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The simulation of heat transfers and flow characterization on wickless loop heat pipe

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Abstract

The severe accident at a nuclear power plant in Japan became an important lesson for aggressively involving passive cooling systems to improve safety. One of the passive cooling system technologies with excellent heat dissipation capabilities and great potential for a passive cooling system is the heat pipe, including the loop heat pipe (LHP). This research aims to study the phenomenon of heat transfer and flow characterization in the wickless loop heat pipe. The method used in this research is a simulation using the software Computational Fluid Dynamics, Fluent. This simulation study gives the effect of filling ratio and heat load in the evaporator at LHP. Demineralized water as the working fluid filled in the LHP was varied at the filling ratio values of 40%, 60%, and 80%. The heat load in the hot water temperature absorbed by the evaporator was varied by 45°C, 55°C, and 65°C. Cooling air as a heat taker in the condenser is given at a fixed temperature value of 25oC. The simulation results obtained indicate that the heat transfer in the wickless LHP has a temperature distribution profile in the LHP, which is almost uniform for every variation of filling ratio and heat load. Compared to filling ratios of 40% and 60%, at 80% filling ratios, the optimal time for the formation of natural circulation flow is achieved when the LHP is given a heat load of 55°C in the evaporator. This simulation shows that the LHP without wick does not produce an excellent natural circulation flow as expected in general natural circulation in the LHP. The results of this simulation can be used as the knowledge that the LHP that will be designed for experimental purposes must be using a wick as a vapor regulator to rise to the condenser only through one adiabatic side.

Keywords: Computational fluid dynamic, filling ratio, heat load, loop heat pipe, passive cooling system.

1. Introduction

The Nuclear Power Plant (NPP) accident at Fukushima Daiichi due to a station blackout became a valuable lesson for nuclear reactor safety design. The accident shows that a passive and inherent safety system (passive system) is needed in the reactor design process. In nuclear reactors, passive systems utilize cooling with natural circulation, the standard for advanced reactor designs [1].

This passive system is specifically dedicated to keeping the reactor system safe under normal operating conditions and in events that go beyond the basic design accident. The passive system concept has already been applied to generation III+ reactors and the design of generation IV reactors for the new generation reactors.

Various designs of small and medium power nuclear power plants (SMR, Small and Modular Reactor) have been developed, one of which is the NuScale reactor. NuScale is a pressurized water reactor (PWR) generation III+ type nuclear power plant with a passive and inherent safety system. The NuScale reactor is one of the alternative power plants that have the potential to be used in Indonesia to meet small amounts of electrical energy [2]. To improve the safety aspects of regular operation and for NuScale to operate more economically, an additional passive cooling system technology is needed in the pool water bath that immerses the reactor. One technology that can be used for this purpose is to use heat pipes.

The heat pipe is a heat transfer device consisting of an evaporator section, a condenser section, and an adiabatic section. Heat pipes work through a phase change process in a closed container [3]. As a heat dissipater in natural circulation, the heat pipe has been widely studied because of its enormous heat transferability.

Heat pipe model with straight geometry and large scale has been studied through simulation and experimental. This heat pipe is a passive heat exchanger without an external power source. Experimental and simulation results show that the heat pipe has excellent performance as a heat sink and can be used as a coolant in used nuclear fuel storage ponds [4, 5]. We have used nanofluid as a working fluid in the heat pipe, and the experimental results show that nanofluid can improve the thermal performance of the heat pipe [6]. Many researchers have done mathematical and CFD modeling to study the details of two-phase flow and heat transfer processes by using volume model [7]. The results of the CFD simulation are used to validate experimental data and show phenomena that are by the experiments [8]. CFD modeling an axis less heat pipe to simulate two-phase flow to study heat transfer phenomena using refrigerants R134a and R404a. The simulation results show that boiling in the evaporator section of the pond and condensation in the condenser section are clearly shown, and the temperature profiles are similar between simulation and experimental. [9]. Develop a three-dimensional CFD model of a wickless heat pipe and predict water boiling at low power. The simulation results show multiphase flow visualization and the relationship between power output and boiling characteristics [10].

