ANALYSIS OF THE EFFECT OF ELEVATION DIFFERENCE BETWEEN HEATER AND COOLER POSITION IN THE FASSIP-01 TEST LOOP USING RELAP5

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ABSTRACT

ANALYSIS OF THE EFFECT OF ELEVATION DIFFERENCE BETWEEN HEATER AND COOLER POSITION IN THE FASSIP-01 TEST LOOP USING RELAP5. To understand the natural circulation phenomena on the passive residual heat removal system (PRHRS), development of a test section describing that phenomena in particular in the one phase condition is required. That test facility is named as FASSIP-01 in form of a vertically closed loop consisting of piping components, one cylinder tank featured with heater elements and one cooler. The heater tank will work as the heat source, and the cooler as the heat sink. This research is intended to support the experimental activity of the FASSIP-01 by conducting a simulation using the RELAP5/SCDAP/Mod3.4. Beside the standard loop configuration, the simulation is also conducted by varying the elevation of heater and cooler position to evaluate the best position resulting in the most optimal natural circulation. The results will be used as the comparison with the later performed experiment. The simulation result shows that for the case where the heater position is at the same level with the cooler position, the temperature distribution of the water after the heater and after the cooler are higher than the other two position. Looking at the natural circulation, that position results in the lowest mass flow. The position with the heater below the cooler will result in the best mass flow. On that position, only an optimization in the heat transfer surface area is needed to increase the heat transfer coefficient and secondary mass flow to remove the heat are needed to obtain more optimal performance of the water circulation caused by the density difference in the FASSIP-01 test loop.

Keywords: elevation difference, heater, cooler, natural circulation, simulation, RELAP5

ABSTRAK

ANALISIS PENGARUH PERBEDAAN KETINGGIAN HEATER DAN COOLER DI UNTAI UJI FASSIP-01 MENGGUNAKAN RELAP5. *Untuk memahami fenomena sirkulasi alam pada sistem passive residual heat removal system (PRHR), perlu dilakukan pembuatan suatu untai uji yang dapat menggambarkan proses sirkulasi alam terutama pada kondisi satu fasa. Untai uji tersebut disebut sebagai FASSIP-01 yang terdiri dari satu untai tertutup vertikal terdiri dari komponen perpipaan, tabung silinder yang dilengkapi dengan heater dan tabung penukar kalor. Tabung silinder dengan heater akan berfungsi sebagai sumber panas fluida, sementara tabung penukar kalor atau cooler sebagai heat sink. Penelitian ini bertujuan untuk mendukung proses eksperiman untai uji FASSIP-01 yang akan dilakukan dengan melakukan simulasi menggunakan program perhitungan RELAP5/SCDAP/Mod3.4. Selain melakukan simulasi dengan konfigurasi standar, juga dilakukan variasi perbedaan ketinggian antara heater dan cooler sehingga dapat dikaji posisi heater dan cooler yang akan menghasilkan sirkulasi alam yang optimal. Hasil simulasi menunjukkan distribusi temperatur antara air yang keluar dari heater dan air yang keluar dari cooler lebih besar pada posisi heater di atas atau sama dengan cooler. Dari sisi pergerakan sirkulasi alam, posisi tersebut menghasilkan laju alir yang paling rendah. Posisi dimana heater lebih rendah daripada cooler akan menghasilkan kinerja sirkulasi alam yang paling baik. Pada posisi tersebut hanya diperlukan optimisasi pada luasan perpindahan panas untuk meningkatkan koefisien perpindahan kalor dan laju alir sisi sekunder sehingga akan mempengaruhi kinerja dari sistem pergerakan air secara sirkulasi alam yang disebabkan oleh perbedaan densitas di dalam untai uji FASSIP-01*

Kata kunci *: perbedaan ketinggian, heater, cooler, sirkulasi alam, simulasi, RELAP5*

INTRODUCTION

The nuclear power plant (NPP) accident at Fukushima Dai-ichi site in 2011 occured in the Boiling Water Reactor (BWR) type, which was caused by external event of earthquake and tsunami. That event led to the station blackout (SBO) accident due to the failure of diesel generator set to supply the required emergency power to the reactor system important for safety [1]. Therefore the weakness of the Fukushima BWR type NPP has been identified. Based on that, one of the reactor design innovation to increase the reactor safety is shown in the several Generation III and III+ reactor design as found in the ESBWR (BWR type) and AP1000 (Pressurized Water Reactor / PWR) reactor design [2]. In general, the passive safety feature in the Genaration III / III+ reactor design utilizes the phenomena of coolant conversion in a natural way in form of natural circulation to yield the high fluid temperature. That feature is realized as passive systems not requiring operator intervention or active systems such as pumps and diesel generator [3].

