Study of Natural Convection Passive Cooling System for Nuclear Reactors

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Abstract. Fukushima nuclear reactor accident occurred due to the reactor cooling pumps and followed by all emergencies cooling systems could not work. Therefore, the system which has a passive safety system that rely on natural laws such as natural convection passive cooling system. In natural convection, the cooling material can flow due to the different density of the material due to the temperature difference. To analyze such investigation, a simple apparatus was set up and explains the study of natural convection in a vertical closed-loop system. It was set up that, in the closed loop, there is a heater at the bottom which is representing heat source system from the reactor core and cooler at the top which is showing the cooling system performance in room temperature to make a temperature difference for convection process. The study aims to find some loop configurations and some natural convection performances that can produce an optimum flow of cooling process. The study was done and focused on experimental approach and simulation. The obtained results are showing and analyzing in temperature profile data and the speed of coolant flow at some point on the closed-loop system.

1. Nuclear Passive Cooling System

Nuclear reactor accident in Fukushima, Japan, becomes one of the important issues to increase the level of nuclear reactor safety especially due to the natural disaster which affected the nuclear reactor system. Lack of electricity to cool the reactor and spent nuclear fuel for longer time caused by station black out (SBO) condition due to the giant earthquake which was happened.

Fukushima nuclear reactor accident occurred due to the reactor cooling pumps and followed by all emergencies cooling systems could not work, that affected to the increase of reactor temperature and made the reactor core melted with the fuel and water. Therefore, the system which has a passive safety system that rely on natural laws such as natural convection passive cooling system which can work without any active system or electricity dependence, is strongly recommended for the next advance nuclear power plant.

2. Natural Circulation Theory

In natural convection, the cooling material can flow due to the different density of the material due to the temperature difference. Like all other substances, fluid composed of molecules. But in this paper, the macroscopic behavior seen from the fluid and the fluid is considered as a substance that is a continuous distribution.
In the case of fluid dynamics, control volume approach was used. There are three laws of physics that can explain the phenomenon of fluid dynamics, namely the conservation of mass, Newton's second law of motion, and the law of conservation of energy or the first law of thermodynamics.

In natural convection, fluid flow occurs due to the buoyancy of the fluid produced by changes in fluid density. Fluid density changes can be caused by differences in fluid temperature. The relationship between the density changes with temperature difference can be written as follows:

\[ \rho = \rho_0 (1 - \beta \Delta T) \]  

with \( \rho_0 \) is the initial density of the fluid, \( \rho \) the fluid density in a layer that is heated, \( \beta \) is thermal expansion coefficient, and \( \Delta T \) is the temperature difference between the fluid that is heated by the initial fluid temperature. Equation (4) is an equation derived from Boussinesq approach which considers density changes only affected by temperature differences. Due to the density change will occur buoyant force per unit volume (\( \bar{f}_a \)) expressed as

\[ \bar{f}_a = (\rho_0 - \rho) \bar{g} \]  

by substituting equation (4) into the equation (5), it will obtain the equation

\[ \bar{f}_a = \rho_0 \beta \bar{g} \Delta T \]  

3. Methods
In this study, we used two methods, simulation and experimental methods.

3.1. Simulation
Simulations performed using software that uses finite element principles. In the simulation, the closed loop is formed as follows.

![Figure 1. Natural Convection loop system](image1)

![Figure 2. Position of sensor](image2)

The loop is filled with water, on the lower right side, there is a hot wall and on the top left, there is a cold wall. This simulation will look for the value of the speed and temperature at multiple points. Measurement points can be seen in the following figure.
Points A, B, C, and D is the temperature measurement point and point E, F, G, and H is the velocity of fluid flow measurement point. Simulations carried out using three different models. Here is a table that explains the configuration of the three models.

| Model | l (cm) | h (cm) | $T_h$ (°C) | $T_c$ (°C) | $\Delta T$ (°C) |
|-------|--------|--------|------------|------------|-----------------|
| I     | 50     | 50     | 40         | 15         | 25              |
| II    | 50     | 80     | 40         | 15         | 25              |
| III   | 50     | 100    | 40         | 15         | 25              |

Simulation is run for a span of 1800 second, the simulation results can be seen in the following graph.

**Figure 3.** Graph of Temperature of water versus Time for height 50 cm

**Figure 4.** Graph of Temperature of water versus Time for height 80 cm

**Figure 5.** Graph of Temperature of water versus Time for height 100 cm

**Figure 6.** Graph of Velocity of water versus Time for height 100 cm
Figure 7. Graph of Velocity of water versus Time for height 80 cm

Figure 8. Graph of Velocity of water versus Time for height 50 cm

Figure 9. Comparison of Velocity of water versus Time for height 50 cm, 80 cm, and 100 cm

Figure 10. Graph of velocity versus height of loop

3.2. Experiment

Figure 11. Design of Apparatus of Natural Convection Loop

Figure 12. Apparatus of Natural Circulation Loop

The experiment begins with the installation of a temperature sensor and flow sensor on a loop system apparatus. A temperature sensor placed at points A, B, C, and D and a flow sensor placed at point E (see Figure 11).
Temperature and flow sensor then connected with a data acquisition system. After that, put in a water circulation system. The heater is then activated and put the ice as a cooling material into the cooler. After that enable computer and data acquisition system to function receives the data from the sensors.

The results of the experimental data collection is as follows.

**Figure 13.** Graph of Temperature versus time from experiment data (height of loop 80 cm)

**Figure 14.** Graph of Temperature versus time from experiment data (height of loop 100 cm)

### 4. Results

From the simulation results, it can be seen that the height of loop apparatus affects the transient time to get the stationary temperature. The higher the loop apparatus, the longer the time of the transient (see Figure 3 - Figure 5). And when compared with experimental results (see Figure 13 and Figure 14), while transient temperature experimental result is greater than the time transient simulation results. This happens because at the beginning of the simulation cooling and heating temperature is constant from the beginning of the simulation, while the experiment heating and cooling in the loop apparatus takes time to reach the desired temperature.

Based simulations showed that the higher the loop apparatus, the higher the velocity of water flows in the apparatus. This is shown in Figure 9 and Figure 10. The simulation results have not been compared with experimental results. In the experiment we did, fluid flow sensor that we have not been able to detect the velocity of water flow in the loop apparatus. Our hypothesis is that our flow sensor less sensitive, so it can’t detect small flow velocity.

### 5. Future plan experiment

From the experiments we have done, we plan to improve our flow sensor system. Furthermore, we have plan to increase the level of loop apparatus at a maximum of 5 meters to find out more about the effect of height of loop apparatus on the flow of water in the apparatus.

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