From research on heat pipes with CFD modeling that previous researchers have done, many still use heat pipes with straight geometries as passive cooling systems for heat dissipation. Heat pipe with rectangular geometry or loop heat pipe (LHP) was chosen as a passive cooling system technology in the pool that immerses the reactor because it has a simple shape, works without needing an external drive source, and the shape can be adjusted to the NuScale geometry.

This study investigates the phenomenon of heat transfer and visualization of two-phase flow in wickless LHP. The method used in this research is to simulate using fluent software. In the simulation, working fluid in water is used with a filling ratio of 40%, 60%, and 80%, respectively. In the evaporator section, the heat load given to the evaporator section is 45°C, 55°C, and 65°C, while in the condenser section, the coolant temperature is set at 25°C.

The simulation results are used to compare experimental results and help analyze the description of LHP as a passive cooling system in NuScale and are used to find out phenomena that are difficult to know experimentally.

2. Simulation method

In general, the CFD simulation process is divided into 3. each is Pre-Processing, Processing, and Post-Processing, as shown in Figure 1.

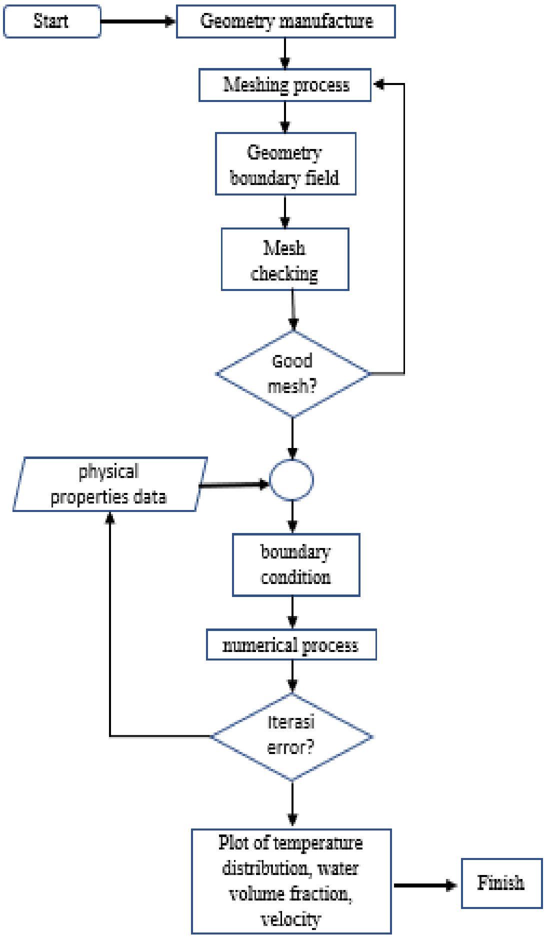


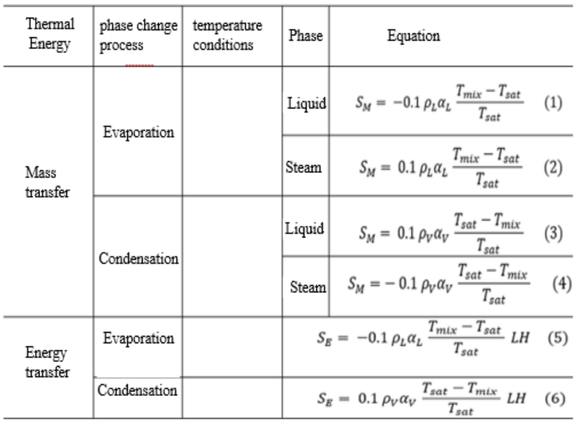
Figure 1. Flowchart of the simulation process

Pre-Processing is the initial stage in CFD simulation, such as creating geometry, meshing, defining the boundary plane on the geometry, and checking the mesh. Processing includes determining boundary conditions, numerical processing, and iteration. Post-Processing includes plots of temperature distribution, volume fraction, and velocity.

The general approach for modeling two-phase flow in the wickless LHP simulation uses water as the working fluid based on the volume of fluid (VOF) method. Multiphase flow has density and viscosity changes at different phase interfaces, thus requiring intensive computational calculations by determining the motion of all phases and defining the interface motion.[8, 9].

