Analysis of Natural Circulation in a parallel-channel for single phase flow instability with RELAP5/MOD3

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1. Introduction

The development of a small and medium-sized reactor (SMR), which has low cost for construction and is well adapt for a small-scale distributed power source, is underway worldwide. Among the water-cooled SMRs, CAREM-25, IMR, ABV-6M, VK-300, SMR-160 [1] adopted soluble boron-free reactor core with full power natural circulation design.

In a large commercial pressurized water reactor (PWR), a reactor coolant pump (RCP) provides energy to heat up the reactor coolant system (RCS) from ambient temperature to greater than the minimum temperature for criticality prior to the reactor startup.

On the other hand, SMR with full power natural circulation capability during normal operation, the RCS cannot be heated through the RCP, so an additional heating source is required. The additional heat source can be classified into internal and external heat sources. In this paper, an internal heating is examined, especially by using the core power only.

In contrast to the forced circulation with RCP operation, the natural circulation is established and maintained only with the core power. The flow instability due to local temperature rise cannot be ruled out and therefore it requires research work. In general, the flow instability may cause mechanical vibration of components, disturb control systems and make operation unstable in reactors. Furthermore, in terms of core integrity, the flow instability may cause a CHF to occur due to flow reversal, and consequently damage the core.

Therefore, it is necessary to investigate the flow instability that can occur when the SMR is heated only with the core power.

In this paper, the flow instability that can occur due to unbalanced channel heating in parallel channels is reviewed. And the flow instability caused by the difference in control rod speed was simulated using the RELAP5/MOD3 [2] computer code when the control rod was pulled out from the SMR.

2. Simulation & Results

2.1 Flow Instability

Prior to the simulation, a definition of the flow instability is needed. The classification of the flow stability can be divided into three categories (stable, neutrally stable, unstable) [3]. For the single phase multi-channel flow instability it is most likely that the system moves to a new steady state very abruptly if there is a perturbation from external.

There are many research works about the instabilities in a parallel-channel configuration theoretically and experimentally. Among them, two studies are mainly reviewed in this paper. Ref. 4 uses non-dimensional variables in four parallel-channels without downcomer (DC), and Ref. 5 uses RELAP5/MOD3 in 3 parallel-channels with 1 DC to complete a metastable map.

The base deck and transient deck (4 Cases) are prepared with Ref. 5 information to confirm the natural circulation instability simulation ability of RELAP5/MOD3 and verify input deck used in this paper.

The schematic of the loop is shown in Fig. 1 and the variables related to the loop are listed in Table 1 for steady state.

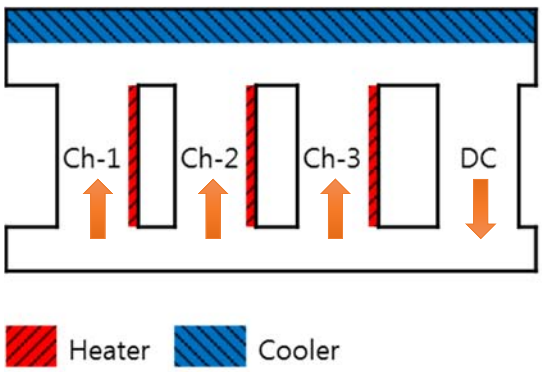

Fig. 1. Schematic of the natural circulation loop

If the same and uniform heat flux is delivered to each channel, the flow from channels 1 to 3 will be directed upward and the flow of DC will be directed downward, as shown in Fig. 1.

However, as shown in Table 2, the same heat flux was applied to all the channels until 1000 seconds, and after

1,000 seconds, the flow reversal phenomenon was simulated by giving the heat flux increasing or decreasing in the channel 2.

Figs. 2 through 5 show density difference between bottom and top of each channel and mass flow rate for channel 2 of Case 1 and Case 3 in Ref. 5. The values agree with the reference values reasonably. The flow reversal in channel 2 is caused by the difference in density between the bottom and top of channel 2, which is the same as reverse flow phenomenon described in Ref. 5.

The difference between the simulated events in Fig. 2 and Fig. 3 is the heat flux decreasing rate of channel 2, 10w/s and 100w/s. In both cases, the heat flux is reduced in channel 2, indicating that the overall tendency is similar, although there is only a difference in the timing of flow reversal.

Table 1 Variables related to the loop.

