

SIMULATION OF OPERATIONAL CONDITIONS OF FASSIP-02 NATURAL CIRCULATION COOLING SYSTEM EXPERIMENTAL LOOP

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ABSTRACT

SIMULATION OF OPERATIONAL CONDITIONS OF FASSIP-02 NATURAL CIRCULATION COOLING SYSTEM EXPERIMENTAL LOOP. The natural circulation is considered in the design of emergency passive core cooling system in a nuclear power plant. In that context, FASSIP-02 experimental loop is designed in order to investigate the characteristics of the natural circulation in a closed loop. This paper simulates the various operational conditions of FASSIP-02. The objective is to obtain the best operational conditions of FASSIP-02 once it is built. For that purpose, the simulation is done with different condition of the heater power, the pipe insulation and the expansion tank's valve using RELAP5 code. The simulation time is up to 50,000 s. The simulation results show that until 50,000 s the steady state condition could not be achieved yet when the heater power greater than 10 kW. The pipe insulation causes faster increase of the water temperature inside the pipe and the induced water flow rate, as well. While, if the expansion tank's valve is closed during the operation, the pressure inside the loop would increase, faster when the heater power is higher and could reach the critical pressure. It is concluded that in all cases to avoid the saturation condition, the heater power should be maintained lower than 10 kW, especially when the loop pipe is insulated.

Key words: natural circulation, simulation, RELAP5, single-phase

ABSTRAK

SIMULASI KONDISI OPERASI UNTAI EKSPERIMENTAL SISTEM PENDINGIN SIRKULASI ALAMIAH FASSIP-02. Sirkulasi alam telah banyak dipertimbangkan dalam desain sistem pendingin teras darurat pasif pada pembangkit daya nuklir. Dalam konteks tersebut, telah dirancang untai eksperimen FASSIP-02 untuk menginvestigasi karakteristik sirkulasi alam pada suatu untai tertutup. Studi ini mensimulasikan berbagai kondisi operasi FASSIP-02. Tujuannya adalah memperoleh kondisi operasi terbaik untuk melakukan eksperimen. Untuk itu, dengan menggunakan program perhitungan RELAP5, simulasi dilakukan dengan berbagai nilai daya pemanas, kondisi isolasi pipa dan katup tangki ekspansi. Simulasi dilakukan hingga waktu 50.000 detik. Hasil simulasi menunjukkan bahwa hingga akhir perhitungan 50.000 detik, kondisi tunak tidak dapat tercapai jika daya pemanas sama atau lebih besar dari 10 kW. Isolasi perpipaan mempercepat kenaikan temperatur air di untai FASSIP-02 dan akibatnya laju alir juga meningkat. Jika katup tangki ekspansi ditutup, tekanan akan meningkat, khususnya pada daya pemanas yang tinggi, bahkan mencapai tekanan kritis. Berdasarkan hasil tersebut, dapat disimpulkan bahwa untuk semua kondisi operasi, jika diinginkan kondisi satu fasa cair, maka daya pemanas dijaga di bawah 10 kW, terlebih ketika pipa diisolasi.

Kata kunci: sirkulasi alam, simulasi, RELAP5, satu fasa

1. INTRODUCTION

The implementation of passive safety system into the nuclear power plant (NPP) design was recommended by the International Atomic Energy Agency (1). While, several new design of NPP have considered the passive safety system (2–4). Difference from the active safety system, the passive safety system works without any external prime movers or electric sources. The passive system functions following a natural phenomenon, such as gravity, once actuated. As consequence, the passive system is appropriate to cope the station blackout (SBO) event where all electric sources are interrupted to the safety equipments. The accident of Fukushima Dai-ichi NPP reaffirmed the importance of the passive safety system during the SBO (5).

Natural circulation is the flow of a fluid driven by the buoyancy and gravitational forces. When a fluid is heated, its density decreases and tends to flow upward due to the buoyancy. But, when it is cooled, the temperature decreases and the density increases. By gravitational force, the cooled fluid flows downward. Then, if there is a piping loop containing a fluid with one heat source at one side and one cooling source at an other higher side, a natural circulation can be established. Based on that phenomenon, several of NPP designs consider their emergency residual heat removal systems by using the natural circulation principle (6, 7). In such case, it is importance to assure that the natural circulation has enough capacity to transport sustainably the residual heat for the

considered period of time. While, the importance of the natural circulation could also be found in the application of renewable energy sources, such as in the geothermal (8) and solar energy (9).