To simulate the evaporation and condensation processes in a wickless LHP precisely, UDF (user-defined function) in fluent software is used. This UDF is needed to calculate the mass and heat transfer between the liquid and vapor phases during the evaporation and condensation, precisely the continuity and energy equations.

Tabel 1. Formation of energy and mass equations[11]



Thermal Energy	phase change process	temperature conditions	Phase	Equation
Mass transfer	Evaporation		Liquid	$S_M = -0.1\,\rho_L\alpha_L\,\frac{T_{mix}-T_{sat}}{T_{sat}}$ (1)
			Steam	$S_M = 0.1\,\rho_L\alpha_L\,\frac{T_{mix}-T_{sat}}{T_{sat}}$ (2)
	Condensation		Liquid	$S_M = 0.1\,\rho_V\alpha_V\,\frac{T_{sat}-T_{mix}}{T_{sat}}$ (3)
			Steam	$S_M = -\,0.1\,\rho_V\alpha_V\,\frac{T_{sat}-T_{mix}}{T_{sat}}$ (4)
Energy transfer	Evaporation			$S_E = -0.1\,\rho_L\alpha_L\,\frac{T_{mix}-T_{sat}}{T_{sat}}\,LH$ (5)
	Condensation			$S_E = 0.1\,\rho_V\alpha_V\,\frac{T_{sat}-T_{mix}}{T_{sat}}\,LH$ (6)

The mass and energy transfer equations in Table 1 have been applied to the UDF. The VOF model determined the volume fraction for each phase in the cell. Therefore, two mass sources are needed for mass transfer calculations in the evaporation process. Equation (1) describes the amount of mass removed from the liquid phase, equation (2) describes the amount of mass added to the vapor phase. The procedure for the condensation process is described in equation (3), while equation (4) describes the amount of mass transfer from the vapor phase to the liquid phase. Heat transfer calculation has been determined by multiplying the source mass by the latent heat for evaporation or condensation described in equation (5) and equation (6), respectively [11].

The model used to simulate two-phase flow and heat transfer phenomena in the Wickless LHP is two-dimensional. The schematic of the wickless loop heat pipe used in this study can be seen in Figure 2.

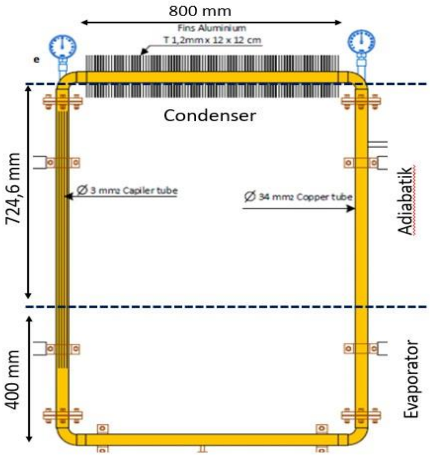
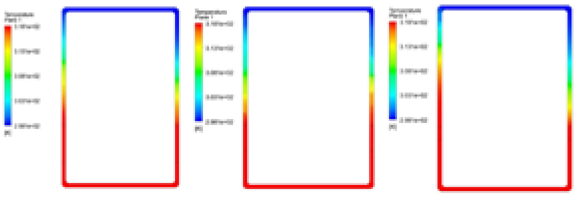


Figure 2. Schematic of Loop Heat Pipe (*courtesy of Mukhsinun Hadi Kusuma*)

The horizontal section of the LHP pipe is 800 mm and the length of the vertical pipe is 1150 mm, made of copper material with a diameter of 25.4 mm. LHP is divided into three parts: the evaporator section has a length of 400 mm, and the adiabatic section has a length of 724.6 mm. The working fluid used in LHP is water. In this simulation, a Pressure-based solver is used. Gravity is activated with a value (-9.81 m2/s) Y-axis. The energy model is activated to include thermal effects in the simulation. The multiphase model selects the Volume of Fluid (VoF) and activates implicit body force [12, 13]. Copper, water liquid, and steam (water vapor) materials are selected from the Fluent database. Water liquid is the primary phase, while water vapor is the secondary phase. The inter-phase surface tension is set as a constant value of 0.072 N/m. Temperature variations on the outer wall of the evaporator are 45°C, 55°C, and 65°C to simulate the heat from the pool according to the experimental matrix. The temperature on the outer wall of the condenser is fixed at 25°C, while the adiabatic section is set as zero flux assuming this section is isolated. The Filling Ratio in this simulation was varied by 40%, 60%, and 80% of the evaporator volume with the initial operating pressure set at 7375 Pa for a saturation temperature condition of 40°C. The iteration process does not wait for convergence because this flow type is transient with a time step accuracy of 0.001 and a total time of 2000.