In the power reactor, the natural circulation phenomena is used as a process to transfer heat generated inside the core, mainly in the shutdown condition and due to the unavailability of active systems such as forced convection to remove the heat. One example of the core heat removal design in the Generation III+ power reactor is the passive residual heat removal system (PRHRS) in the AP1000 [4]. In general, the system consists of piping design connected with a heat exchanger, which is submerged in a water pool with a specific volume and at higher elevation. In the heat exchanger, heat transfer process is taken place, where the higher temperature fluid resulted from core heating with lower density, will go up and discard the heat by convection to the coolant inside the pool. The fluid with removed heat undergoes a density increase and by gravity falls down to return in to the reactor cooling system.

To understand the natural circulation phenomena in the PRHRS and to study the significance of that phenomena for reactor safety, a plan has been made to construct a test loop capable to characterize the natural circulation process mainly in the one-phase condition at the center of nuclear reactor technology and safety (PTKRN) of BATAN. The planned test loop is called as FASSIP-01 consisting of a vertically closed loop featured with piping components, one cylinder with heater rods and one cylinder connected to the secondary loop. The cylinder with heater rods will serve as heat sources or heater, while the other as heat sink or cooler. The activity described in this paper is aimed to support the FASSIP-01 experiment by doing a simulation using the RELAP5/SCDAP/Mod3.4 thermalhydraulic code. The result can be used as a comparison and to predict the outcome of the experiment. The simulation is done with the standard configuration of the loop and by varying the elevation of the heater and cooler position to assess the fluid temperature distribution and mass flow due to the natural circulation and to evaluate the suitable heater and cooler position resulting the most optimum natural circulation. The results will be available to be compared with the planned experiment as necessary.

THEORY

A flow mechanism by natural circulation in a closed loop is also known as thermosiphon resulted from density difference due to the fluid expansion following a temperature increase. The fluid flow energy is caused by temperature difference in a particular system requiring two distinct sources, which characterize a hot temperature (heat source) and a cold temperature (cold source). Besides the temperature difference, the fluid flow by natural circulation is also determined by the height of fluid column with different density. The column height is then determined by position difference of the heat source and the heat sink. If the cold source is located below the hot source, then a temperature stratification occurs, which does not produce a hot and cold column and there is no energy to drive the fluid flow. That discrepancy between the cold source inlet and the hot source inlet becomes a significant parameter for establishing the flow in the thermosiphon. Figure 1 shows a simple schema of thermosiphon with two opposing direction from hot and cold source to produce the natural circulation mechanism.

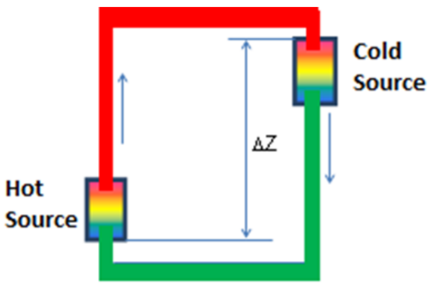

Fig. 1. Schematic diagram of thermosiphon

As shown on that figure, the fluid flow is driven by an head energy HT or Head Thermosyphon. This energy is a function of temperatur difference between the water fluid of the hot source TH (K) and that of the cold source TC (K), elevation difference between the two sources DZ (m) by considering that the hot source position is lower or in the same level with the cold source position, and a function of expantion coefficient b (1/K), as explained by following correlation:

$$H_T = \beta \,.(T_H - T_C).\Delta Z \qquad \text{.........................(1)}$$

The elevation difference D Z in this case is measured from the cold source inlet to the hot source inlet. The driven energy HT in a closed loop will be affected by resisting energy to flow, which is called as the friction head consisting friction inside pipes and other components such as elbow, tee, reducer, etc as shown in the following correlation:

$$H_F = f\frac{L}{D}\frac{V^2}{2g} + K\frac{V^2}{2g} \qquad \text{..................................(2)}$$

A steady natural circulation will be achieved as the Head Thermosyphon corresponds to the Head friction [5]. By comparing the equation (1) and (2), a flow velocity is obtained as follows:

$$V = \sqrt{\frac{\beta.(T_H - T_C).\Delta Z}{f.\frac{L}{D}.\frac{1}{2g} + \frac{K}{2g}.}} \qquad \text{................................(3)}$$

To calculate mass flow of the thermosiphon, the velocity, system dimensions, and fluid physical properties must be determined as indicate below:

$$m' = \rho.V.A \qquad \text{...(4)}$$

where A is fluid flow area (m^2), r is density, (kg/m^3), and V is flow velocity from the equation (3).