The research on the natural circulation phenomenon and its application in the NPP have been performed by many researchers. The researches by (10–14) are the study on the basic phenomenon of the natural circulation by experimental and/or numerical simulation. The experimental facilities used are of simple geometry, i.e. square loop. On the other hand, the study performed by (15–17) were to investigate the natural circulation application in a geometry, which represent the ones in the NPP. While, Basu et al. (18) conducted a comprehensive review on the natural circulation.

In accordance with the main task, the Center for Nuclear Reactor Technology and Safety (PTKRN) of National Nuclear Energy Agency of Indonesia (BATAN) puts the research on the development of the passive safety system as one of main research programme. As starting point, a research using a simple and small experimental equipment named NC-QUEEN has been done to study the generated natural flow (19). After that, a large scale vertical-rectangular loop, so-called FASSIP-01, has been constructed and was used to study the stability of the natural circulation (20). A series of experiments has been conducted and the analysis using an analytical approach and the RELAP5 code were performed, as well (21, 22). Another large scale facility named FASSIP-02 is being built. The facility is to model the residual

heat removal in a NPP, though it is not a scale down of the existing design. It is also to show the use of heat pipe technology in the passive residual heat removal system (23). The preliminary study on the design of the FASSIP-02 has been previously done (24). The current study is to investigate the operational conditions of this loop through numerical simulation using the RELAP5 code. The effect of three operation conditions, which are the heater power, the piping heat insulation and the condition of expansion tank valve, are studied with the focus on the profile of the water temperature inside the pipe and the water mass flow rate generated. Those three operation conditions studied here are important to be known prior to the experiment conduct because it would have the effect in the natural circulation and/or the facility operational safety. The objective is to obtain the appropriate operational conditions for the experiments. Then, it is expected that the results from the present study could be considered to support the operation of the FASSIP-02.

2. METHODOLOGY

Experimental Set up

The FASSIP-02 facility comprises of a water heater tank (WHT), a water cooling tank (WCT), an expansion tank and piping system connecting WHT and WCT as a loop. Figure 1 shows the schematic diagram of the FASSIP-02 design. In the WHT, water is heated by four electrical heaters of 5 kW maximum power each. Those electrical heaters are located at the bottom part of the WHT. The hot water from the WHT will flow

upward due to buoyancy force through the vertical pipe, named hot leg or riser, to the WCT. The hot leg is connected to a C-pipe, which is submerged in the WCT and functions as a heat exchanger where the hot water transfer its heat to the water in WCT. This heat exchanger pipe is made of Copper. When the hot water is cooled, its density increases. It causes the water flows downward back to the WHT through the cold leg pipe. The difference of height between the WHT and the WCT is approximately 10 meters.

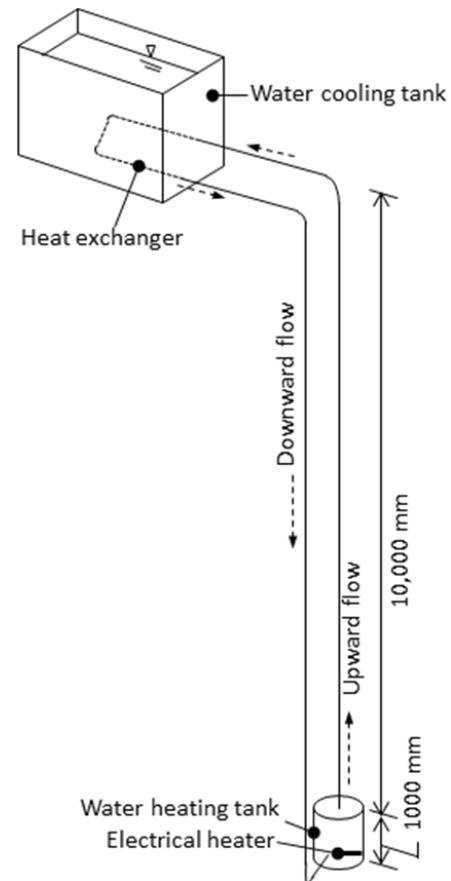


Figure 1. Schematic diagram of FASSIP-02.

