

Effect of graphenenano-fluid on heat pipe thermal performance for passive heat removal in nuclear spent fuel storage pool

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Abstract. After Fukushima Dai-ichi nuclear power reactor accident, spent fuel in spent fuel storage pool (SFSP) became an important thing to pay attention to, due to its decay heat release. If station blackout occurred, the active system for SFSP cooling system will experience malfunction to remove the product of decay heat. To keep spent fuel safe, heat pipe as passive cooling system device can be used to remove spent fuel decay heat even if the active cooling system failed. Heat pipe with 6 m on length will be proposed as a passive cooling system in SFSP. For that, it is necessary to analyze the effect of Graphene nano-fluid as heat pipe working fluid. The objective of this research is to know the effect on Graphene nano-fluid to enhance the heat pipe thermal performance and to know the heat transfer phenomena inside the heat pipe based on Graphene nano-fluid. Graphene nano-fluid with 1% weight concentration was used as working fluid with filling ratio of 80%. The experimental investigation is conducted with varying the evaporator heat load of 1000, 1500, 2000, and 2500 W. Water as coolant flows in the condenser with a constant volumetric flow rate of 8 L/min. The experiment results show that there was an overshoot, zigzag and stable phenomena inside the heat pipe. The thermal resistance of heat pipe is obtained at 0.015 °C/W. The use of Graphene nano-fluid as working fluid can enhance the heat pipe thermal performance significantly and can be used as an alternative working fluid in heat pipe for the passive cooling system in SFSP of nuclear power plant.

1. Introduction

The Fukushima Dai-ichi nuclear reactor accident becomes a valuable lesson for the safety design of nuclear power plants in the world. The safety concept that is fully dependent on the active cooling system is being abandoned so that when the similar accident occurred, it can be addressed with a passive safety system [1]. The passive cooling system as an additional safety system is utilized when the accident began to be noticed in the nuclear field. Passive cooling systems are expected to operate when all reactor systems undergo station blackout. One of the passive cooling systems that can be applied as an additional safety system in spent fuel storage pool is the use of heat pipe technology.

The heat pipe is a closed-loop heat exchanger that works by utilizing the natural circulation of the phase change of the working fluid. The heat pipe is a technology that naturally absorbs heat in the



evaporator part and discharges heat in the condenser. The steam generated in the evaporator section will rise towards the condenser section. The heat from the steam in the condenser will be absorbed by the cooling system in the condenser until it becomes condensate. The condensate will fall back to the evaporator by utilizing the capillary force or the gravitational force [2]. The heat pipe is a highly efficient thermal conductor for use in applications requiring high heat flux discharges, in very limited airflow environments, non-uniform heat generation, and weight or space limitation[3].

Research on the use of heat pipe as a passive cooling system in the nuclear field has been largely done by previous researchers. Sabharwall et al. conducted research on the performance of heat transfer in a two phase thermosyphon which will be proposed as a residual heat result in advanced nuclear reactors. The thermosyphon used are made of alkali metals. The results of the analysis show that thermosyphon has a good heat transfer capability and can be recommended as a heat exchanger that works passively in nuclear reactors[4]. Jeong et al. perform simulations using CFDs in order to determine the thermal performance of heat pipes as a passive cooling system to remove residual heat on the nuclear reactor core during an accident. The simulated results show that the heat pipe can be used to reduce the temperature at the reactor core from 290°C to 195.1°C [5]. Mochizuki et al. have studied the cooling system using a heat pipe loop for a decay heat dissipation system on a BWR reactor core. The evaporator part of the heat pipe loop is located near the reactor core, and the condenser section with fin is located outside the containment. The released heat in the condenser is then cooled by the outside air. The results show that the heat pipe has a small total thermal resistance and is able to heat the resulting decay to keep the reactor core safe [6].

We have also conducted experiments and simulations using the RELAP5/MOD3.2 code on the use of wickless-heat pipes as a passive cooling system in the spent fuel storage pool. The heat pipe used is made of copper using demineralized water as the working fluid. Our results show that a straight wickless-heat pipe has excellent thermal performance and can be used as an alternative passive cooling technology to remove residual decay heat generated in the spent fuel storage pool when the blackout station occurs[7-9].