A BRIEF DESCRIPTION OF THE FASSIP-01 TEST LOOP

Passive system simulation facility version 1 (FASSIP-01) is a facility to study cooling characteristic of natural circulation using water as working fluid. This facility is a development from a smaller thermosiphon facility of USSA-FT01 and USSA-FT02 built specifically to study the effect of facility tilt angle to mass flow and temperature parameter [6, 7]. Main components of this facility are piping system with 1 inch outside diameter forming a closed loop, one heater cylinder attached in the bottom position of one vertical pipe, and one cooler cylinder in the upper position of the other vertical pipe. The heater component will rise the water and the cooler works as a heat sink to remove heat from the water. The closed loop of FASSIP-01 has a rectangular form with 3.5 m width and 6 m height. Figure 2 shows the FASSIP-01 test loop design and its geometrical dimension about to construct..

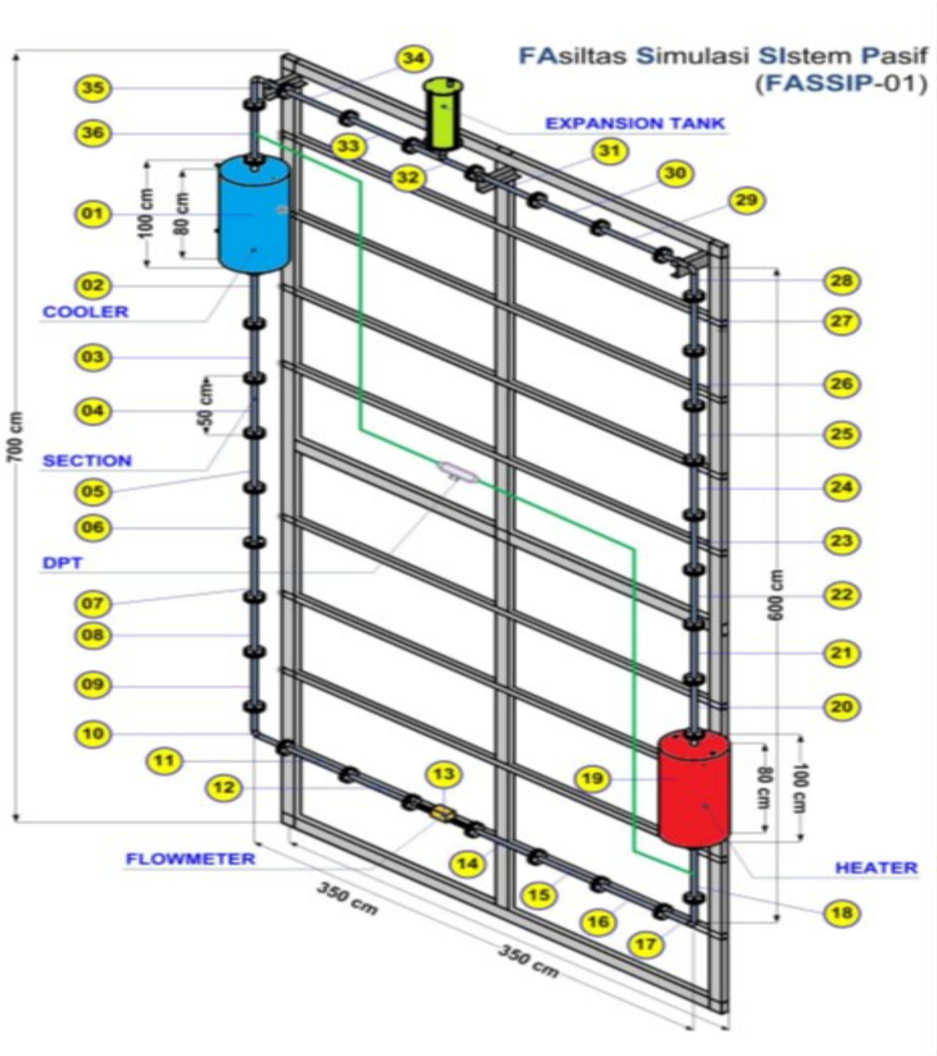

Fig. 2. Design of FASSIP-01 test loop facility by natural circulation

Heater component of FASSIP-01 is a cylindrical tank filled with water with 0.8 m height, 0.4 m diameter, and 100 liter volume heated by electric rods of 8000 Watt in total. The piping components are connected with outside environment through an expansion tank so that the highest pressure of the loop is 1 atm. The cooler component is a tank having similar dimension with the heater, except that cooler water with temperature of 30 °C is flowed from the bottom of cooler tank with the variable mass flow. On the other side, the pipe with hot water goes through the cooler tank filled with water from the secondary loop, where a heat transfer occurs via the pipe wall in to the cooler secondary side.