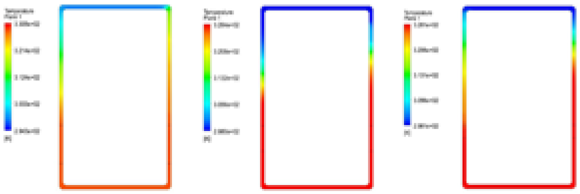
3. Results and Discussion

The simulation results of the fluid temperature contour on the evaporator section are shown in Figures 3 – 5.



a. *Filling Ratio 40%* b.*Filling Ratio 60%* c.*Filling Ratio 80%*

Figure 3. Temperature contour with a heat load of 45°C



a. *Filling Ratio 40%* b. *Filling Ratio 60%* c. *Filling Ratio 80%*

Figure 4. Temperature contour with a heat load of 55°C

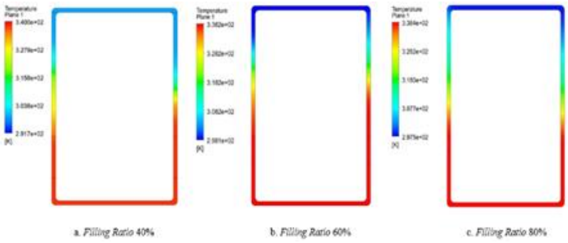


Figure 5. Temperature contour with a heat load of 65°C

The distribution of the temperature profile along the LHP is presented with various filling ratios and three different heaters in the evaporator section of 45°C, 55°C, and 65°C, respectively. In Figure 3-5, it can be seen that the temperature distribution profile is almost uniform for each added temperature increase, the temperature change in the evaporator at the filling ratio of 60% looks lower than the filling ratio of 40%, this is due to the difference in the height of the working fluid in the LHP. The working fluid in the LHP will undergo an evaporation process because of the heat given to the walls of the evaporator, and the steam will flow through the adiabatic section to the condenser section. The steam will be cooled in the condenser section, turned into condensate, and then returned to the evaporator section because of the force of gravity.

Figure 6-8 shows the temperature distribution along with the LHP in the vertical section when natural circulation flows occur.

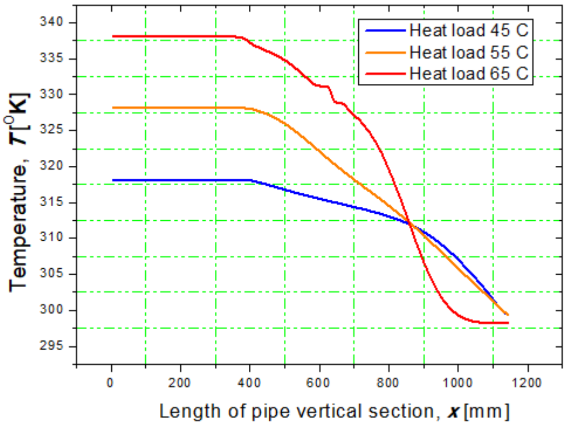


Figure 6. Graph of temperature distribution on variations in heat load and filling ratio of 40%

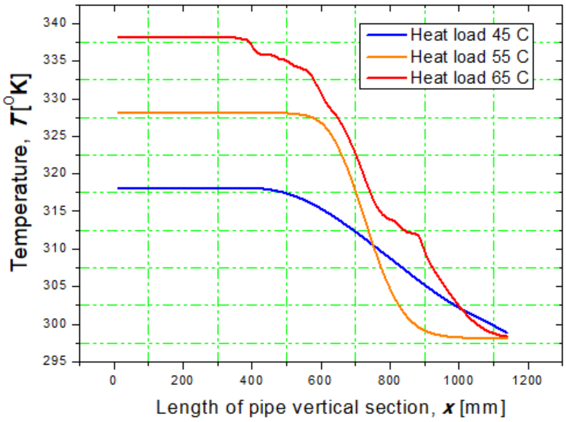


Figure 7. Graph of temperature distribution on variations in heat load and filling ratio of 60%

