

Numerical study on natural circulation characteristics in FASSIP-02 experimental facility using RELAP5 code

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Abstract. As in many other energy generating system, in the nuclear power plant, the use of natural circulation principle for the safety system is increasingly considered. The natural circulation could play an important role in providing emergency cooling of the nuclear reactor. The reliability of the use of natural circulation in the nuclear power plant should be demonstrated in order to assure the level of its safety. FASSIP-02 is a large scale test facility to study the natural circulation in the safety system of a nuclear power plant. To study the characteristics of the natural circulation and to help validating the design of FASSIP-02, a numerical study using RELAP5 code is undertaken. Based on the existing design of FASSIP-02, the numerical simulation is done with two variables, i.e. the heat flux and the pipe diameter. The effect of heat transfer surface area for dissipating the heat is also studied. The results show the natural circulation established in the FASSIP-02. The characteristics of the natural circulation with the values of several important parameters such as temperature, mass flow rate and pressure in the loop are obtained. The RELAP 5 calculations have provided the results that could be used to support the design and future operation of FASSIP-02.

1. Introduction

In the natural circulation, the fluid circulates as the result solely of buoyancy and gravity forces. There is no fluid moving machinery needed. The natural circulation system consists of a heat source, a heat sink and a loop piping system. The heat source is located lower than the heat sink allowing heated fluid flowing upward by buoyancy force. Contrarily, cooled fluid moves downward by gravitational force due to higher density. Such phenomena could be utilized to remove the heat from one hotter location to another cooler point while creating a cyclic process.

The use and existence of natural circulation based system could be found in many renewable energy generation system, such as solar energy based system [1] and geothermal system [2]. In the nuclear power plant (NPP), the implementation of natural circulation is increasingly considered as one of the passive safety system [3]. The passive safety system is a safety system that does not need an electrical sources, such as gravitation in the natural circulation. The need of the passive safety system is much more important in the case of station blackout (SBO) accident as in the Fukushima Daiichi NPP where all electrical sources to run the system were lost. In the case of SBO, the natural



circulation is to be used for removing the heat from the nuclear reactor to the outside heat sink. Several designs of the small modular type NPP, which are under design, have included the passive safety system based on the natural circulation [4,5]. In the nuclear research reactor, the passive system and the natural circulation plays also in important role to keep its safety, such shown in [6]. In order to assure its reliability, system using natural circulation concept should show their stability in terms of continuous availability and performance for removing the heat. Then, many researches are still being performed to study such aspects, as for example in [7].

The Centre for Nuclear Reactor Technology and Safety (PTKRN), National Nuclear Energy Agency of Indonesia (BATAN) has since several years ago started the programme of the research and development on the use of natural circulation for nuclear reactor safety system. Mulya et al. started the study using a simple natural circulation test facility named NC-QUEEN [8]. Based on that study, a large scale rectangular single phase natural circulation loop called FASSIP-01 was built. Several studies have been done to assess the characteristic of the natural circulation in this facility [9-11].

On the other hand, in order to study more relevant geometry of an NPP, another facility FASSIP-02 is being designed. The geometry of this facility is designed to represent the passive residual heat removal system in a NPP design, though it is not intended to scale the real facility. This paper describes the preliminary results of the study on the characteristics of FASSIP-02 facility design. The study uses the RELAP5 computer code to simulate the existing FASSIP-02 design. The objective is to study the effect of the two important variables, which are the electrical heater power (heat flux) and the piping diameter on the characteristics of the natural circulation. Those characteristics studied are the evolution of the temperature in the loop, the water mass flow rate established in the loop and the heat removed to the cooling tank. As this study is conducted prior to the facility construction, the results of this study are expected to be considered in the finalization of the facility and the experimental design.

2. Methodology

2.1. RELAP5 computer code

RELAP5 computer code is one dimensional thermal-hydraulic code which is developed to study loss of coolant accident and transient in a light water reactor [12]. The code solves the mass continuity, momentum and energy conservation equations for each control volume to obtain thermal-hydraulic parameters such as temperature, pressure, void fraction etc. The system is divided into several thermal-hydraulic control volumes, named single volume, pipe or branch. The control volumes is connected to other using junction. To account the heat transfer, RELAP5 has a model of heat structure, which could exchange the heat with the fluid in its adjacent.

