Preliminary Study of Single Phase Natural Circulation Flow Instability in Multiple Parallel-Channel Systems with RELAP5/MOD3

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1. Introduction

It has been identified in the previous works that a small and medium-sized reactor (SMR) with full power natural circulation capability during normal operation requires an additional heat source. The internal heating option was examined, which uses the core power to initiate the natural circulation flow [1].

Table 1 shows APR1400 operation mode [2], and it is divided into 6 modes in total. A nuclear power plant with forced circulation design, a reactor coolant pump (RCP) provides enough energy to heat up the reactor coolant system (RCS) from ambient temperature and pressure to greater than the minimum temperature and pressure before the nuclear reactor core produces any heat during startup. However, a nuclear power plant operating with the natural circulation, only core power can be used from mode 5 to full power mode if there is no external heat or flow source, and flow instability may occur at this time by unbalanced heating between fuel channels.

Table 1 Operation Mode for APR1400

Mode	Title	Cold leg temperatures	Forced Convection	Natural Convection
1	Power Operation	N/A	Control rod Power increasing	Nuclear heat
2	Startup	N/A		
3	Hot Standby	≥ 350 °F (177 °C)	RCP operation Temperature ↑ Flow formation Flow direction	
4	Hot Shutdown	350 °F > T_{cold} ≥ 210 °F (177 °C) (99 °C)		
5	Cold Shutdown	≤ 210 °F (99 °C)		
6	Refueling	N/A		

Prior to studying the single phase natural circulation flow instability that can occur during startup in a natural SMR, study of flow instability that may occur in multiple parallel-channel systems is needed.

The single phase flow instability that can occur in multiple parallel-channel has been studied previously in the literature [3, 4]. However, these previous studies are not sufficient to reflect the configuration of the SMR core and operating conditions.

In this paper, finding multiple parallel-channels that can represent the shape of the SMR fuel channel is presented, and the phenomena are studied by using the RELAP5/MOD3 [5] computer code.

2. Multiple Parallel-Channel Systems

A typical multiple parallel-channel system consists of several channels and one downcomer, as shown in Fig. 1, where the lengths of the heating channel and downcomer are the same. However, in order to represent the shape of the actual SMR core, the heating length and downcomer length should be different as shown in Fig 2.

Furthermore, the fluid is heated in the channel as shown in Fig. 3, mixed in the upper plenum, and then directed to the cooler. It is more realistic to consider cross flow between channels, but at this stage, cross flow between channels is not considered. The length ratio between the channel and the downcomer is arbitrarily assumed to be 0.5, but further study is required to evaluate if the assumption is valid. Various multiple parallel-channel systems in this paper are summarized in Table 2 and shown in Fig. 1 through 9.

Table 2 Configuration of Multiple Parallel-Channel Systems

System #	Heated CH	DC	Heated CH/ DC Length ratio	Upper plenum
1	3	1	1	X
2			0.5	X
3			0.5	O
4	5		1	X
5			0.5	X
6			0.5	O
7	4	2	1	X
8			0.5	X
9			0.5	O

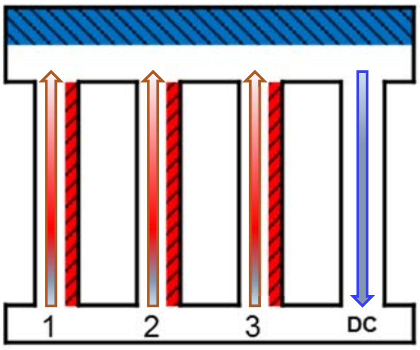

Fig. 1. Three channel with one downcomer (System 1)