The selection of the working fluid is an important aspect of the heat pipe design. One of the alternatives for a heat pipe's working fluid is Graphenenano-fluid. Graphene is a flat monolayer of carbon atoms tightly packed into a two-dimensional honeycomb lattice. The particular 2D structure leads to high electric and thermal conductivity providing easy movement of the charge carriers[10]. Graphenenano-fluid has been studied in the form of nano-fluid to use the excellent thermal conductivity of grapheme while maintaining the stability of the nanoparticles in the suspensions. The use of Graphenenano-particles in pool boiling could enhance boiling heat transfer and critical heat flux[11]. Researches on the use of nano-fluids as working fluids in heat pipe have been done by many researchers. Nandy Putra et al. has conducted experiments using Al_2O_3 nano-fluid as a working fluid in a heat pipe with a capillary axis of screen mesh. The experimental results show the use of nano fluid as a working fluid improves the thermal performance of heat pipe[12, 13]. Asirvatham et al. have conducted experiments using graphene-acetone nano-fluid as a working fluid on a thermosyphon to determine the performance of heat transfer. Their results showed that the overall thermal resistance of the heat pipe was reduced by 70.3% in comparison to the acetone under the same condition. At the same time, the heat transfer coefficient in the evaporator section was increased by 61.25%[14].

From several previous studies, it can be seen that the selection of working fluid is important to improve the thermal performance of the heat pipe. Graphenenano-fluid is expected to improve thermal performance for several reasons including high stability for a long time span and high thermal conductivity. The objective of this research is to know the effect on Graphenenano-fluid to enhance the heat pipe thermal performance and to know the heat transfer phenomena inside heat pipe based on Graphenenano-fluid. Graphenenano-fluid with 1% weight concentration was used as working fluid with filling ratio of 80%. The experimental investigation is conducted with varying the evaporator heat load of 1000, 1500, 2000, and 2500 W. Water as coolant flows in the condenser with a constant volumetric flow rate of 8 L/min.

2. Methodology

2.1. Experimental setup

In figure 1, it is shown the experimental setup used in this study. The heat pipe is made of copper with a length of 6 m, the inner diameter of 0.1016 m and outside diameter of 0.1031 m. The heat pipe consists of 3 sections with an aspect ratio of 2 m: evaporator, adiabatic, and the condenser section. In the evaporator section, 8 heater belts as a heat load source are installed with a maximum heat load capacity of 2800 W. The condenser section is installed in a water jacket with the coolant flow rate of 8 L/min. It is circulated from the thermostatic bath to the condenser. The flow rate is controlled by 2 flowmeters with an accuracy of $\pm 4\%$. Heat loads with variations of 1000, 1500, 2000 and 2500 W are supplied to the heater in the evaporator section that is controlled by the voltage regulator. The heat pipe is filled with graphene nano-fluid with a weight concentration of 1% as the working fluid. Before the working fluid is inserted, the heat pipe was made vacuum first by using the vacuum pump. Once the pressure inside the heat pipe reaches a pressure of -74 cm Hg, the working fluid is inserted with filling ratio of 80%. Filling ratio is the volume ratio of the working fluid that is charged to the evaporator volume. To keep the safety of heat pipe system, a pressure relief valve was installed at the top of the condenser section to control the operating pressure of the steam. Temperature measurements, which are used in this experiment, are the National Instruments data acquisition system of cDAQ 9174. Fourteen channels of K type thermocouples are installed on the system: 3 on the condenser's outside wall, 3 on the adiabatic's outside wall, 3 on the evaporator's outside wall, 1 on the cooling inlet, 1 on the cooling outlet, 2 on the insulation wall and 1 channel for the ambient temperature. To reduce heat loss during the experiment, the heat pipe is insulated with glass wool and then covered with aluminum sheet. The position of the thermocouple, which is used to measure the wall temperature of the heat pipe is shown in figure 2.

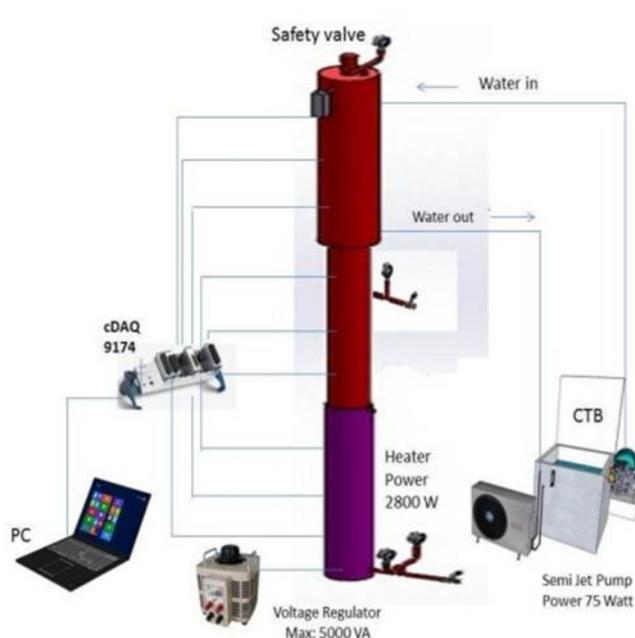


Figure 1. Experimental setup.