RELAP5 code

RELAP5 is a one-dimensional thermal-hydraulic system code that models the complex system into a number of simple hydrodynamic control volumes, heat structure and component models (25). The code equation system, known as Navier-Stokes equation, gives two-fluid simulation system using a non-equilibrium, non-homogeneous, six-equation representation. The code is being developed since its initial version, which was used for loss of coolant accident (LOCA) analysis in Pressurized Water Reactor (PWR), to three dimension version. The code has been validated with many experimental results representing many type of accident scenarios in various

design of nuclear power reactors. Moreover, the code is also validated and used for analysing of research reactors thermal-hydraulic and other nuclear related installations (26, 27). RELAP5 has also been used to investigate the natural circulation phenomenon in several previous researches (28, 29).

Model and nodalization

To conduct the simulation using RELAP5 code, all of the FASSIP-02 main components are modelled as depicted in the Figure 2. While, the Table 1 shows the component and each component's node numbers.

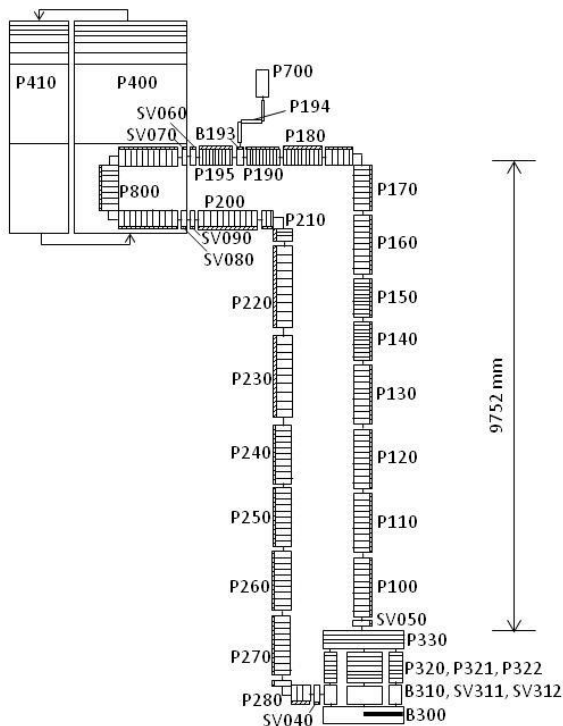


Table 1. Main component and component's nodalization number.

Component	Component's Number
Hot leg	SV050, P100, P110, P120, P130, P140, P150, P160, P170, P180, P190, P193, P195, SV060
Cold Leg	SV090, P200, P210, P220, P230, P240, P250, P260, P270, P280, SV040
Heat Exchanger	SV070, P800, SV080
WHT	B300, B310, SV311, SV312, P320, P321, P322, P330
WCT	P400, P410
Expansion Tank	P194, P700

Figure 2. RELAP5 model and component nodalization of FASSIP-02.

3. RESULTS AND DISCUSSION

Four series of calculation have been done to simulate the FASSIP-02 operational conditions based on the heater power variation, the insulated or non-insulated pipe and the operating status of the expansion tank valve connecting to the environment, i.e. open or close. In all calculation, the

environment temperature is assumed constant, i.e. 30 °C. In order to assess a longer term period of operation, each calculation is conducted for 50,000 s. While, the heater power is varied between 100 W and 20 kW. Table 2 summarizes the matrix of those four series of calculation

Table 2. Matrix of calculation.

No.	Calculation	Insulation		Expansion tank valve		Heater Power
		Yes	No	Open	Close	
1.	Series 1		√	√		100 W, 200 W, 500 W, 1 kW, 10 kW, 20 kW
2.	Series 2	√		√		100 W, 200 W, 500 W, 600 W, 1 kW, 10 kW, 20 kW
3.	Series 3		√		√	100 W, 200 W, 500 W, 1 kW, 10 kW, 20 kW
4.	Series 4	√			√	100 W, 200 W, 500 W, 600 W, 1 kW, 10 kW, 20 kW

The Table 3 summarizes the simulation results for all series of calculation. To show the temperature profile in the loop pipe, the values of water temperature in six nodes are given. The nodes 050-01, 140-04, 170-08 and 060-01 represent the hot leg

and the nodes 200-05 and 280-03 represent the cold leg of the loop. The water induced mass flow rate is also given in the Table 3

Table 3. shows the temperature at 50,000 s at six different component's nodes (See also fig. 2 for the component number).

