Experimental Investigation of Heat Transfer on Vertical Two-Phased Closed Thermosyphon

M. Hadi Kusuma, Nandy Putra, Anhar Riza Antariksawan, Ficky Augusta Imawan

Abstract—Heat pipe is considered to be applied as a passive system to remove residual heat that generated from reactor core when incident occur or from spent fuel storage pool. The objectives are to characterized the heat transfer phenomena, performance of heat pipe, and as a model for large heat pipe will be applied as passive cooling system on nuclear spent fuel pool storage. In this experimental wickless heat pipe or two-phase closed thermosyphon (TPCT) is used. Variation of heat flux are 611.24 Watt/m^2 - 3291.29 Watt/m^2. Variation of filling ratio are 45 - 70%. Variation of initial pressure are -62 to -74 cm Hg. Demineralized water is used as working fluid in the TPCT. The results showed that increasing of heat load leads to an increase of evaporation of the working fluid. The optimum filling ratio obtained for 60% of TPCT evaporator volume, and initial pressure variation gave different TPCT wall temperature characteristic. TPCT showed best performance with 60% filling ratio and can be consider to be applied as passive residual heat removal system or passive cooling system on spent fuel storage pool.

Keywords—Two-phase closed thermo syphon, heat pipe, passive cooling, spent fuel storage pool.

I. INTRODUCTION

IN nuclear power plant, spent fuel which still have high radioactivity and decay heat transferred from reactor core and stored in cooling water pool called spent fuel pool storage for certain period. It must be done to avoid nuclear radioactive released to the environment. The water that submerged the spent fuel is very important to protect the radiation release to the environment, cooling down the spent fuel and these will trap all radionuclide gaseous if spent fuel leakage occurs [1].

Cooling system on many nuclear power reactor are dependent on active safety system. Its mean that all driven source of cooling system is given from electrical source. Furthermore if the active cooling system doesn't work due to station blackout (SBO), there is only temporary cooling backup that only withstand for few days, 14 days for AP1000 spent fuel pool reactor [2]. Then, if temporary passive cooling water runs out, and the active cooling system is still not running, the water inside the pool will not be circulated and then water temperature increase. It will cause of increasing of

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water temperature and occur on water evaporation process. The evaporation process that continues to be causes of loss of pool coolant in the spent fuel pool storage. Excess heat generated that could not be cooled will cause of fuel melt. It happened in Fukushima Daiichi Nuclear accident [2].

Fukushima Daiichi nuclear power station accident became an important moment to the design development of current nuclear safety system. This accident showed that the passive system become important things to be applied in nuclear power plant. Special attention was devoted to the design of passive residual heat removal system. Residual heat produced in the reactor core when an incident occurs (such as SBO or loss of coolant accident) should be removed to keep the reactor system safe and no radioactive release to environment. Confinement integrity (containment) should be maintained in the event of a beyond design basic accident (BDBAs) to prevent radiation release to the environment [3]-[5].

A method considered removing that residual heat was using heat pipe. Heat pipe is a technology that uses a certain size pipe, containing a certain liquid as working fluid to carry heat from the evaporator to the condenser. Heat pipe is a technology with high heat transfer capability for working in two phases and in its operation does not require any additional external driving source (passive system). Heat pipe is naturally circulated condensate from the condenser to the evaporator. Heat pipe works well and naturally by utilizing capillary pumping system of porous media (or without porous media, thermo syphon). The performance of the heat pipe was affected by selection of wick material and working fluid and also geometry of heat pipe itself. Heat pipe can be used in cases where the heat source and heat release is intended to help separate or spread of heat conduction process in the field. The amount of heat per unit time that transferred by the heat pipe will be greater because of utilizing the latent heat of the working fluid [6]-[12].

Research about two-phase closed thermo syphon (TPCT) have conducted experimental studies in the field of nuclear reactors. Heat pipe which is using gravitation as its working fluid driving force and wickless called TPCT [13]. TPCT has been proven as a passive heat exchanger with a very high thermal conductivity [14]. TPCT has been used for many applications such as de-icing of roadways [15], as heat pipe heat exchanger in power generators [16], water heater [17], and etc. The results obtained show that the loop heat pipe and thermo syphon can be used to dispose of residual heat that generated from a nuclear reactor accident.

