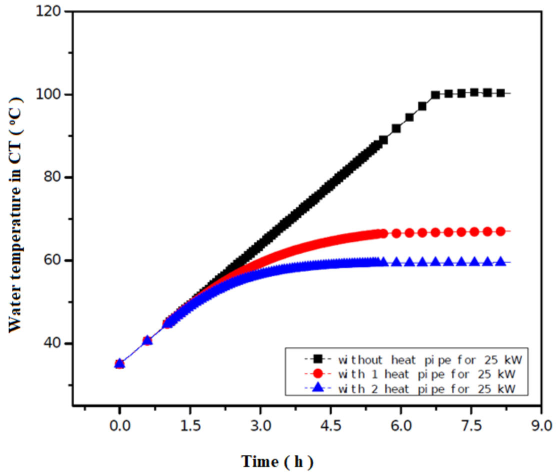

Fig. 7. Water temperature distribution in the CT for the heat of 35 kW

Figure 7 indicated in a case for heat load of 35 kW, it was obtained that the water temperature could decrease with a difference of 25.76ºC when 1 UHP is inserted. In the case of 2 UHPs inserted, the temperature difference is 36.55ºC lower when compared to without UHP inserted and 10.79ºC lower compared to 1 UHP inserted.

Figure 8 shows the water temperature in CT with and without UHP inserted for a heat load of 50 kW.

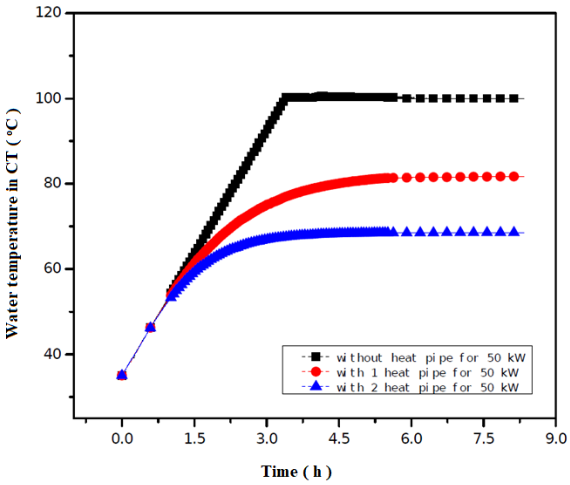

Fig. 8. Water temperature distribution in the CT for the heat of 50 kW

Figure 8 shows that, in a case for heat load of 35 kW, it was obtained that water temperature decreased by 17.74ºC when 1 UHP is inserted. In the case of 2 UHPs inserted, the temperature difference of the water is 31.44ºC lower when compared to without the UHP inserted, and 13.67ºC lower compared to 1 UHP inserted.

The obtained results show that, in the case of without UHP, the time needed for water in CT to reach the highest temperature is getting shorter with the higher heat load given. However, because CT was in atmospheric condition, the highest temperature achieved in all variations of the heat load given is 100ºC. With UHP inserted, after the steady condition is reached, the water temperature in the CT becomes lower when the water receives the lowest heat.

These simulation results show UHP has a significant influence on the water temperature in the CT when steady conditions have been reached. The number of UHP greatly influences the steady temperature of water in the CT. The more UHP that are inserted into the CT, the steady temperature of the water becomes lower.

Both experiment and simulation show UHP has a significant influence in removing heat from CT to the environment. The UHP can also keep the temperature of water in CT not excessively high at the given heat load, so the evaporation of water in CT is not overly fast when compared to CT without inserted UHP. These results are hugely useful for the basis of designing large-scale UHP as a PCS in CT, with further study.

5. CONCLUSION

The thermal characteristics of UHP with experiment and simulation were studied. It was obtained that UHP had similar heat transfer phenomena with other heat pipe types, such as during overshoot, zigzag, and stable phenomena. From the experiment, it was obtained the lower UHP thermal resistance is 0.000027 ± 0.0000000593 °C/W for higher evaporator heat load and air velocity . Meanwhile, based on the RELAP5 simulation model, it was shown that UHP could dissipate heat and keep the water temperature low. This study has shown the UHP has a potential as an alternative PCS in the CT of nuclear installations, with further investigation.

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AUTHOR CONTRIBUTION

Mukhsinun Hadi Kusuma equally contributed as the main contributor to this paper. All authors read and approved the final version of the paper.