Table 3. Temperature and flow rate at 50,000 s at different component's number.

No.	Calculation- Heater power	Temperature (°C)						Flow rate (kg/s)	Specific Remarks
		050-01	140-05	170-08	060-01	200-05	280-03		
1.	Series 1 (S1)								
1.1	100 W	29.01	28.99	28.99	28.99	28.99	28.99	0.0007	steady
1.2	200 W	29.22	29.16	29.16	29.16	29.15	29.16	0.0012	steady
1.3	500 W	29.99	29.69	29.68	29.68	29.66	29.67	0.0028	steady
1.4	1 kW	31.47	30.66	30.6	30.59	30.56	30.55	0.0055	steady
1.5	10 kW	56.19	50.21	49.15	48.78	48.50	47.39	0.0319	unsteady
1.6	20 kW	80.72	71.33	69.51	68.88	68.41	66.43	0.0473	unsteady
2.	Series 2 (S2)								
2.1	100 W	47.81	46.9	46.52	46.32	46.25	44.76	0.0170	unsteady
2.2	200 W	49.92	48.96	48.55	48.35	48.26	46.68	0.0185	unsteady
2.3	500 W	56.93	55.8	55.32	55.09	54.95	53.07	0.0224	unsteady
2.4	1 kW	68.77	67.33	66.71	66.42	66.2	63.77	0.0263	unsteady
2.5	10 kW	100.81	100.67	100.52	100.32	100.3	100.13	0.0043	saturated
2.6	20 kW	102.93	102.39	101.7	93.35	99.64	101.51	0.0098	saturated
3.	Series 3 (S3)								

3.1	100 W	29.01	28.99	28.99	28.99	28.99	28.99	0.0007	steady
3.2	200 W	29.22	29.16	29.16	29.16	29.15	29.16	0.0012	steady
3.3	500 W	29.99	29.69	29.68	29.68	29.66	29.67	0.0028	steady
3.4	1 kW	31.47	30.66	30.6	30.59	30.56	30.55	0.0055	unsteady
3.5	10 kW	56.2	50.22	49.16	48.79	48.51	47.4	0.0319	Pressure increase
3.6	20 kW	80.73	71.34	69.52	68.88	68.41	66.42	0.0472	Pressure increase
4.	Series 4 (S4)								
4.1	100 W	47.81	46.90	46.52	46.32	46.25	44.76	0.0170	unsteady
4.2	200 W	49.91	48.95	48.55	48.34	48.25	46.67	0.0185	unsteady
4.3	500 W	56.93	55.80	55.32	55.09	54.95	53.07	0.0225	unsteady
4.4	1 kW	68.77	67.33	66.71	66.42	66.2	63.77	0.0263	unsteady
4.5	10 kW	103.34	100.45	99.15	98.47	97.35	92.39	0.0476	Critical pressure at 7,500 s
4.6	20 kW	101.31	97.48	95.73	94.77	92.9	86.31	0.0566	Critical pressure at 3,600 s

As in the Table 3, some results are mentioned steady and others are unsteady. It is steady when the change in temperature considered insignificant. Otherwise, they are unsteady; the water temperature steadily decreases or increases. Based on the simulation results given in Table 3, the analysis on the effect of different operation conditions are done below.

Effect of Heater Power

The effect of heater power to the induced natural circulation could be known by analysing the water temperature and mass flow rate at different heater power of each series of calculation. Figure 3 depicts the water temperature profile taken at the outlet of WHT (node 050-01) for 100 W and 10 kW of heater power for all series of calculation. In that figure, the temperature profile of S1-100 W and S3-100 W, S1-10 kW and S3-10 kW, S2-100 W and S4-100 W

and S2-10 kW and S4-10 kW are identical each others, so the curves are overlapping. In general, it is obvious that the increase of heater power causes the increase of the water temperature. The increase of temperature is more significant when the loop pipe is insulated. It is because the heat loss from the pipe is smaller. As shown in Figure 3, when the heater power is 10 kW, the temperature is increasing until the end of the calculation for case of S1-10 kW and S3-10 kW and even reach the saturation temperature for the case of S2-10 kW and S4-10 kW. Contrarily, in case of S2-100 W and S4-100 W, the temperature is continuously decreases. These are called unsteady condition. Figure 4 shows the effect heater power on the water temperature. In that figure, the water temperature is represented from the node 050-01, which is the outlet pipe of WHT.