	Channel	Plenum	Cooler
ID, mm	25.5	250	150
Thickness, mm	2.7		
Length, m	5	0.964	0.964
Roughness, mm	$45 \cdot 10^{-6}$		
Material	SS-316 (Volumetric heat capacity: 3.83×106 J/m^3·K)		

Table 2 Cases studied with initial heat fluxes (kW/m^2)

Case No.	Ch-1	Ch-2	Ch-3
	Initial heat flux		
1	10	10	10
2	5	5	5
3	10	0	10
4	5	0	5
	Heat flux during transient		
1	10	Heat flux ↓	10
2	5	Heat flux ↓	5
3	10	Heat flux ↑	10
4	5	Heat flux ↑	5

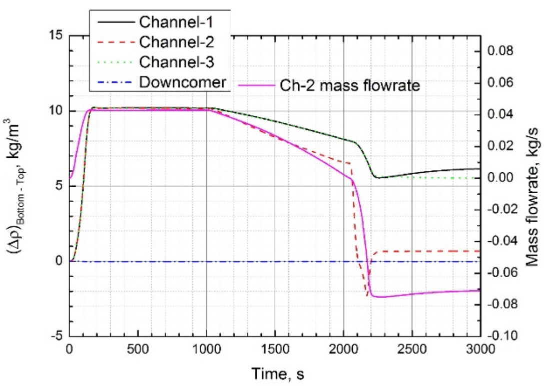

Fig. 2. Case 1 - Density difference between bottom and top of each channel and mass flow rate for channel 2 (10w/s decreasing)

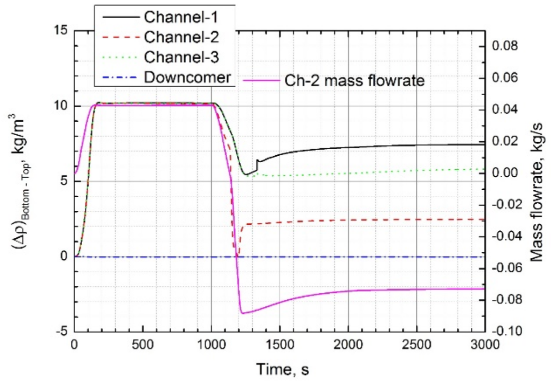

Fig. 3. Case 1 - Density difference between bottom and top of each channel and mass flow rate for channel 2 (100w/s decreasing)

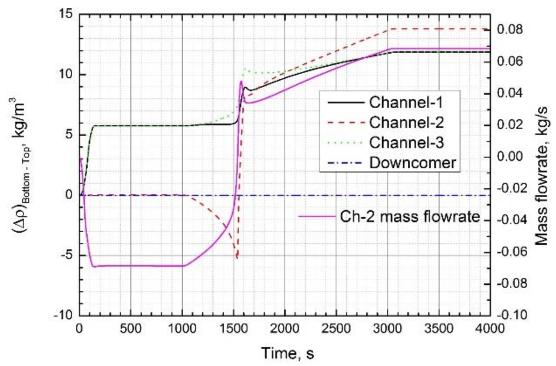

Fig. 4. Case 3 - Density difference between bottom and top of each channel and mass flow rate for channel 2 (10w/s increasing)

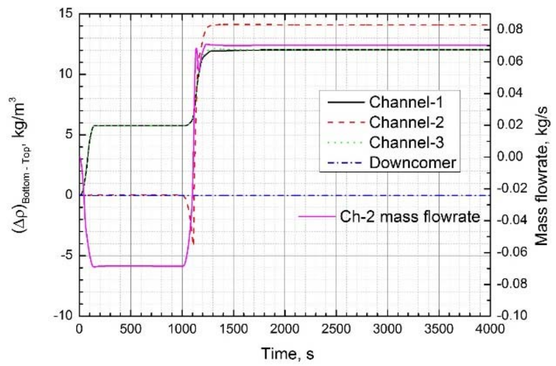

Fig. 5. Case 3 - Density difference between bottom and top of each channel and mass flow rate for channel 2 (100w/s increasing)

2.2 Parametric study

In Section 2.1, the objective is to complete the steady and transient simulations while reproducing the cases that were reported in Ref. 5. In this section, the completed input deck is used to perform sensitivity study on some parameters that may affect the flow instability.

The factors affecting the flow instability can be broadly divided into the systematic part and the part by the characteristics of the REALP5/MOD3 computer code. In this section, options affecting REALP5/MOD3 computer code calculation are evaluated when simulating natural circulation.

Fig. 6 shows only the flow of channel 2 where reversal flow occurs, and the following three cases are simulated;

1) Cross flow between channels
2) Heat structure option change
3) Plenum option change

It can be seen that the overall phenomenon is similar in the remaining cases, except when the cross flow between the channels is present. However, the steady-state flow rate of each channel for these events is significantly lower than the flow and power of the SMR. Therefore, it will be important to confirm the flow instability study to generate a metastable map under the condition similar to the SMRs.