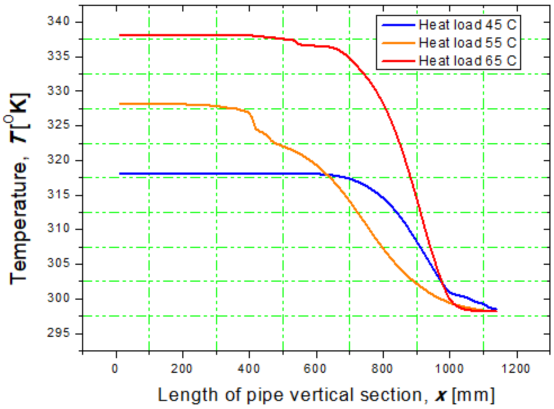


Figure 8. Graph of temperature distribution on variations in heat load and filling ratio of 80%

The length of 0-400 mm, as shown in Figure 6-8, is part of the evaporator. When there is a natural circulation flow, the steam alternately flows to the left and right. The temperature in the evaporator and condenser sections is fixed so that in the adiabatic section, the temperature varies. When there is a natural circulation flow, the stream alternately flows to the left and right.

Figure 9-11 shows the contour of the boiling volume fraction in LHP, and Figure 12-14 shows a graph of the volume fraction characterization with filling ratios of 40%, 60%, and 80%, respectively, the heat load applied to the evaporator is 55°C. and it was cooling in the condenser section of 25°C.

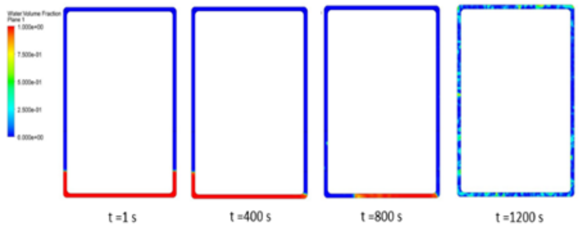


Figure 9. Distribution of volume fraction on filling ratio of 40% and heat load of 55°C

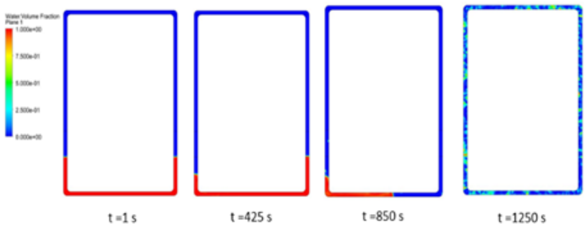


Figure 10. Distribution of volume fraction on filling ratio of 60% and heat load of 55°C

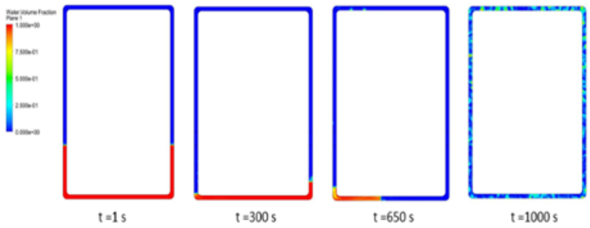


Figure 11. Distribution of volume fraction on filling ratio of 80% and heat load of 55°C

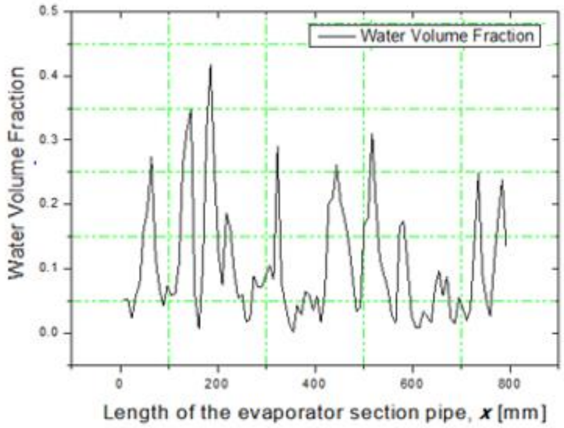


Figure 12. Graph of volume fraction distribution characterization at filling ratio of 40%