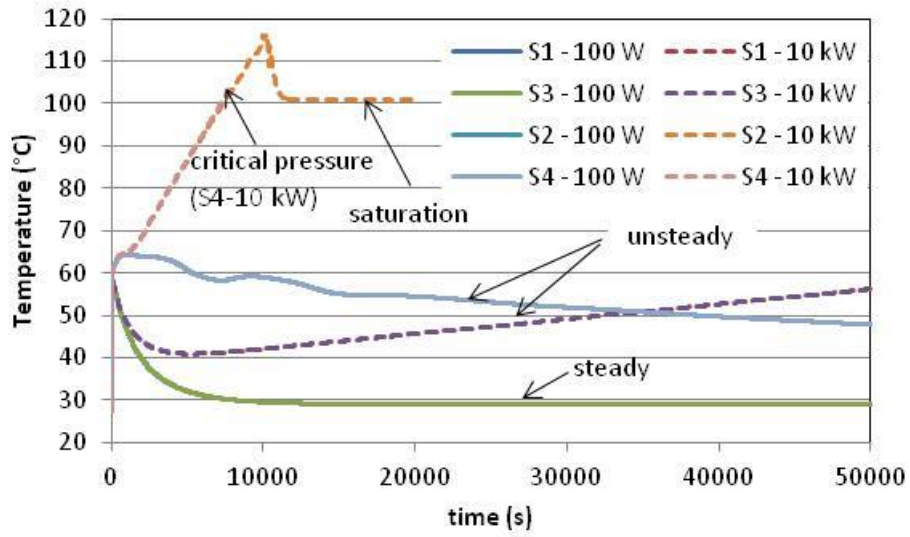


Figure 3. Water temperature profile at the outlet of WHT for 100 W and 10 kW heater power.

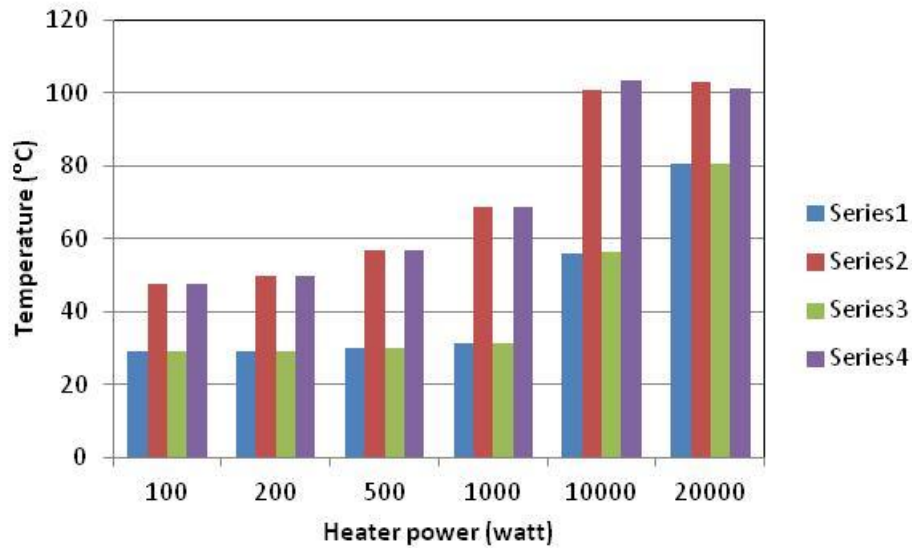


Figure 4. Effect of heater power on the water temperature.

Figure 5 depicts the mass flow rate as a function of the heater power in all cases studied. The increase of mass flow rate is associated with the increase of the temperature, which causes the increase of buoyancy force. As shown in Figure 5, in

Series 2 the mass flow rate decreased at 10 kW and 20 kW of heater power. It is due to the achievement of the saturation condition. In general, these results are similar to the results obtained in (30).