REFERENCES

1. Ha H., Lee S., Kim H. Optimal Design of Passive Containment Cooling System for Innovative PWR. Nucl. Eng. Technol. 2017. **49**(5):941-952.
2. Li Y., Zhang H., Xiao J., Travis J.R., Jordan T. Numerical Investigation of Natural Convection Inside the Containment with Recovering Passive Containment Cooling System using GASFLOW-MPI. Ann. Nucl. Energy. 2018. **114**:1-10.
3. Xing J., Song D., Wu Y. HPR1000: Advanced Pressurized Water Reactor with Active and Passive Safety. Engineering. 2016. **2**(1):79-87.
4. Sun D.C., Li Y., Xi Z., Zan Y.F., Li P.Z., Zhuo W.B. Experimental Evaluation of Safety Performance of Emergency Passive Residual Heat Removal System in HPR1000. Nucl. Eng. Des. 2017. **318**
5. Jouhara H., Chauhan A., Nannou T., Almahmoud S., Delpech B., Wrobel L.C. Heat Pipe Based Systems-Advances and Applications. Energy. 2017. **128**:729-754.
6. Nazarimanesh M., Yousefi T., Ashjaee M. Experimental Investigation on the Effect of Nanofluid on the Thermal Performance of Symmetric Sintered U Shaped Heat Pipe. Heat Mass Transf. 2016. **52**(7):1255-1264.
7. Wang Y., Wang J., He X., Duan J. Experimental Investigation of the Thermal Performance of a Heat Sink with U-shaped Heat Pipes. Appl. Therm. Eng. 2021. **186**:116387.
8. Hakim I.I., Sukarno R., Putra N. Utilization of U-shaped Finned Heat Pipe Heat Exchanger in Energy-efficient HVAC Systems. Therm. Sci. Eng. Prog. 2021.:100984.
9. Luo Y., Wu G., Bai P., Wang H., Cai R., Tang Y., et al. Modeling and Experimental Analysis of U-shaped Segmented Unidirectional Heat Pipe Array Cogeneration Unit. Case Stud. Therm. Eng. 2021.:101074.
10. Ye C., Zheng M.G., Wang M.L., Zhang R.H., Xiong Z.Q. The Design and Simulation of a New Spent Fuel Pool Passive Cooling System. Ann. Nucl. Energy. 2013. **58**:124-131.
11. Fu W., Li X., Wu X., Zhang Z. Investigation of a Long Term Passive Cooling System Using Two-phase Thermosyphon Loops for the Nuclear Reactor Spent Fuel Pool. Ann. Nucl. Energy. 2015. **85**:346-356.
12. Xiong Z., Wang M., Gu H., Ye C. Experimental Study on Heat Pipe Heat Removal Capacity for Passive Cooling of Spent Fuel Pool. Ann. Nucl. Energy. 2015. **83**:258-263.
13. Choi J., Lim C., Kim H. Fork-end Heat Pipe for Passive Air Cooling of Spent Nuclear Fuel Pool. Nucl. Eng. Des. 2021. **374**:111081.
14. Kusuma M.H., Putra N., Antariksawan A.R.,

Koestoer R.A., Widodo S., Ismarwanti S., et al. Passive Cooling System in a Nuclear Spent Fuel Pool Using a Vertical Straight Wickless-heat Pipe. Int. J. Therm. Sci. 2018. **126**:162-171.

15. Kusuma M.H., Putra N., Antariksawan A.R., Imawan F.A. Investigation of the Thermal Performance of a Vertical Two-phase Closed Thermosyphon as a Passive Cooling System for a Nuclear Reactor Spent Fuel Storage Pool. Nucl. Eng. Technol. 2017. **49**(3):476-483.
16. Kusuma M.H., Antariksawan A.R., Ismarwanti S., Juarsa M., Haryanto D., Widodo S., et al. Preliminary Experiment of U-Shaped Heat Pipe as Passive Cooling System in High Temperature Gas-Cooled Reactor Cooling Tank. in: *Journal of Physics: Conference Series*. 2019. p. 22055.
17. Gedik E. Experimental Investigation of the Thermal Performance of a Two-phase Closed Thermosyphon at Different Operating Conditions. Energy Build. 2016. **127**:1096-1107.
18. Sözen A., Menlik T., Gürü M., Boran K., Kılıç F., Aktaş M., et al. A Comparative Investigation on the Effect of Fly-ash and Alumina Nanofluids on the Thermal Performance of Two-phase Closed Thermo-syphon Heat Pipes. Appl. Therm. Eng. 2016. **96**:330-337.