2.2. FASSIP-02 model and nodalization

Figure 1 depicts the scheme of FASSIP-02 test facility. The test facility consists of heater tank, the open cooling tank and the piping system. The pipe delivering hot water from the heater tank is called hot leg and the one flowing the cooler water from cooling tank is named cold leg. An electrical heater is placed in the bottom of the heater tank to heat the water. The hot water is cooled when it passes the tube which is submerged in the water placed in the open cooling tank. The submerged tube serves as a heat exchanger. The cooling tank is only cooled through natural circulation by transferring its heat to the air. All piping system is made of stainless steel, except the heat exchanger tube is from copper. The piping loop is equipped with the expansion tank to accommodate the hot water expansion and keep the loop pressure to the atmospheric pressure approximately.

Figure 2 shows the model RELAP5 for FASSIP-02 test facility. The system composes of the heater, the hot leg, the heat exchanger, the cold leg, the cooling tank and the expansion tank. The expansion tank and the cooling tank are connected to the atmosphere. All piping is insulated with an adiabatic boundary condition between the pipe wall and the environment.

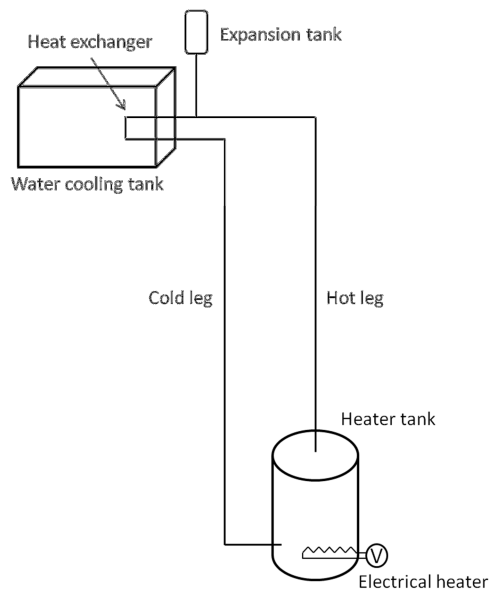


Figure 1. Scheme of FASSIP-02 facility.

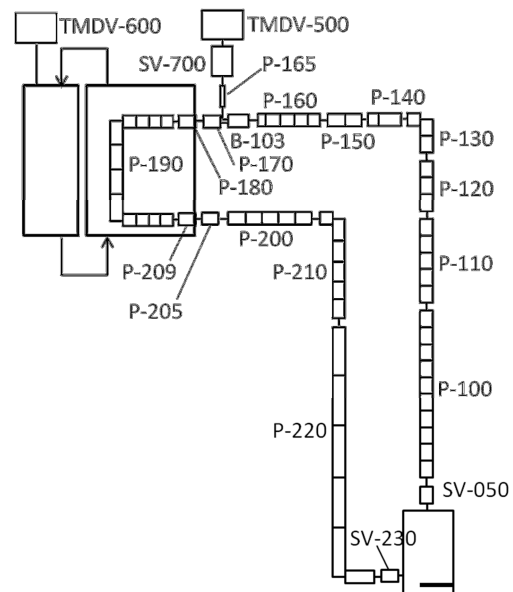


Figure 2. Nodalization of FASSIP-02 facility (P: pipe, B: branch, SV: single volume, TMDV: time dependent volume).

2.3. Calculation

The calculation with the pipe diameter of 2 inch (NPS), the electrical heater power of 10 kW and four variations of the heat transfer surface area of the submerged heat exchanger are done as the base calculation. The heat transfer surface area is an important parameter to be determined because it controls the heat removal from the natural circulation loop to the cooling tank. For that purpose, the heat exchanger is modelled as a bundle of vertical 1 inch pipe with 1 m length, which is composed of a number of pipes. There are four variation of the number of pipes, i.e. one pipe (case 1), ten pipes (case 2), twenty five pipes (case 3) and one hundred pipes (case 4). Based on the obtained results, the simulation to assess the effect of the pipe diameter and the electrical heater power is conducted while the heat transfer surface area of the heat exchanger is kept constant. Three pipe diameters, i.e. 1 inch, 2 inch and 3 inch, and three variations of electrical heater power of 2 kW, 5 kW and 10 kW are simulated. The initial and boundary conditions are identical for all calculation.

The calculation was done for the duration of approx. 55.5 hours of problem time to simulate the long term characteristic of the circulation. As the concern is only for about the duration of the planned experiment, the discussion will be focused for the first 10 hours of the calculation time period.

3. Results and Discussion

3.1. General characteristics

Table 1 shows the results of the base calculation. The case 1 to 4 are to simulate the variation of the heat transfer surface area. While the case 5 is similar to case 4 except with higher heater power. On the other hand, figure 3 shows the temperature of water at the horizontal hot leg region for four cases.