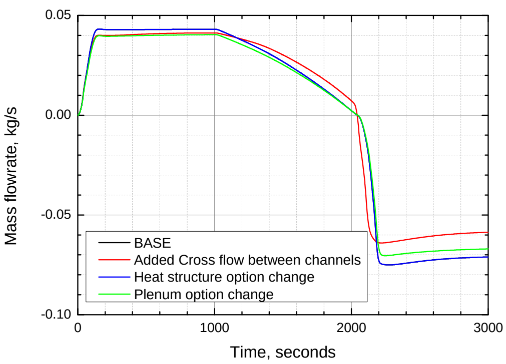

Fig. 6. Mass flowrate (Channel 2) - additional parameter study

2.3 Rod withdrawal simulation

In the previous analysis, the heat flux was simulated to be evenly distributed to the channel (pipe component). In a real nuclear power plant, however, as the control rod is withdrawn, the core begins to gradually heat up from the bottom by positive reactivity insertion. If the ejection speed of the control rods is different from each other, the flow instability may occur.

Fig. 7 shows a simplified drawing of the phenomenon of heating from the bottom of the core while the control rod is being pulled out. Fig. 8 shows that channel 2 control rod is pulled out at relatively slow rate compared to channels 1 and 3. The slope is assumed to be the heat flux rate that is transferred to each heat structure of channel as the control rod is withdrawn. The withdrawal speeds of all channels are equal to 10 w/s. Although these assumptions are not identical to the actual phenomenon, there is no problem in confirming that flow instability can be caused by the difference in control rod withdrawal speed. Fig. 9 shows the flow rate for each channel. As expected, the flow at channel 2, where the control rod is slowly ejected, is initially formed downward direction. After 1600 seconds, the flow rate and flow direction of channel 2 become equal to channels 1 and 3.

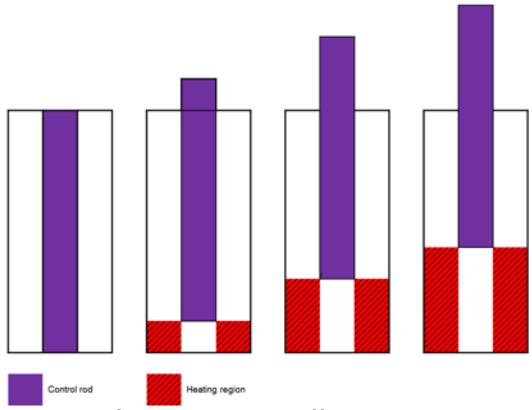

Fig. 7. Simplified drawing with different control rod withdrawal speed

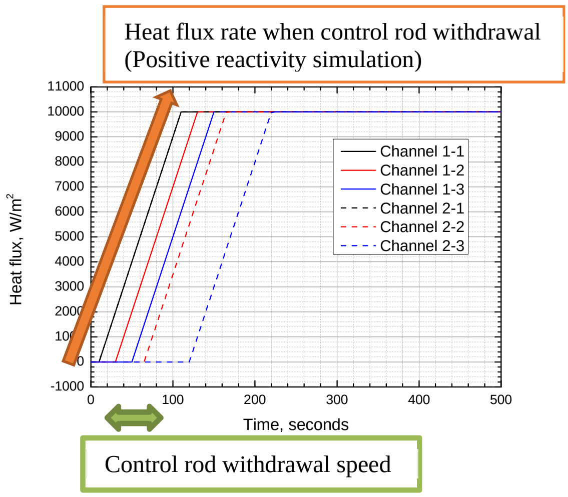

Fig. 8. Heat flux with different control rod withdrawal speed

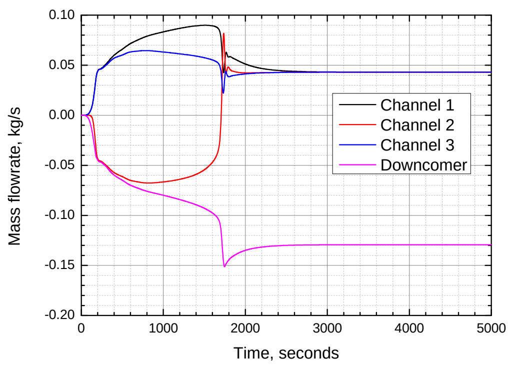

Fig. 9. Mass flowrate with different control rod withdrawal speed

3. Summary and Further Works

In a SMR operating with natural circulation only, an additional heat source is required because the RCP cannot be used as in the commercial PWRs when heating the initial core. In this paper, the case of heating the RCS using only the core power was examined. It was found that a flow instability during formation of initial natural circulation flow and instability of flow distribution within the core fuel channels may occur.

RELAP5/MOD3 input was completed based on the previous research and experiments on a parallel-channel system before simulating the natural circulation case of SMR. Also, additional sensitivity analysis was performed, and it was confirmed that flow instability could be caused by control rod withdrawal speed difference by simulating the phenomenon that may appear when the actual control rod is withdrawn from the fuels.

In the next phase, the completion of the metastable map through dimensionless parameterization of variables that can affect flow instability as performed in References 4 and 5 for the parallel channels will be followed. The second is to verify the metastable map using the input deck simulating the SMR operating conditions with similarity. Finally, the SMR operation procedure may be established by examining what operation area is unstable during the initial start-up of a SMR.

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