RESULTS AND DISCUSSION

FASSIP-01 nodalization using RELAP5

Figure 3 shows the FASSIP-01 nodalization results using RELAP5 for original configuration (Heater_Bottom) and configurations with elevation variation of heater and cooler position by modifying the input deck in the original configuration. The elevation variation is done by moving the heater position in the middle of the vertical connected piping (Heater_Middle), and in the top of the piping (Heater_Top), while the cooler position does not change. From the Figure 3, the FASSIP-01 nodalization consists of several PIPE components for the closed loop model, heater, cooler, and expantion tank, three TMDPVOL components for boundary conditions of the secondary loop and the atmosphere above the expantion tank, one BRANCH model for connecting the loop with the expantion tank, several SNGLJUN components, and one TMDPJUN for modelling the forced convection of the secondary loop. The heater and cooler model are featured with HEAT STRUCTURE components each for modelling the heat transfer mechanism inside. Along the pipe wall also is connected with HEAT STRUCTURE components for modelling the heat transfer from the inside to outside through the stainless-steel wall or without insulation with the outside temperature is determined as much as 27 °C. Those heater elevation changes will result in to variation of DZ value from 5.455 m (Heater_Bottom), 3.455 m (Heater_Middle), and 0.955 m (Heater_Top), calculated from the inlet heater and inlet cooler.

Simulation results for different elevation of the heater

For the heater component, because the electric heater elements are fully submerged with the cooling water and connected with the atmosphere, the highest water temperature to be reached is 100 °C. In the beginning, the initial condition of the system is in the room temperature of around 28 °C. Simulation was performed by setting the heater power of 1000 Watt and the secondary mass flow to 5 kg/second. Parameter to be evaluated is cooling water temperature after flowing out of the heater and before entering the cooler, cooling water temperature out of the cooler and in to the heater, and coolant mass flow by natural circulation due to water density differences between the hot and cold water in the adjacent vertical pipes in the loop.