All calculation shows an instability at the beginning of calculation, but then the water temperature increases steadily with time. This increase is caused by the increase of the water temperature in the cooling tank, while the heat flux input is constant. The gradient temperatures in all cases are similar. However, in the case 1, the saturation temperature is reached earlier than other cases due to smaller total heat capacity, which is corresponding to smaller number of the pipe of the heat exchanger. As it could be seen from the figure 3, after 5 hours the water temperature of case 1 is the highest after which it increases with the same rate as three other cases. From the table 1, it also could be seen that after 10 hours, the water temperature in the case 1 has reached about 80.4 °C, while in the case 4 the

temperature is 52.2 °C. On other hand, with comparing the case 5 and case 4, the increase of the heat from the electrical heater resulted in faster achievement of the saturation temperature and the higher rate of the water temperature increase.

Table 1. Base case calculation.

Case number	Pipe diameter (inch)	Heater power (kW)	Number of pipe in the heat exchanger	Time to reach the saturation temperature (h) ^a	Temperature at t = 10 hours (°C) ^a
Case 1	2	10	1	35.8	80.4
Case 2			10	> 50	60.5
Case 3			25	> 50	54.7
Case 4			100	> 50	52.2
Case 5		15	100	36.0	59.7

^a temperature at horizontal hot leg

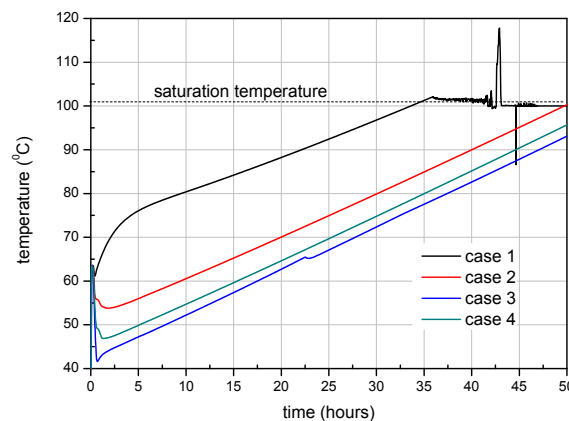


Figure 3. Evolution of the water temperature in hot leg for four cases.

The calculation results also indicate that increasing the heat transfer surface area did not increase the heat removed to the cooling tank. This is because the increase number of pipe of the heat exchanger, the velocity of the water flows in the pipe diminishes. As consequence, the overall heat transfer coefficient may unchange. The result might be different if it uses finned tube to increase heat transfer surface area, while the number of tube is not increased too much. The bundle of 25 tubes will be used for the next calculations because of it represents a reasonable number of pipe and provides good results.

3.2. Effect of the pipe diameter

To assess the effect of the pipe diameter, three diameters are simulated, i.e. 1 inch, 2 inch and 3 inch. In all cases, the heat exchanger is similar, which is a bundle of 25 pipes of 1 inch of diameter and 1 m of length. While, the electrical heater power is 10 kW. Table 2 shows the matrix of the calculation and the main results.

The results show that with smaller diameter size, the water was heated faster because of having smaller water mass. On the other hand, the water mass flow rate is almost similar for three cases. However, the bigger size of pipe tends to result a higher mass flow rate. This is due to lower friction loss for bigger diameter. The results from [13] indicated the same trend of the effect of the diameter.

3.3. Effect of the heat flux

Table 3 shows the simulation matrix and the main results to assess the effect of the heat flux transferred from the electrical heater to the water. The pipe diameter of 1 and 2 inch are chosen to be

simulated because these sizes are the most likely used for loop of the FASSIP-02 facility. For each pipe size, the heat flux is varied, i.e. 2 kW, 5 kW and 10 kW. Figure 4 and 5 show the simulation results of the effect of heat flux on the temperature increase and the water mass flow rate for 1 and 2 inch pipe diameter, respectively.

Table 2. Matrix and main results of simulation for the effect of the pipe diameter.

Case number	Heater power (kW)	Number of pipe in the heat exchanger	Nominal diameter of the pipe (inch)	Temperature at t = 10 hours (°C) ^a	Mass flow rate in the loop (kg/s) ^b
Case 6	10	25	1	100. ^c	0.019 (0.05 ^d)
Case 7			2	54.6	0.19
Case 8			3	50.1	0.20

^a temperature at horizontal hot leg

^b average value from t=0 s to t=10 hours

^c saturation temperature is reached at approx. 2.4 hours

^d the average mass flow before the saturation temperature reached at about 10,000 s

Table 3. Matrix and results of simulation for the effect of electric power heater.

