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Investigation of the Natural Circulation Flow Map in NuScale Small Modular Reactor

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Abstract

Natural Circulation (NC) is an important mechanism in several industrial systems and knowledge of its behavior is of interest to nuclear reactor design, operation and safety. The main safety issue in present nuclear reactors is to ensure the sufficient removal of decay heat during accidents. Recently, Small Modular Reactors (SMRs) have increasingly received a lot of positive attention and even several types of these reactors are in different stages of design and construction. Some of this SMRs such as NuScale are designed to operate in full NC mode as the main mechanism of the primary coolant drive force for heat removal from the reactor core during normal operation. The present study deals with investigation of Natural Circulation Flow Map (NCFM) in NuScale reactor as one of the SMRs that operate in full NC mode. At first, NuScale reactor elements are modeled with RELAP5 thermal-hydraulic code. Then, after the verification of the steady-state modeling, the operational point of the NuScale reactor is indicated in NCFM that is based on the database of different PWR simulators (gathered from the experimental test facilities). The evaluation of Natural Circulation Performance (NCP) of this reactor is proved the good design of NCP during normal operation.

Keywords: Natural Circulation Performance (NCP), Integral Small Modular Reactors, Full Natural Operating Reactors, RELAP5.

1. Introduction

The main safety objective of the nuclear reactor is to ensure the sufficient removal of generated heat. At the nuclear power plants traditionally, the primary loop pumps provide forced circulation to remove the heat from the core and transfer it to the secondary cycle through Steam Generators (SGs) and natural circulation (NC) may be used for cooling safety purposes in low powers. NC in a Pressurized Water Nuclear Reactors (PWR) occurs due to the presence of the heat source (core) and the heat sink (SGs). In a gravity environment, with core located at a lower elevation than steam generators, those driving forces generate a flowrate suitable for removing nuclear fission decay power [1]. At present, the NC core power removal capability is only exploited for accident situations, basically to demonstrate the inherent safety features of the plants.

Small Modular Reactor (SMR) deployment, with its enhanced safety features and multi-purpose applications, proposes new opportunities in the nuclear industry and global energy systems and numerous researchers all over the world have been working on this concept [2, 3]. Also, the new design of SMRs are proposed to operate in full NC condition. Some of these SMRs, Such as NuScale and CAREM, have been designed to remove overall heat by NC as the main mechanism of primary coolant drive force. In this study, the NC performance of the NuScale reactor is assessed based on NCFM that are collected from the experimental test facilities and simulators of the PWRs.

2. Materials and methods

2.1. Description of the Nuscale Reactor

NuScale power plant is an SMR design (under licensing process) that supports the operation of up to 12 NuScale power modules (NPM). Each NPM is an advanced integrated pressurized water reactor (IPWR) with 45 MWe power that the primary coolant is based on natural circulation. General specifications of each NPM has been presented in Table 1. Figure 1 shows the Nuscale reactor schematic, along with primary and secondary side coolant path lines [4].

The NC driven flow in the Nuscale reactor is one of the important features that distinguish this reactor from the other SMR designs. Inside the reactor pressure vessel, the heated coolant water in the core outlet passes through the central riser channel and is cooled by a helical one-through SG. The coolant turns to the core entrance by the down-comer after cooling through the SG.

Table 1: NuScale power modules characteristics [4]

Parameter	**Value**
Nominal gross electrical output (MWe)	50
Core thermal output (MWth)	160
Number of fuel assemblies	37
Fuel assembly lattice	17×17
Fuel rods per fuel assembly	264
Effective fuel length (ft)	6.56
Number of control rod assemblies	16
Operating pressure (psia)	1850
Hot leg temperature (°F)	590
Steam generator type	Helical coil
Number of the steam generator tubes	1380
Steam generator heat transfer area (ft^2)	Approximately 18,000