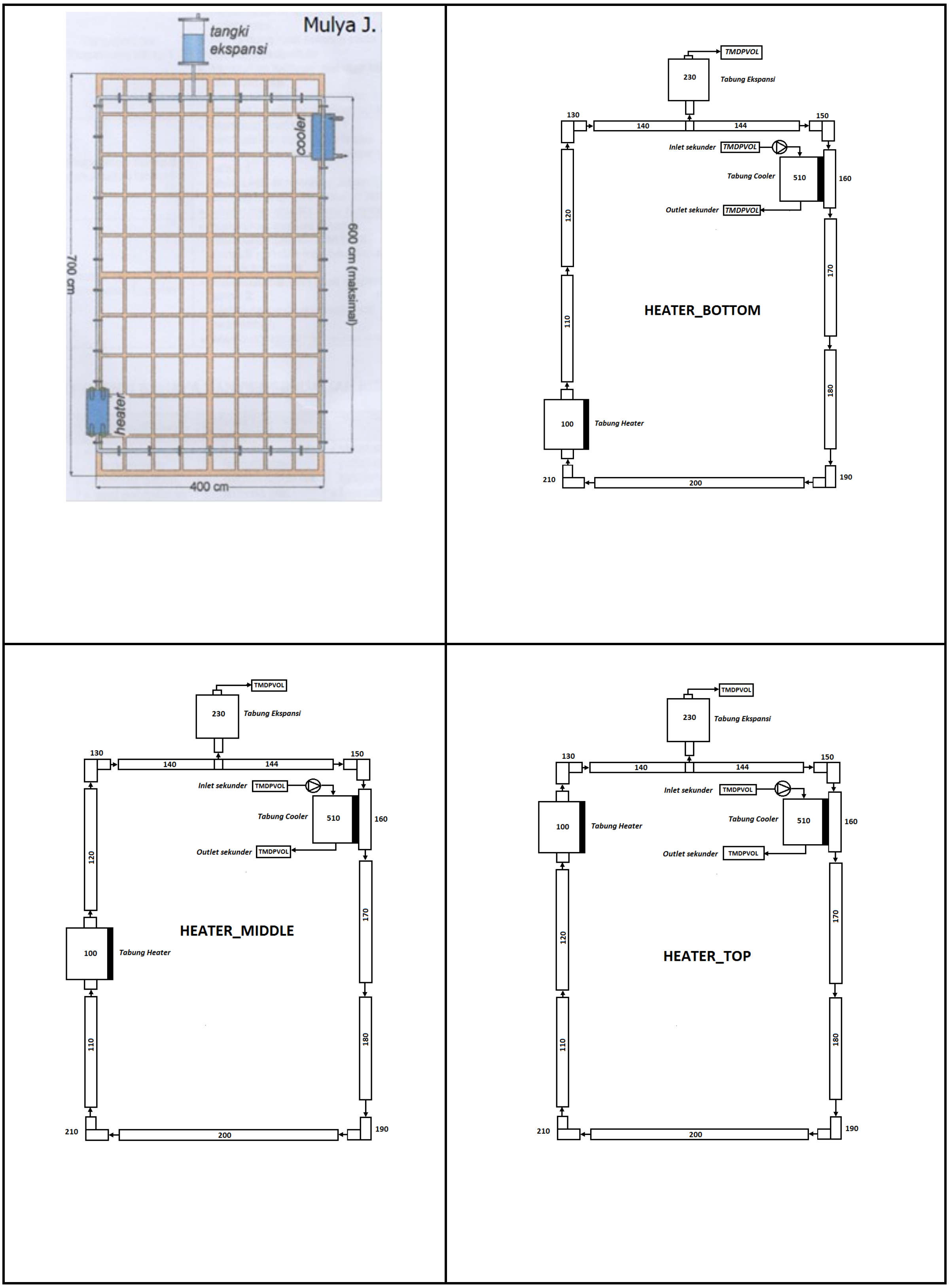

Fig. 3: RELAP5 nodalization scheme of FASSIP-01 test loop with heater elevation variation

The simulation results for temperature distribution in the heater inlet and cooler outlet for three heater position are shown in Figure 4, 5, and 6. The loop temperature changes simultaneously with the heat energy induced in to the heater and then removed by the cooler, whereas its removal is not as much as the heat in the water. Therefore, water temperature after the cooler becomes higher than temperature entering the previous heater. Up to 100,000 seconds of simulation, a balance between heat entering and heat removal starts to establish. The steady state condition is achieved in the heater inlet and cooler outlet with temperature of 67 °C.

Looking at all figures, in general the heater inlet temperature is similar with the cooler outlet temperature, and the cooler outlet temperature is also similar with the heater inlet temperature. It shows also that the increase of the inlet and outlet heater temperature are almost similar in the Heater_Bottom and Heater_Middle, even the temperature difference is higher in the Heater_Middle. A drastic result is visible in the Heater_Top with a bigger temperature difference between the heater inlet and heater outlet temperature. It is caused by the heat accumulation in the water in the upper piping close to the heater leading to a low density. The water tends to move up and is restrained to enter the cooler below as indicated in the water temperature in the expantion tank achieving 75 °C. On the other side, a water temperature decrease out of the cooler occurs due to longer vertical piping with a bigger density and restrains the water buoyancy force for entering the heater through the vertical piping. Therefore, the water temperature in the heater inlet becomes lower than the water temperature after the heater outlet as clearly seen in the Heater_Top compared with the other loop configuration.

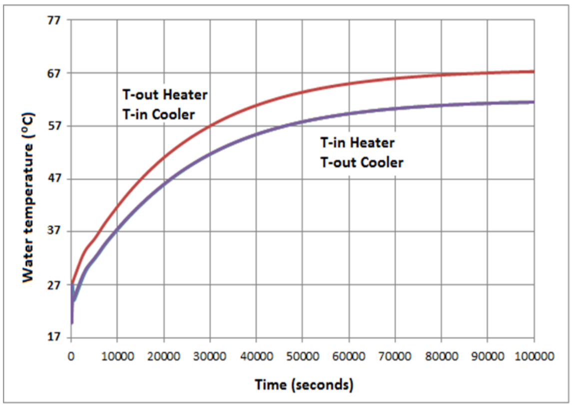

Fig. 4. Water temperature in the heater and cooler inlet and outlet in the Heater_Bottom