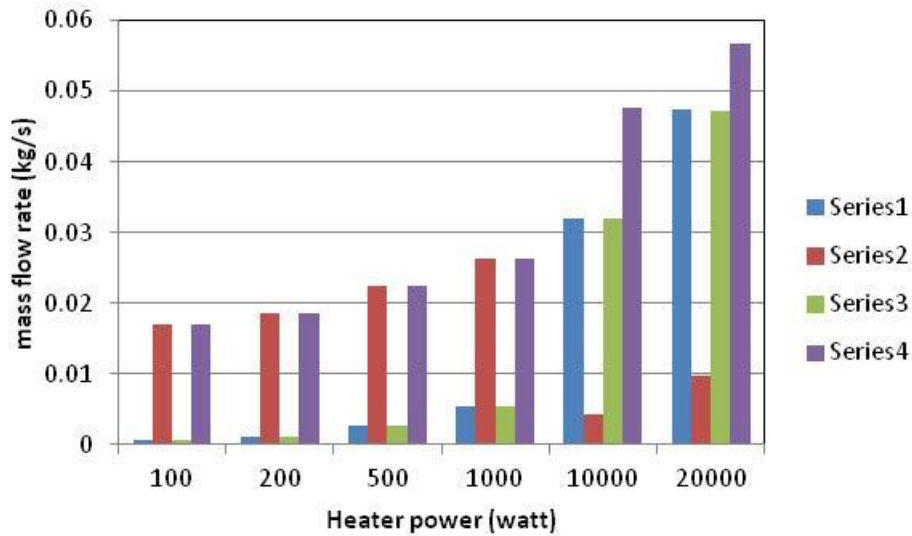


Figure 5. Effect of the heater power on the water mass flow rate.

On the other hand, from Table 3, it could be seen that the difference temperature between hot leg (node 060-01) and cold leg (200-05) is relatively small. It indicates that the heat transferred from the water inside to the WCT is small, only between 0.1 W to 1.5 kW. Previous study figured out that the heat transfer surface area of the heat exchanger should be extended to increase the heat transferred (24).

Effect of the pipe insulation

The effect of insulation could be assessed by comparing the calculation results of the series 1 to 2 and the series 3

to 4. There are shown that at the same heater power, the water temperature and the mass flow rate of the series 2 and series 4 are higher than the series 1 and 3, respectively. It is obvious that the insulation applied to the loop's piping reduces the heat loss from the piping to the environment and increases the water temperature inside the loop increases. As a consequence, the water mass flow rate increases. Figure 6 shows the water temperature of node 050-01 for four cases of calculation; S2 - 1 kW and S4-500 W are higher than S1-1 kW and S3-500 W, respectively. However, the steady condition could not be achieved.

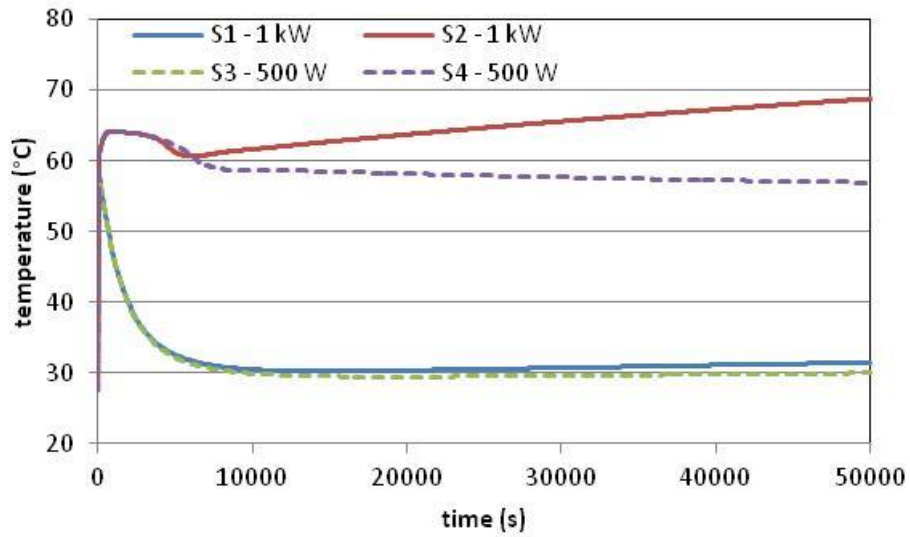


Figure 6. The effect of insulation on the water temperature.