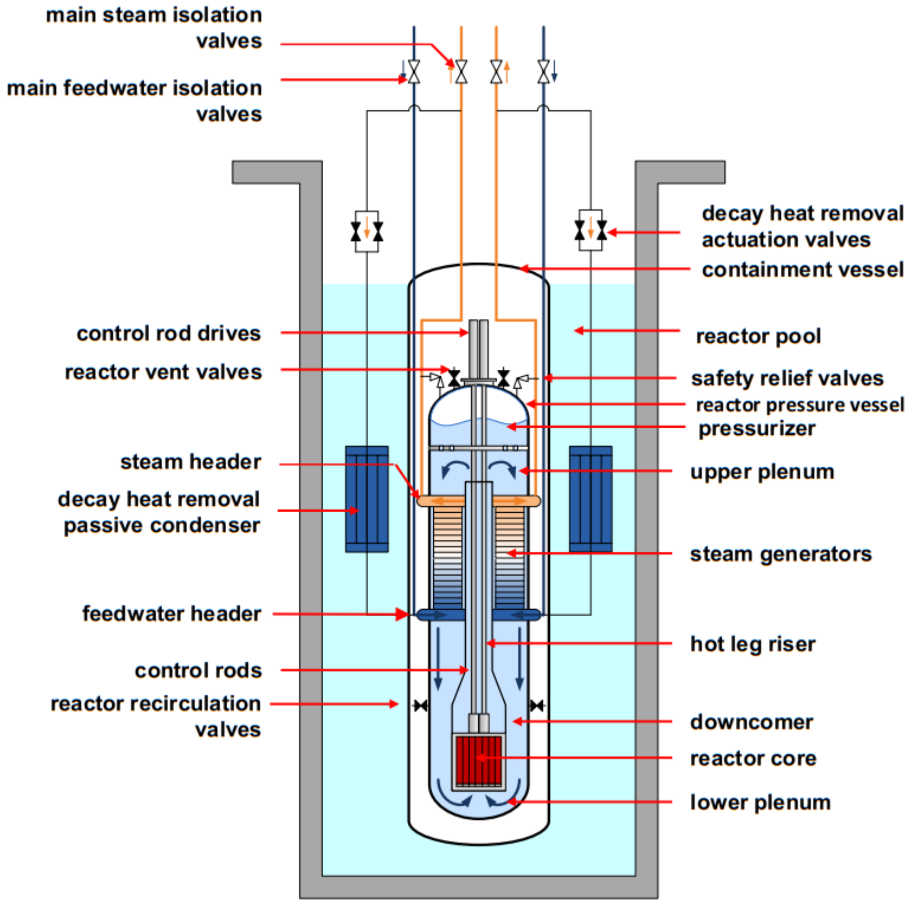

Figure 1: The primary loop component and safety-related systems [4].

2.2. Natural Circulation Phenomena

2.2.1 Natural Circulation Flow Regimes

The Natural circulation mechanism could be used for the residual heat removal and safety systems or depend on reactor design, at the naturally driven systems at the normal and other operational conditions. Primary flow NC pattern is categorized to Single Phase NC (SPNC), Two-Phase NC (TPNC), Siphon Condensation NC (SCNC), Reflux Condensation NC (RCNC), and finally, the dry-out occurs [1, 7].

- **SPNC:** NC at the single-phase which no void exists at the top of the core. In this phase, the forcing derives because of fluid density differences in core and SG.
- **TPNC:** NC in a stable co-current two-phase regime in which the pressure drops and coolant loss at the primary loop cause two-phase flow formation.
- **SCNC:** The unstable two-phase flow in which siphon condensation occurs and the main mass flowrate in this regime is close to 60% of the initial value.
- **RCNC:** In this regime, stable reflux condensation occurs, and the main mass flow rate is close to 30-40% of the initial value.
- **Dry-out occurrence:** low flow rate of primary coolant in the presence of immense value of void fraction causes film boiling formation with very low heat transfer. Consequently, the heat removal from the fuel rod goes toward instability, which is not acceptable from the technological point of view.