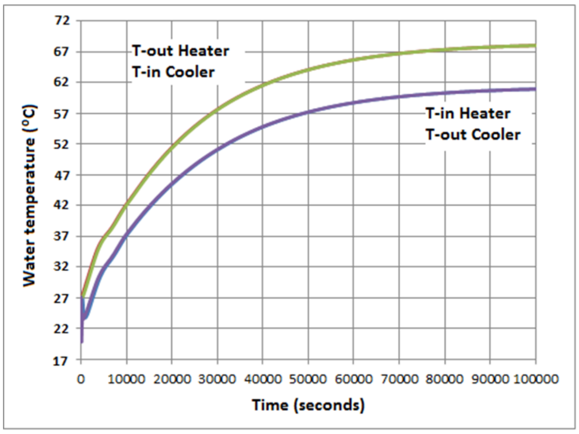

Fig. 5. Water temperature in the heater and cooler inlet and outlet in the Heater_Middle

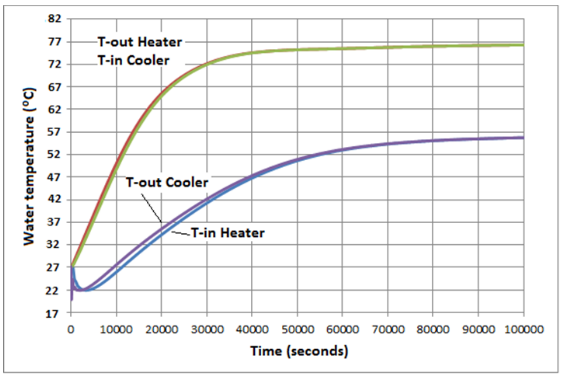

Fig. 6. Water temperature in the heater and cooler inlet and outlet in the Heater_Top

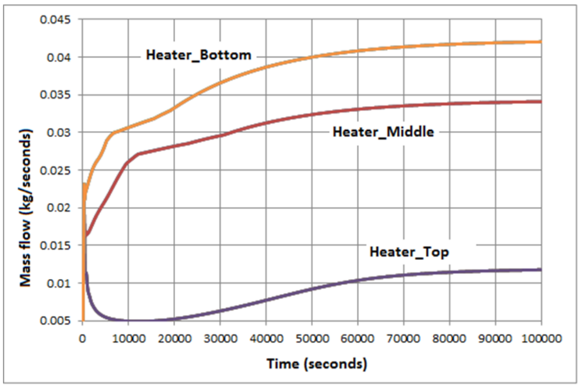

Fig. 7. Natural circulation mass flow for the heater and cooler elevation variation

The difference in the heater position also affects the water mass flow due tu the density difference between the heater and the cooler. Figure 7 shows the water mass flow for all heater position against the cooler. The simulation result shows a uniform mass flow values on all piping position in the FASSIP-01 test loop. Figure 7 also indicates a higher natural circulation mass flow on the Heater_Bottom compared with the other heater position. The Heater_Top position shows the lowest natural circulation mass flow caused by the big resistance of the cold water from the cooler to raise up in to the heater, whereas the water from the heater tends to go up and is hampered to flow down in to the cooler. Therefore the natural circulation is not enough established because the hot and cold water column are not formed enough to move the circulation inside the loop. On the Heater_Bottom, the mass flow finds the steady state condition at 0.04202 kg/seconds; 0.03409 kg/seconds for the Heater_Middle, and 0.01178 kg/seconds for the Heater_Top.

From those results, it can be concluded that the position with the heater on lower elevation than the cooler will result in a better natural circulation condition by considering the heat removal aspect by the secondary system. On that position, an optimization in the heat transfer area to increase the heat transfer coefficient and the secondary mass flow can affect the performance of the water driving mechanism by natural circulation caused by the water density difference.

CONCLUSIONS

A Model of FASSIP-01 test loop with the elevation difference between the heater and the cooler position has been developed using the RELAP5 code. By assuming a similar heating and cooling condition for all heater elevation variation, the simulation results show that the position with the heater on lower elevation than the cooler will result a better natural circulation condition by considering the heat removal aspect by the secondary system. On that position, an optimization in the heat transfer area is needed to increase the heat transfer coefficient and the secondary mass flow to remove the heat as necessary. That measures can affect the performance of the water driving mechanism by natural circulation caused by the water density difference in the FASSIP-01 test loop. Therefore the FASSIP-01 configuration with the heater position in the bottom is the most suitable configuration for the programmed experiment.

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