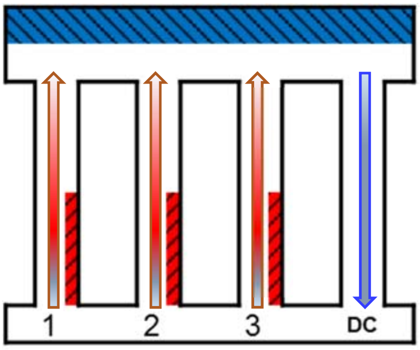

Fig. 2. Three channel with one downcomer and half-heating (System 2)

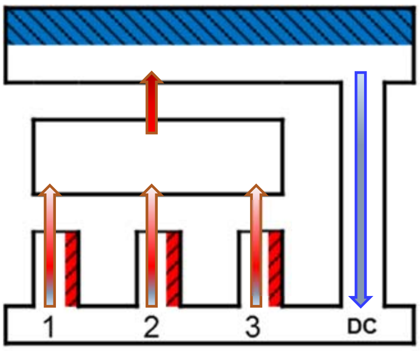

Fig. 3. Three channel with one downcomer, half-heating, and core outlet region (System 3)

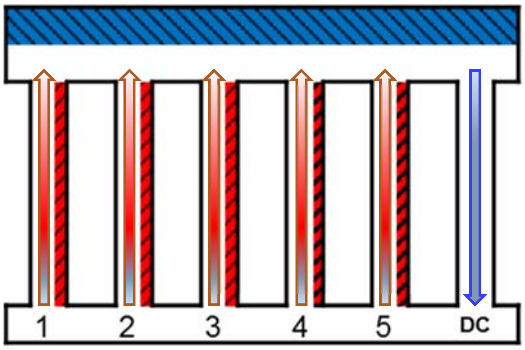

Fig. 4. Five channel with one downcomer (System 4)

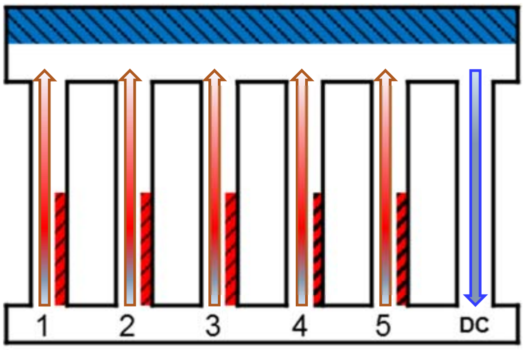

Fig. 5. Five channel with one downcomer, half-heating (System 5)

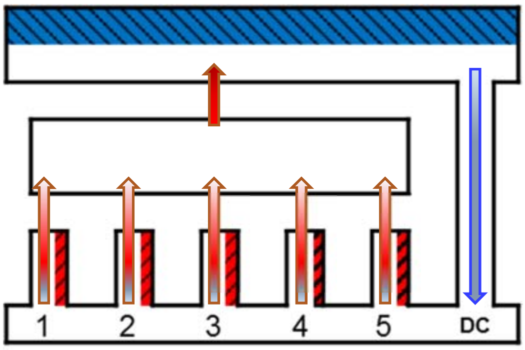

Fig. 6. Five channel with one downcomer, half-heating, and core outlet region (System 6)

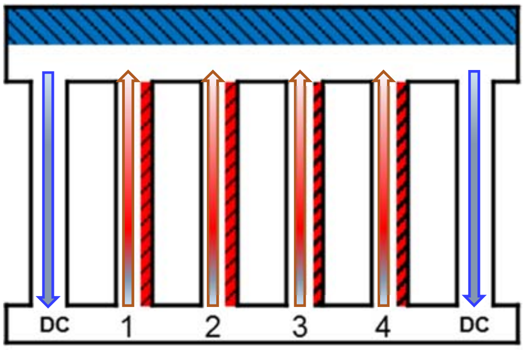

Fig. 7. Four channel with two downcomer (System 7)