Effect of the expansion tank's valve status

Comparing the calculation Series 1 and 3 and Series 2 and 4 shows the effect of closing or opening the valve, which connects the expansion tank and the environment. The expansion tank is connected to the loop to accommodate the expansion of the water due to the temperature increase. It consists of a 6 inch tank of 500 mm length. The tank is half-filled with the water. A valve is located on top of the tank. When the valve is open, normally the pressure in the loop is determined only by the static pressure of the

water. However, when the valve is closed, the pressure is expected to increase if the temperature of the water increase. Figure 7 shows the example of the simulation results on the pressure evolution in case of the valve is open and close at heater power of 10 kW. In case of non insulated pipe, when the valve is opened, the pressure is almost constant (see S1-10 kW). But, when the valve is closed, the profile of the pressure is different; it decreases at the beginning and then it increases continuously as the temperature increases.

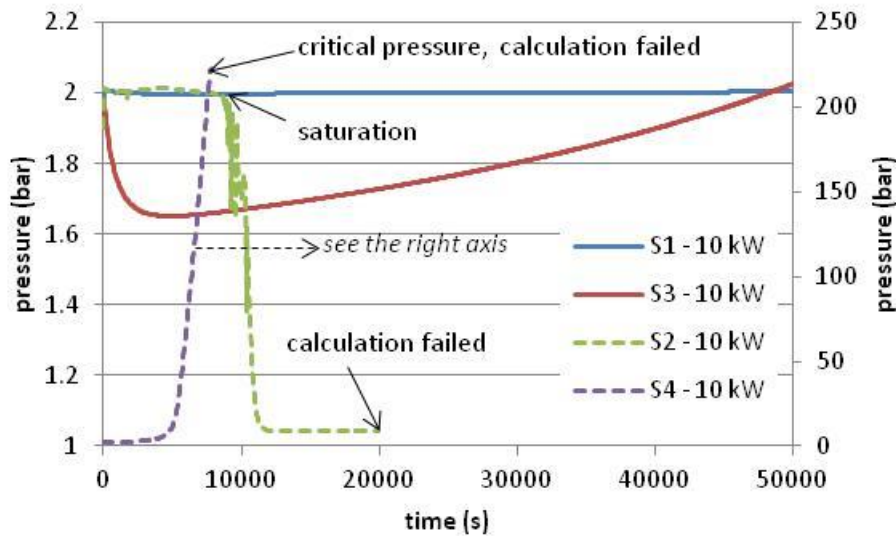


Figure 7. The effect of the operation of the expansion tank valve on the loop pressure.

In case of the insulated pipe, the effect of the closing of the expansion tank's valve is more significant. The pressure could reach the critical pressure, i.e. 220 bars. Contrarily, when the valve is opened, instead of increasing, the pressure decreases because the water reaches at saturation condition causing evaporation and the pressure decreases. Such phenomenon is not happened in case of lower heater power.

4. CONCLUSIONS

The simulation of operational conditions of FASSIP-02 experimental loop using RELAP5 code has been conducted. The influences of different parameter of operations are as follow.

Increasing the heating power increases the induced water mass flow rate. The lowest flow rate of about 0.001 kg/sec in the case of unisolated pipe and the

expansion tank valve open. While the highest mass flow rate is about 0.055 kg/s when the pipe is isolated and the expansion tank valve closed. However, the single-phase steady state natural circulation could only be achieved at relatively low heater power, less than 1 kW.

When the expansion tank's valve is closed, the pressure increases quickly at the higher heater power, even up to the critical pressure in about 7800 s in the case of isolated pipe and 10 kW of power. In that case, the water temperature increases, as well.

It is concluded that in all cases to avoid the saturation condition, the heater power should be maintained lower than 10 kW, especially when the loop pipe is insulated.

On the other hand, it is predicted that the heat transferred from the water inside the loop to the WCT is small. It causes that the steady state is difficult to achieve. The

modification of the heat exchanger should be considered to allow higher heat removal to WCT.

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