Case number	Pipe diameter (inch)	Number of pipe in the heat exchanger	Electrical heater power (kW)	Temperature at t = 10 hours (°C) ^a	Percentage of heat flux transferred to the cooling tank (%)
Case 9	1	25	2	95.6	0.4 ^b
Case 10			5	saturated	0.4 ^c
Case 11			10	saturated	0.4 ^c
Case 12	2	25	2	36.7	94.9 ^b
Case 13			5	44.6	94.4 ^b
Case 14			10	54.6	94.5 ^b

^a temperature at horizontal hot leg

^b average value for the period t = 3 to 10 hours (when the heat flux relatively steady)

^c average heat flux for the period prior to the saturation condition.

It is obvious that the higher heat flux, the faster temperature increase for all diameter of pipe. For 1 inch pipe, for 5 and 10 kW heat flux, the water saturation temperature is reached at about 2.4 h and 4.8 h, respectively (see figure 4). For 2 inch pipe, the hot leg temperature reached about 54 °C, still far below saturation temperature, in the case of heat flux of 10 kW (see figure 5). As it could be seen from the figure 4, the water mass flow rate tends to be unstable at the beginning of the saturation.

While, the heat flux transferred to the cooling tank is quite small, approx. 0.4%, of the heat flux from the heater in case of 1 inch pipe and about 95% for 2 inch pipe. The heat transfer is small in case of 1 inch pipe might be due to very low mass flow rate. The heat received from the electrical heater is mostly used to increase the water temperature inside the pipe and also losses to the pipe wall.

On the other hand, the mass flow rate increases with the heat flux and the pipe diameter as well. In case of 1 inch pipe, the mass flow rate is low (about 0.03 to 0.05 kg/s) causing the heat flux transferred is small. In case of 2 inch pipe, the mass flow rate for 3 different heat fluxes is about 0.1 to 0.2 kg/s (see figure 5). Again these results agree well with the results from [13].

4. Conclusion

As expected, the characteristic of FASSIP-02 shows the establishment of a natural circulation. The smaller diameter of the pipe resulted smaller mass flow rate, heat flux transferred to the heat sink and faster achieving the water saturation temperature. The higher heat flux applied will cause faster water temperature increase and higher mass flow rate. If, the 1 inch pipe will be used, the power should be lower than 2 kW to avoid two phase flow in the loop. The 2 inch pipe provides more flexibility in terms of heat flux variation.

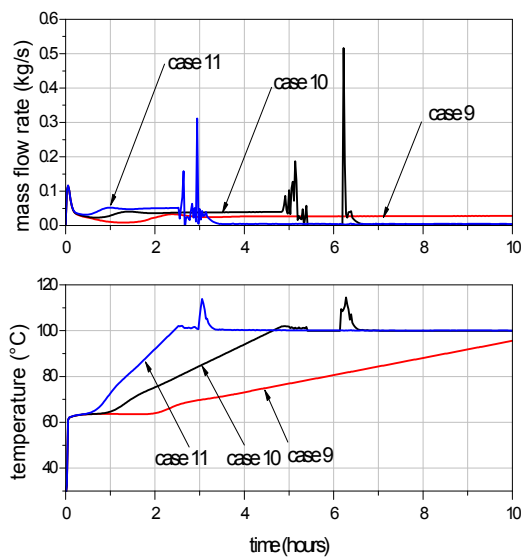


Figure 4. Mass flow rate and the water temperature for different heat flux for 1 inch pipe.

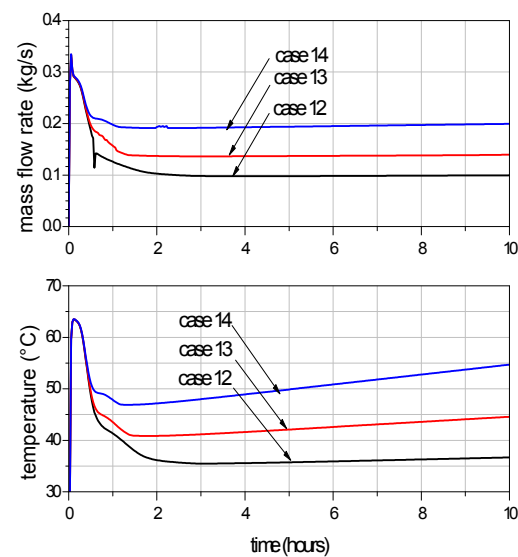


Figure 5. Mass flow rate and the water temperature for different heat flux for 2 inch pipe.

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