Alizadehdakhel et.al studied the effect of filling ratio to the TPCT performance. Filling ratio variation were 30%, 50%,

and 80% from evaporator volume. It was found that the optimum filling ratio was 50% from evaporator volume [15]. Thanapol et.al was doing TPCT experiment with R-134a refrigerant as its working fluid. From the experiment, it was found that the optimum filling ratio was 15% [18]. Noie et.al was doing TPCT experiment to obtain the optimum filling ratio with distilled water as its working fluid and with aspect ratio as variation. The filling ratio varied at 30%, 60%, and 90% from evaporator volume. It was found that with the aspect ratio 7.45, 90% of evaporator volume filling ratio gave lower evaporator temperature than 30%, and 60%. For the aspect ratio 11.8, it was founded that 60% of filling ratio had lower evaporator temperature [14].

From the previous research can be seen that the filling ratio variation interval to obtain the optimum filling ratio still have long range. The experimental method is used to get and analyze the heat transfer phenomena and performance of wickless heat pipe (two-phase closed thermo syphon, TPCT). Variation of heat flux are 611.24 Watt/m^2, 1300.84 Watt/m^2, 2344.65 Watt/m^2, and 3291.29 Watt/m^2. Filling ratio variation was made with closer range. The filling ratio interval in this experiment is 45% to 70% of evaporator's volume with 5% increment. Variation of filling ratio are 45%, 50%, 55%, 60%, 65%, and 70%. The vacuum pressure initiation was also varied in order to find its effect to TPCT performance. Variation of initial pressure are -62 cm Hg, 64 cm Hg, -68 cm Hg, -70 cm Hg, -72 cm Hg, and -74 cm Hg. Demineralized water is used as working fluid on the TPCT. Circulated water inside water jacket with 1 liter/minute of mass flow rate is used as external cooler. TPCT geometry has 1.5 m of length, 0.0254 m of diameter, and same length ratio on evaporator, adiabatic and condenser section. The objective of the research are to get the heat transfer phenomena, performance of heat pipe, and as a model for large heat pipe will be applied as passive cooling on nuclear spent fuel pool storage, due to variation of heat flux, evaporator filling ratio, and initial pressure.

II. THEORY

TPCT is made from a pipe or tube which is closed at both end, and charged certain amount of working fluid inside the pipe. The condenser section of TPCT must be placed upper the evaporator section. On the process, heat will transmitted through evaporator section through pipe wall, heating the working fluid to boiling and or boiling at film region, and then evaporate working fluid. TPCT working fluid absorb the heat and changes it to latent heat [17]. The TPCT working principal is shown in Fig. 1. Working fluid vapor on the evaporator has higher pressure than on the condenser section, and it will cause of working fluid vapor stream to condenser. At the condenser section, the working fluid vapor condensed because of latent heat released to condenser wall. Heat removed by conduction through liquid film which adhere at inside condenser wall and then released to the other media outside TPCT. Then, liquid which adhere at inside condenser wall return to evaporator by gravity force [14], [15], [17]. With the dependency to gravitational force to return the liquid to evaporator section, TPCT will not working if the inclination angle is near to horizontal, or at horizontal position. Factors affecting on thermal performance of TPCT are: working fluid properties, filling ratio, mass flow and temperature of coolant, heat load at the evaporator, pressure inside TPCT, material properties of TPCT, dimension, aspect ratio, length of sections (evaporator, adiabatic, and condenser), and inclination angle of TPCT [17].
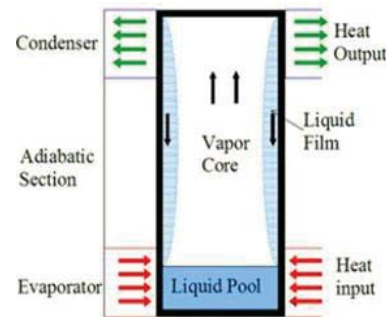

Fig. 1 TPCT working principle [17]