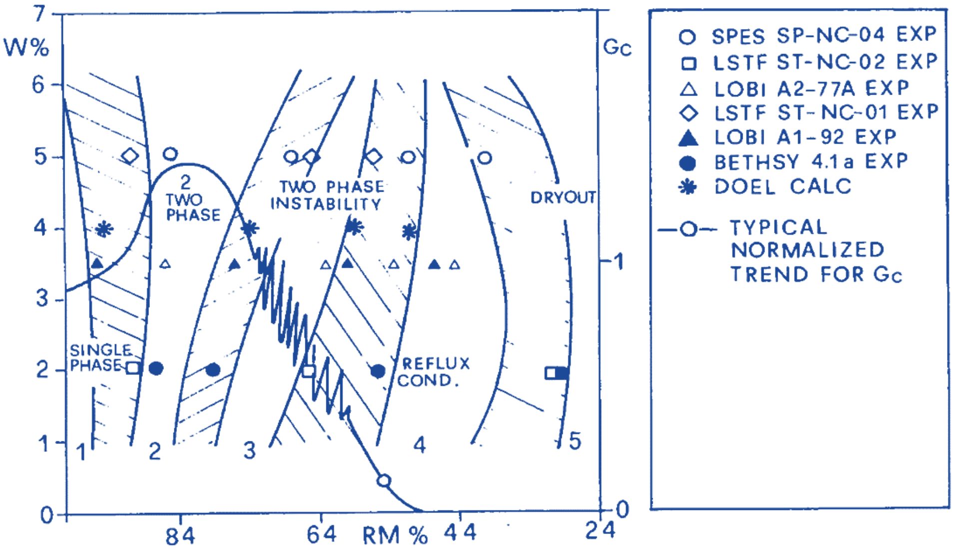

Figure 2: Characterization of NC flow regimes based on experimental data and system code calculations in PWR systems. [1].

The NC flow regimes are summarized in Figure 2, which reports both experimental and calculated data in PWR simulators. The percentage of the core mass flowrate (W) (the vertical axis) versus the residual mass inventory in the primary circuit (RM) (the horizontal axis) is reported in Figure 2.

2.2.2 Natural Circulation Flow Map (NCFM)

The NCFM envelope has been derived from several test facility data with different power and volume, so for taking into account the scaling parameters, the flow rate (G, kg/s) and mass inventory (RM, kg) have been normalized to the power (P, MW) and volume (V, m3), respectively.

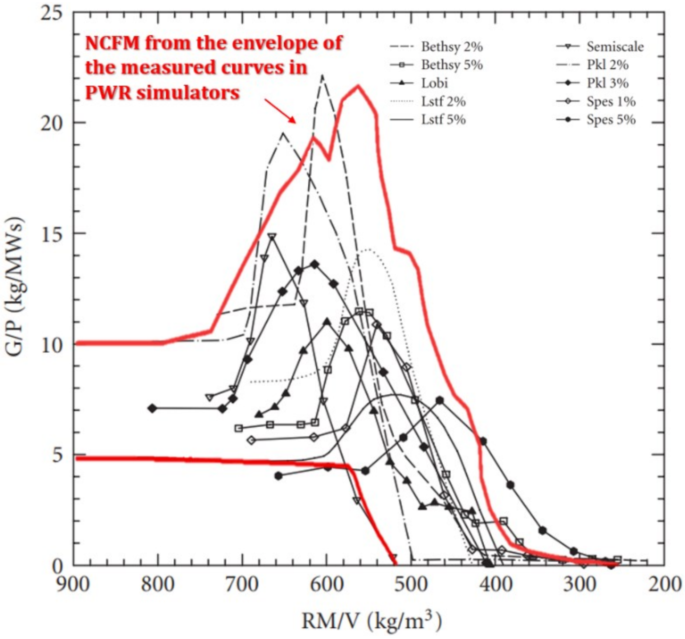

Figure 3: Natural circulation system behavior measured in ten experiments performed in six PWR simulators along with NCFM diagram [5].