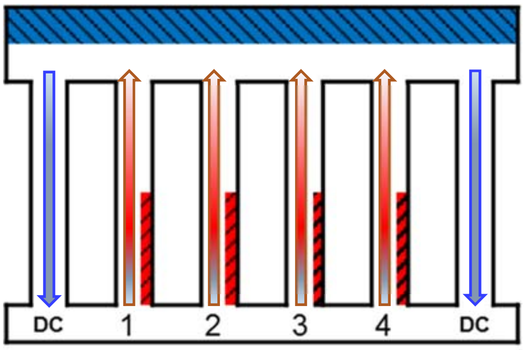

Fig. 8. Four channel with two downcomer, half-heating (System 8)

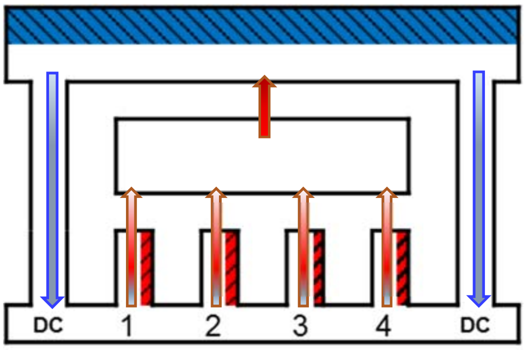

Fig. 9. Four channel with two downcomer, half-heating, and core outlet region (System 9)

3. Start-up Simulation

Initial conditions were set as follows to simulate unbalanced heating between channels at start up, and the initial heat flux ratio between channel 2 and other channels was arbitrarily set at 0.5.

Initial Condition:
Channel 1, 3, 4, 5: Initial heat flux rate = 100 W/m^2s
Final heat flux = 10,000 W/m^2 at 100 sec
Channel 2: Initial heat flux rate = 50 W/m^2s

Fig. 10 through 12 show the mass flow rates of cases 1, 4 and 7 with three channels and one downcomer. As shown in the figure, flow reversal occurs because the amount of heat flux applied to channel 2 is smaller than others at the beginning. Then, as the final heat flux of channel 2 reaches the same value as the other channel, the flow rate of channel 2 gradually reaches the same value as the other channel.

Table 3 shows the tendency of steady state mass flow rate (when uniformly applying 100 W/m^2s heat flux to each channel) in each multiple parallel-channel systems.

As shown in Table 3, if the lengths are the same regardless of the number of channels and downcomer (case 1, 4, channel types studied in existing references [3, 4]), regardless of the heat flux ratio between channels, the steady state mass flow rate is formed as the final heat flux of channel 2 reaches the same value as the other channel.

The important results are for systems 3, 6 and 9 simulated similar to the actual SMR core geometry. In previous studies, flow reversal occurred in unbalanced channel heating. Under the simulated conditions, flow reversal does not occur even if the channel is heated to zero. Further investigation will focus on this area to generalize the findings reported in this paper.

Table 3 Start-up simulation

System	Case	Final heat flux in CH2 (W/m^2)	Final heat Flux ratio	$\frac{\dot{m}_2}{\dot{m}_{steady}}$
1	1	20,000 at 400 sec	1	1
2	2	20,000 at 400 sec	1	$\frac{-0.07621}{0.05056} = -1.50$
	3	30,000 at 600 sec	1.5	$\frac{0.06453}{0.04712} = 1.37$
	4	30,000 at 600 sec 20,000 at 800 sec	1.5 ➔ 1	1
3	5	20,000 at 400 sec	1	1
	6	30,000 at 600 sec	1.5	$\frac{0.06463}{0.04751} = 1.36$
	7	30,000 at 600 sec 20,000 at 800 sec	1.5 ➔ 1	1
4	8	20,000 at 400 sec	1	1
5	9	20,000 at 400 sec	1	$\frac{-0.1236}{0.04268} = -2.89$
	10	30,000 at 600 sec	1.5	$\frac{0.05914}{0.04067} = 1.45$
	11	30,000 at 600 sec 20,000 at 800 sec	1.5 ➔ 1	1
6	12	20,000 at 400 sec	1	1
	13	30,000 at 600 sec	1.5	$\frac{0.05119}{0.03607} = 1.42$
	14	30,000 at 600 sec 20,000 at 800 sec	1.5 ➔ 1	1
7	15	20,000 at 400 sec	1	1
8	16	20,000 at 400 sec	1	1
	17	30,000 at 600 sec	1.5	$\frac{0.07812}{0.05784} = 1.35$
	18	30,000 at 600 sec 20,000 at 800 sec	1.5 ➔ 1	1
9	19	20,000 at 400 sec	1	1
	20	30,000 at 600 sec	1.5	$\frac{0.07832}{0.06086} = 1.29$
	21	30,000 at 600 sec 20,000 at 800 sec	1.5 ➔ 1	1