III. METHODOLOGY

A. Experimental Setup

Fig. 2 shows the experimental setup of TPCT that made of pure copper has 1500 mm on length with inner and outer diameters are 25.4 mm and 25.5 mm respectively. The pure Copper has physical properties such as thermal conductivity of 400 W/m-°C, density of 895.4 kg/m3, and specific heat of 380 J/kg-°C. The TPCT is divided into 3 sections: evaporator section with 500 mm length at the bottom of heat pipe, adiabatic section with 500 mm length at middle section, and condenser section with 500 mm length at the top of TPCT section. At evaporator section, heat generated by Ni-chrome wire resistance veiled with ceramic. The heat input is controlled with analog voltage regulator and the electrical current measured by clamp meter. In the condenser section, water jacket is installed in order to absorb heat in condenser and connected to circulating thermostatic bath to have constant temperature of cooling water at inlet section. The temperature and mass flow rate of coolant were also controlled by circulating thermostatic bath. Flow meter with accuracy ± 4% was also used to measure coolant mass flow rate on water jacket. The coolant water temperature as the heat sink is 30°C with 1 liter/minute of coolant velocity.

Variations of heat flux are 611.24 Watt/m^2, 1300.84 Watt/m^2, 2344.65 Watt/m^2, and 3291.29 Watt/m^2. Demineralized water is selected as the TPCT working fluid. TPCT filling ratio was variation on 45%, 50%, 55%, 60%, 65%, and 70% of evaporator volume. Demineralized water vapor went from evaporator to the upper part through the adiabatic heat pipe and re-condensed to the liquid in condensation section. The demineralized water then return to the evaporation section and repeats the circulation. Experiment data recording using national instrument data acquisition system. 12 channel of K type thermocouple with accuracy 0.05°C were placed on TPCT outside wall. 3

thermocouples were placed on condenser outside wall, 2 thermocouples on adiabatic outside wall, 3 thermocouples on evaporator outside wall, 1 thermocouple on coolant inlet, 1 thermocouple on outlet, 1 thermocouple on evaporator isolation wall, and 1 thermocouple on ambient temperature. The positions of thermocouple can be seen at Fig. 3. On the top of TPCT, pressure transducer is place to measure pressure inside, and a line used as vacuum line. TPCT system was insulated with ceramic blanket and glass wool to minimize heat loss from the system. The preheating and vacuum process were done to remove dissolved gas inside TPCT, or in the working fluid.

1. Computer
2. CDAQ 9174
3. NI 9214
4. Circulating thermostatic bath
5. Flow meter
6. Pressure measurement system and vacuum line
7. Heater Element
8. Voltage Regulator AC
9. Clamp meter

Fig. 2 Experimental setup of TPCT

Fig. 3 Thermocouple placing on TPCT outside wall

B. Data Reduction

Performance or efficiency of TPCT is an indicator of TPCT in this experiment. Performance or efficiency is defined as:

$$\eta = \frac{Q_{out}}{Q_{in}} x100\% \tag{1}$$

where Q_{out} is amount of heat that released from condenser, and Q_{in} is amount of heat input at evaporator section. While Q_{out} is defined as follow:

$$Q_{out} = \tilde{v}\rho C_p(T_o - T_i) \tag{2}$$

where $\tilde{v}$ is volumetric flow rate of coolant, ρ is coolant density, C_p is heat specific of coolant, T_o is outlet temperature of coolant, and T_i is inlet temperature of coolant. While Qin is defined as follows:

$$Q_{in} = V.I - q_{loss} \tag{3}$$

where V is voltage, I is electrical current and q_{loss} is the amount of heat loss through the evaporator insulation wall, which is calculated by newton's law of cooling.

$$q_{loss} = \bar{h}A_s(T_s - T_a) \tag{4}$$

where A_s is surface area of insulation wall on evaporator section. T_s is insulation temperature on evaporator section, T_a is ambient temperature, and $\bar{h}$ is heat transfer coefficient that obtained by:

$$\bar{h} = \frac{\overline{Nu_L}}{L}k \tag{5}$$

where L is height the insulation of evaporator, k is thermal conductivity of ambient air, and $\overline{Nu_L}$ is nusselt number which in this experiment assumed as a vertical plate. So, $\overline{Nu_L}$ can be obtained by Churchill and Chu equation.

$$\overline{Nu_L} = \left(0,825 + \frac{0,387Ra_L^{\frac{1}{6}}}{\left[1+\{\frac{0,492}{Pr}\}^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right)^2 \tag{6}$$

And thermal resistance is calculated by using equation:

$$R_{eff} = \frac{T_e - T_c}{Q_{in}} \tag{7}$$

where T_e is average wall temperature of evaporator, and T_c is average wall temperature of condenser.