The NCFM diagram proposed by D'Auria et al. [1] has been shown in Figure 3. This diagram has attained from several researches based on the database of different PWR TH test facilities including Spes, Semiscale, Pkl, Bethsy, Lobi, and Lstf [8, 9]. At the NC envelope diagram with mass flow rate to power vs. mass inventory to volume axes, when a NC curve or points is placed above the upper boundary or lower than the bottom boundary, the reactor design has a well NCP. For the good performance of NC, at the single-phase and two-phase, the high initial flow rate and high maximum flow rate should be reached, respectively.

3. Thermohydraulic Modeling and Results

3.1. NuScale Steady-state Modeling

In this study, the primary and secondary side elements, such as the core channels, riser, pressurizer, SG, and down-comer, were modeled with RELAP5/Mod 3.3 best estimate TH code. Figure 4 shows the nodalization of the Nuscale primary and secondary side elements.

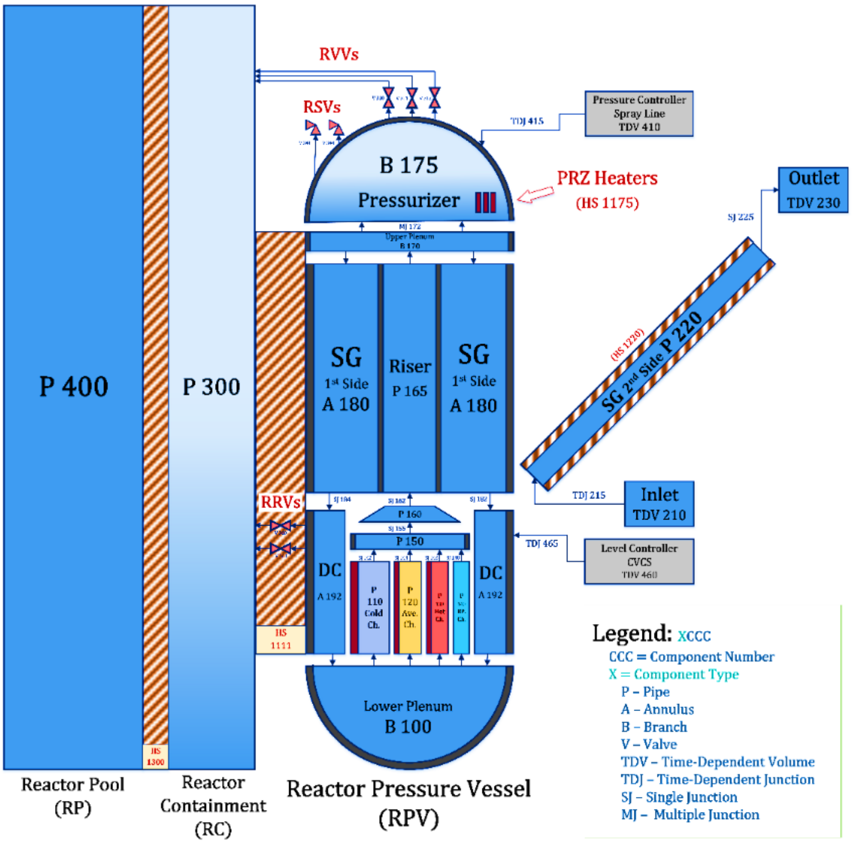

Figure 4: Nodalization of NuScale reactor with RELAP5/Mod3.3.

At the proposed model, the core consists of three heated channels (Hot, Average, and Cold) and one bypass channel. Relative radial power distribution is the basis of the fuel assemblies grouping in the channels. The relative radial power distribution is defined as:

$$K_q = \frac{P_{FA}}{\bar{P}} \tag{1}$$

P_{FA} indicates the power of the one fuel assemblies while $\bar{P}$ is the average power of the fuel assemblies. During the life cycle of the reactor, K_q continually changes. Thus, the condition is considered at the beginning of the cycle (BOC), in which the fuels are fresh. Figure 5 shows the distribution of the K_q in BOC along with core modeling channels. The number of fuel assemblies in hot, average, and cold channels are 2, 15, and 20, respectively, with 1.137, 1.0834, and 0.9236 relative radial power. Also, all channels include 10 axial nodes.