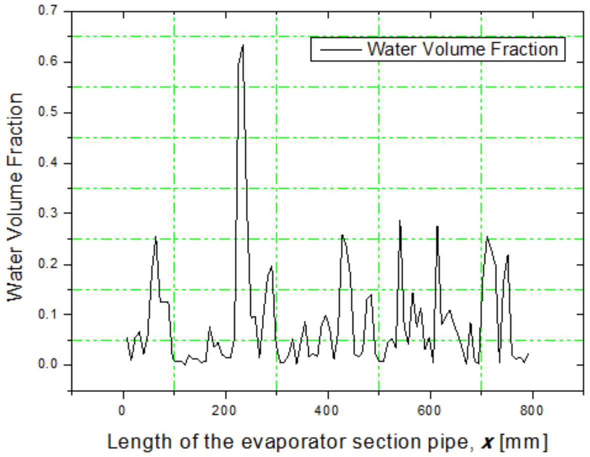


Figure 13. Graph of volume fraction distribution characterization at filling ratio of 60%

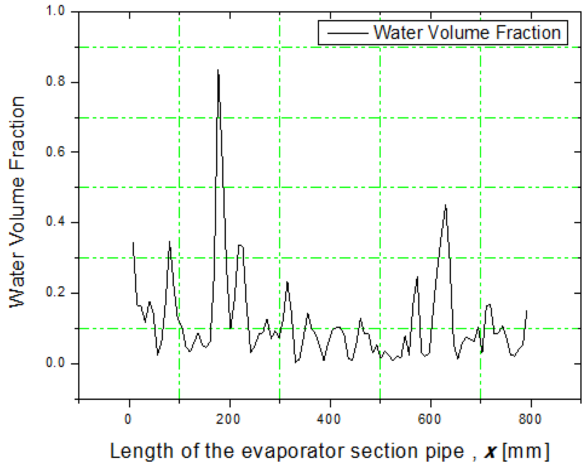


Figure 14. Graph of volume fraction distribution characterization at filling ratio of 80%

In Figures 9-11, the red color represents the presence of working fluid with a water phase (water volume fraction = 1), while the blue color represents the vapor and air phases. At the beginning of the process, the working fluid in the evaporator receives constant heat with a temperature of 55°C, which simulates the heat from boiling steam in the pool. In Figure 9. it can be seen that at t = 1s to t = 800 s, it shows that the initial working fluid reaches the boiling temperature, the working fluid begins to evaporate, and a phase change occurs as seen at t = 1200 s. The same thing also happens in Figures 10 and 11.

The continuous evaporation of the working fluid in the evaporator section results in a decrease in the volume fraction of water and an increase in the volume fraction of steam. When the working fluid evaporates, bubbles are formed and transported to the condenser section. After the steam reaches the condenser wall, the condensation process forms condensation. The condensed water will then fall back into the evaporator. As shown in Figure 12-14, the volume fraction distribution that occurs in the evaporator section of the pipe, the vapor phase is more dominant than the water phase. This phenomenon will continue continuously, which indicates that the natural circulation flow has been formed.

4. Conclusion

The simulation results that have been carried out show that the temperature distribution profile at steady-state conditions that occur in the wickless loop heat pipe looks almost uniform for every variation of filling ratio and heating temperature in the evaporator. In the flow visualization distribution, the evaporation process in the evaporator section, condensation in the condenser section, and phase changes occur in the wickless loop heat pipe for each filling ratio 45°C, 55°C, and 55°C.

In applying a filling ratio of 80%, the optimal time for forming natural circulation flow is obtained at the heat load on the evaporator with a temperature of 55°C, which is 1000 seconds, after the working fluid reaches the saturation temperature. The visualization results show that the movement of steam and condensate flows during natural circulation collides with each other and flows in both directions. The colliding flow patterns can impede the thermal performance of the heat pipe. So that in the LHP prototype research, a wick from the capillary axis is used to make the steam and condensate flow in the same direction.

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