IV. RESULTS AND DISCUSSION

A. Effect of Filling Ratio on TPCT Performance

The effect of filling ratio and heat load variation can be seen in Fig. 4.

Fig. 4 Performance characteristic of TPCT due to filling ratio and Qin variation

TPCT performance was calculated using comparison both heat released in the condenser and heat load into the evaporator. It can be seen that optimum filling ratio was 60% of evaporator volume of TPCT. TPCT has good performance when 60% of working fluid filling ratio used on the evaporator volume. For the filling ratio below and upper 60% of evaporator volume, the performance was getting lower.

B. Thermal Resistance of TPCT with Variation of Filling Ratio

In Fig. 5, thermal resistance of TPCT with filling ratio variation from 45% to 70% at various heat load from 48.75 Watt to 262.5 Watt. The results showed that thermal resistance at 48.75 Watt for filling ratio 45% to 70% was higher if compared with higher heat load. Thermal resistance for various filling ratio was decrease with increase of heat load.
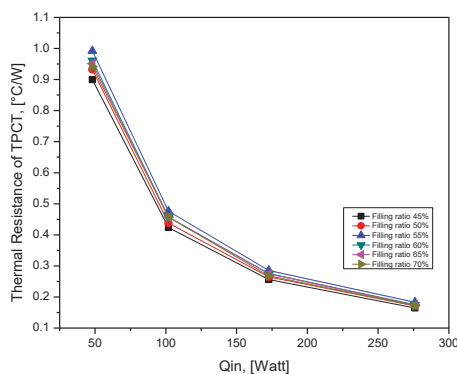
Fig. 5 Thermal resistance of TPCT on various filling ratio and heat load at initial pressure -62 cm Hg

It was found that the thermal resistance of TPCT was getting smaller if the heat load increased. This might be happened because smaller heat load given to evaporator resulted smaller vapor transported to the condenser. The condenser wall temperature was relatively smaller and the evaporator temperature was a little above the saturation temperature and caused higher thermal resistance on TPCT.
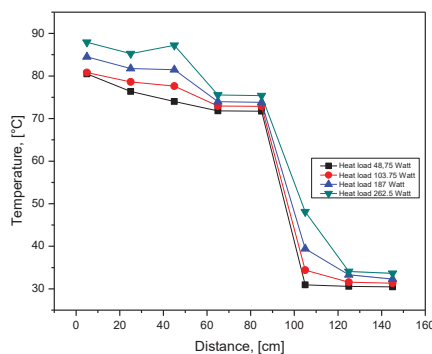
Fig. 6 TPCT temperature distribution for Qin variation at filling ratio 60% and initial pressure -62 cm Hg

When higher heat load given to evaporator, the amount of vapor that transported to condenser and return to evaporator

has more quantities than smaller heat load and caused the condenser temperature relatively higher. Increasing of working fluid temperature and saturation temperature cause of higher evaporator wall temperature, also increasing of internal pressure. In Fig. 6, it can be seen that TPCT wall temperature increased with the increasing of heat load at evaporator.

C. TPCT Performance due to Initial Pressure Variation

In Fig. 7, it can be seen that initial pressure at -74 cm Hg caused highest heat released from condenser.
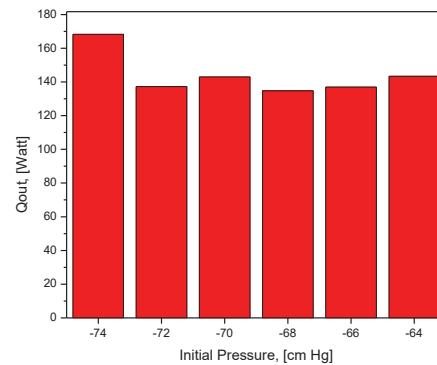

Fig. 7 TPCT performance on evaporator filling ratio of 60% and Qin of 187 Watt with initial pressure variation

The amount of heat released on the condenser was 97.3% of heat load on evaporator. At initial pressure -74 cm Hg, the condenser temperature was the highest from all of pressure initiation variation. It is indicated that TPCT has high performance when it operated with heat load of 187 Watt, evaporator filling ratio of 60%, and initial pressure of -74 cm Hg.