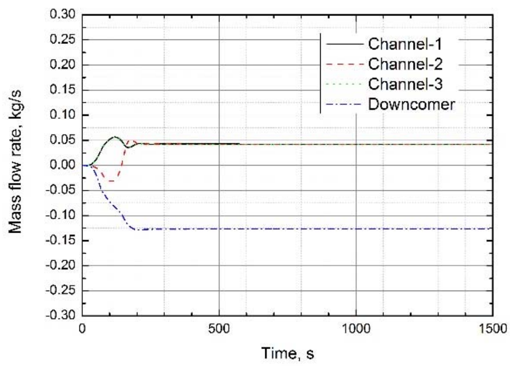

Fig. 10. Mass flowrate for Case 1

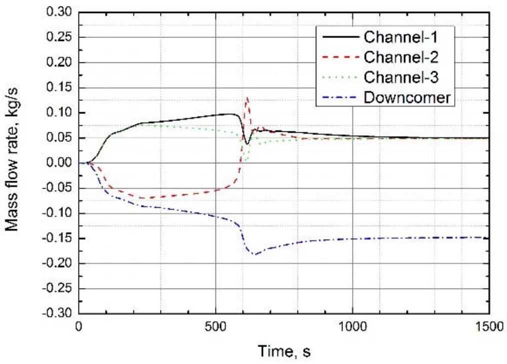

Fig. 11. Mass flowrate for Case 4

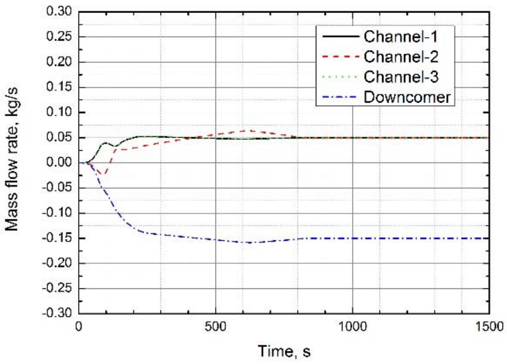

Fig. 12. Mass flowrate for Case 7

3. Summary and Further Works

In the past, single phase natural circulation flow instability was studied under simple multiple parallel-channel systems with the same channel and downcomer lengths. However, there are limitations when completing a stability map using a simple channel geometry and applying or comparing it to an actual SMR configuration.

Therefore, to overcome these limitations, the diverse channel configurations are examined. 21 different cases with nine different channel systems are simulated using RELAP5 / MOD3 computer code to see how the behavior of each system is different. It was confirmed that the simulated case (4 heated channels, 2 downcomer, upper plenum) similar to the SMR core model showed different instability tendency from the previous study.

In the future, the modeling of system 9 will be more fully complemented and will be used to complete the stability map. After that, simple loops will be completed using SMR design data such as Nuscale or Multi-Application Small Light Water Reactor. As the actual start-up situation, the unbalanced heating between channels occurring as the control rod is withdrawn will be simulated and the stability map will be completed.

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[5] RELAP5/MOD3.3 Code Manual "Volume II:Appendix A. Input Requirements," January, 2002.