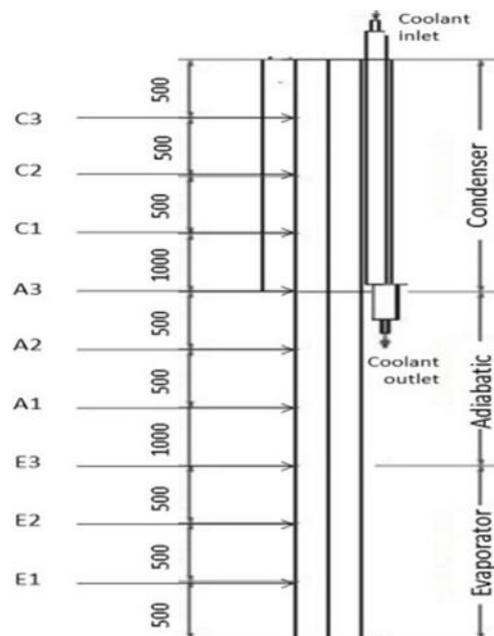


Figure 2. Placement of thermocouples.

2.2. Preparation of Graphene nano fluid

The preparation method of the Graphene nano fluid working fluid is shown in figure 3. To make a working fluid with a concentration of 1% weight Graphene nanoparticles weighed by using a digital

scale of 10 gr, the basic fluid used for mixing is demineralized water with a volume of 990ml. The Graphenenano particles and demineralized water weremixed in the ultrasonic processor for 4 hours of sonification process.

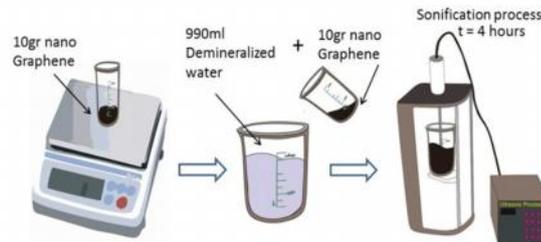


Figure 3. Preparation process of Graphenenano-fluid.

3. Result and discussion

3.1. Transient temperature distribution

The transient temperature as the result of an experiment with filling ratio of 80%, volumetric cooling rate of 8 L/min with varying the evaporator heat load of 1000, 1500, 2000, and 2500 W can be seen in figure 4. When heat load was given to the evaporator at 1000 W, the evaporator temperature 3 (Te-3) was increased drastically, while at evaporator temperature 1 (Te-1) and evaporator temperature 2 (Te-2) was also increased but not as high as in Te-3. This happened because the evaporator wall 3 received the heat coming from evaporator wall 1 and 2 so that Te-3 has a higher temperature. In this condition, the vapor from the Graphenenano-fluid remains largely in the evaporator and has not risen entirely to the condenser. This situation also occurred in the adiabatic and condenser section. The phenomenon in this state is called the overshoot phenomenon.

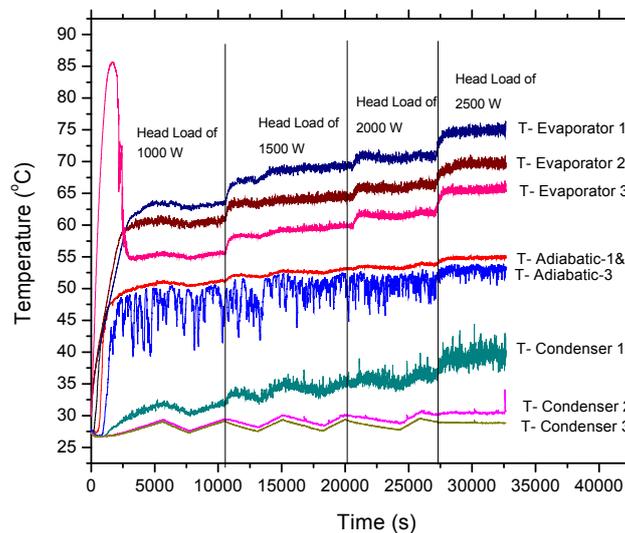


Figure 4. Transient temperature at filling ratio 80% and cooling flow rate 8 Liter/min.

After condensation takes place in the condenser, condensate having a greater density than the steam will descend through the gravitational wall of the heat pipe. The condensate passes through the adiabatic wall to the evaporator. From the figure, it can be seen that the temperature of evaporator wall

3 has decreased previously because condensate was passed foremost compared to the evaporator wall 2 and 1. In this situation zig-zag phenomenon began, where the steam and condensate circulation still has not happened smoothly in the heat pipe.

Zig-zag state continued until there was a more smooth circulation state. This state is called stable phenomenon. The natural circulation is already happening well in the stable phenomenon. The vapor in the evaporator rised to the condenser and the condensate that went down to the evaporator flows in a balanced and continuous way.

These phenomena occur similarly in the heat load given of 1500, 2000, and 2500 W. The experimental results showed that the higher heat load given will increase the evaporator temperature. This happened because the greater the heat load is given to the evaporator will increase the boiling and evaporation process in the working fluid. The boiling and evaporating process on the greater heat load will increase the temperature of each section of the heat pipe to be higher than the smaller heat loads.