D. Analysis of TPCT Transient Temperature on Initial Pressure Variation

The initial pressure was varied from -62 cm Hg to -74 cm Hg with -2 cm Hg interval. From the experiment, it is founded that TPCT has the best performance when it operated with heat load of 187 Watt, evaporator filling ratio of 60%, and initial pressure of -74 cm Hg. In Figs. 8 and 9, it can be seen that the transient temperature distribution of TPCT when it operated with heat load of 187 Watt, evaporator filling ratio of 60%, and two initial pressure of -74 cm Hg and -70 cm Hg.

In Figs. 8 and 9, it can be seen that the evaporator temperature was drop suddenly followed by the increasing of condenser temperature. This phenomenon caused by released heat to the condenser wall. At initial pressure of -74 cm Hg, the coolant temperature formed up and down profile pattern. The coolant temperature rising up when the condenser wall temperature was rising, and it will decrease when the condenser temperature decrease. This phenomenon showed that the condensate flowing back to evaporator periodically. This phenomenon was called zigzag phenomena [19].
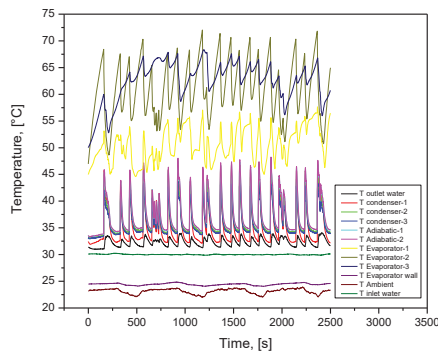
Fig. 8 Transient temperature distribution on evaporator filling ratio of 60%, Qin of 187 Watt and initial pressure of -74 cm Hg
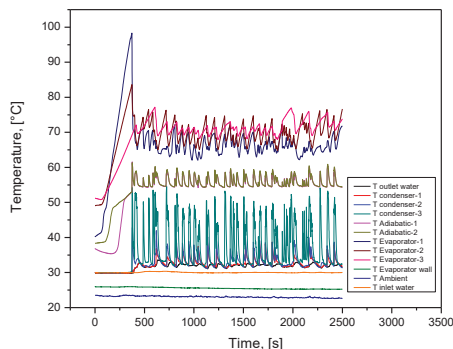

Fig. 9 Transient temperature distribution on evaporator filling ratio of 60%, Qin of 187 Watt and initial pressure of -70 cm Hg

When TPCT initial pressure was decreased, the evaporator temperature became relatively higher because of saturation temperature of liquid was became higher with the decreasing of TPCT pressure inside. Zigzag phenomenon when initial pressure decrease has smaller period and cause of the condensate return to the evaporator by gravity force. On lower initial pressure, water vapor will condense faster than on higher initial pressure because of shorter vapor period to be condense and then return to the evaporator. Saturation temperature of working fluid increased due to increased TPCT pressure inside. The overshoot followed by zigzag phenomenon also happened for initial pressure initiation of -72, -68, -66, -64, and -62 cm Hg. When heat loading to the evaporator, the evaporator temperature rises continuously, and while condenser temperature was still near to the coolant temperature. It was found that there is overshoot phenomena on evaporator when heat is applied. The overshoot phenomena happened at thermocouple evaporator 1 and 2 because of inner wall of thermocouple 1 and 2 directly contact to water vapor. Evaporator temperature 1 and 2 were increase rapidly. No overshoot phenomena on evaporator temperature 3 because of thermocouple of evaporator 3 was located on wall that contact with the liquid pool. Heat released from heater transferred to the liquid pool until the liquid reaches its saturation temperature. After the overshoot phenomena was happened, it was followed by zigzag temperature profile.

Thermal resistance became lower when the different both evaporator and condenser temperature also lower. It is also founded that thermal resistance of TPCT became lower when it operated on higher initial pressure. It is can be concluded that TPCT has best performance on lowest thermal resistance.

V. CONCLUSION

1. TPCT has the best performance when it operated with heat load of 187 Watt, evaporator filling ratio of 60%, and initial pressure of -74 cm Hg.
2. Heat pipe has good performance to be applied as passive residual heat removal system and consider to be used as passive cooling system on spent fuel storage pool.

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