3.2. Steady state temperature distribution

Figure 5 shows the steady state temperature distribution on the heat pipe wall at evaporator heat load of 1000, 1500, 2000, and 2500 W.

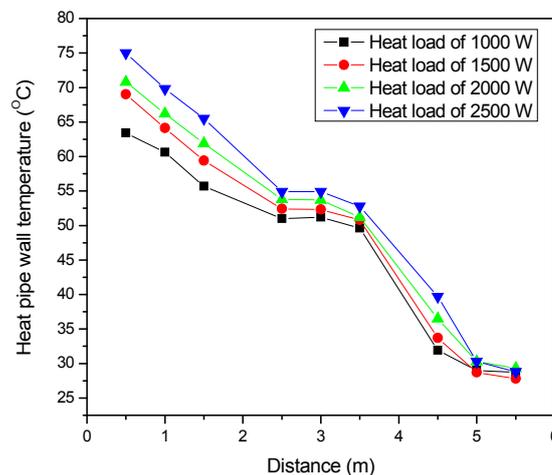


Figure 5. Steadystate temperature distribution at evaporator heat load of 1000, 1500, 2000, and 2500 W.

It can be seen from figure 5 that the steady state temperature of the heat pipe wall increases with the increase of evaporator heat load. The increasing heat load will increase the temperature of the evaporator wall, resulting in more heat transfer from the evaporator wall to the graphenenano-fluid in the evaporator pool, causing faster boiling and vaporizing graphenenano-fluid, increasing the working fluid saturation temperature, generating more steam in the evaporator pool which will be brought to the condenser, and raising the latent heat transferred by the condenser to the cooling system.

3.3. Thermal performance

Thermal resistance is one of the parameters for evaluating heat pipe thermal performance. This thermal resistance is affected by the temperature difference of the evaporator and condenser sections, and the amount of heat load given to the evaporator section. It is generally known that thermal resistance tends to decrease with every increase in the heat load given in the evaporator section. The lower of the thermal resistance obtained, the better the heat pipe thermal performance. The thermal resistance obtained in the experiment is shown in figure 6.

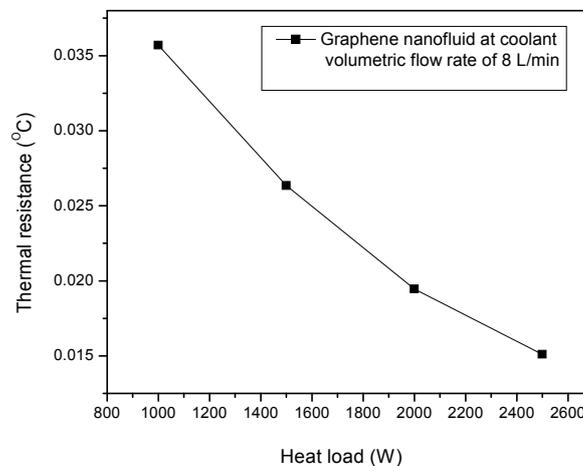


Figure 6. Thermal resistance of the wickless-heat pipe.

Figure 6 shows that the lowest thermal resistance obtained is $0.015^{\circ}\text{C}/\text{W}$. In the previous investigation of wickless-heat pipe using demineralized water as working fluid, it is obtained that the thermal resistance of wickless-heat pipe is $0.0163^{\circ}\text{C}/\text{W}$ for large geometry and $0.22^{\circ}\text{C}/\text{W}$ for small geometry.

From the experiment results, it can be seen that the use of Graphenenano-fluid as a working fluid can improve the thermal performance of heat pipe. This is because the addition of Graphenenano leads to acollision with large bubbles and it creates a number of smaller bubbles, which means Graphenenano-fluid increases the thermal conductivity and convective heat transfer coefficient of working fluid in the wickless-heat pipe. The collision of nanoparticles with large vapors results in more number of smaller vapor bubbles. Similarly, the Brownian motion of nanoparticles increases the convection effects at the evaporator and condenser. This is the reason for lower thermal resistance with nano-fluid[11].

4. Conclusion

The experimental investigation on the effect of Graphenenano-fluid on heat pipe thermal performance for passive heat removal in nuclear spent fuel storage pool has been done. The results obtained are as follows:

1. The use of working fluid is very influential on thermal performance in heat pipes. It can be concluded that Graphenenano-fluid enhanced the heat pipe thermal performance, with the thermal resistance values obtained at $0.015^{\circ}\text{C}/\text{W}$. This value is smaller when compared with previous research results that used demineralized water as a working fluid
2. The temperature distribution phenomena shows the phenomena of overshoot, zigzag, and stable, as also found in our previous investigation.

5. Acknowledgements

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