		1 0.895	2 0.911	3 0.888		
	4 1.033	5 1.137	6 0.957	7 1.135	8 1.033	
9 0.888	10 1.135	11 1.054	12 0.967	13 1.054	14 1.136	15 0.895
16 0.911	17 0.957	18 0.967	19 1.091	20 0.967	21 0.957	22 0.911
23 0.895	24 1.136	25 1.054	26 0.967	27 1.054	28 1.135	29 0.888
	30 1.033	31 1.135	32 0.957	33 1.137	34 1.033	
		35 0.888	36 0.911	37 0.895		

Figure 5: The fuel assemblies' relative radial power (K_q) at BOC with including modeling channels.

The axial power distribution (K_a) at the beginning, middle, and end of the reactor operating cycle are shown in Figure 6 [4]. The heat generation in each of the nodes (q_n) is defined as:

$$q_n = \bar{K}_q \times \bar{K}_a \tag{2}$$

$\bar{K}_q$ is the average of the fuel assemblies radial power distribution in each of the modeling channels. $\bar{K}_a$ is the average axial power distribution in each of the axial nodes.

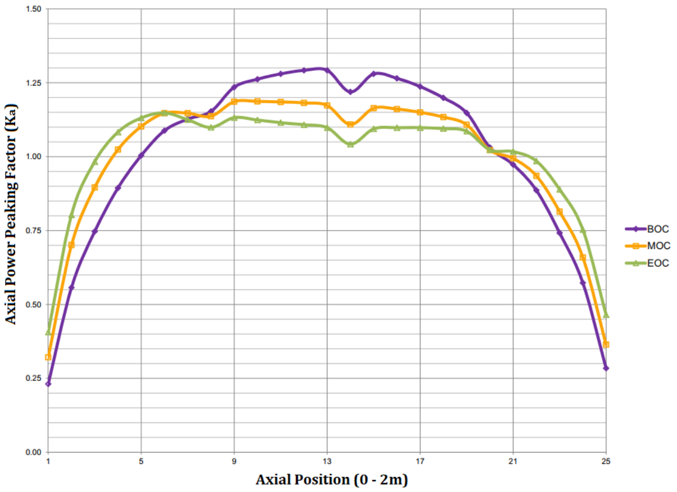

Figure 6: Axial power distribution (K_a) at beginning, middle, and end of cycle [1].

3.2. Verification of Steady-state Results

This section presents the results of the steady-state simulation. To qualify the nodalization and modeling, the steady-state results for the base case is verified with NuScale operational designed values based on standard qualification procedure [10]. Table 2 shows the comparison of the RELAP5 evaluated results with the design values during the normal operation condition of the NuScale reactor. The attained results show that the modeling errors are in the acceptable error ranges.

Table 2: The steady-state results of NuScale reactor during normal operation

Item	Design value	Model value	Acceptable error %	Modelling error %
Overall reactor pressure vessel volume (m3)	70.8204	70.8205	1.0	0.0001
Primary side mass flow rate (Kg/s)	587.15	587.64	2.0	0.08
Secondary side mass flow rate (Kg/s)	67.068	67.7	2.0	1.02
Secondary side pressure (MPa)	12.755	12.751	0.1	0.03
Primary side pressure (MPa)	3.448	3.451	0.1	0.09
Core inlet temperature (K)	531.48	533.65	0.5	0.4
Core outlet temperature (K)	587.04	584.58	0.5	0.42
Core bypass mass flow rate (Kg/s)	42.86	45.46	10.0	6.0

3.3. Investigation of the NCP in NuScale Reactor

The NFCM can be used to evaluate the NCP of PWR systems. This is specifically helpful for the design of innovative reactors. According to the NCFM envelope diagram in section 2.2.2, G/P vs RM/V values of a reactor should be located at the top of the upper boundary or lower than bottom boundary to show good NCP.

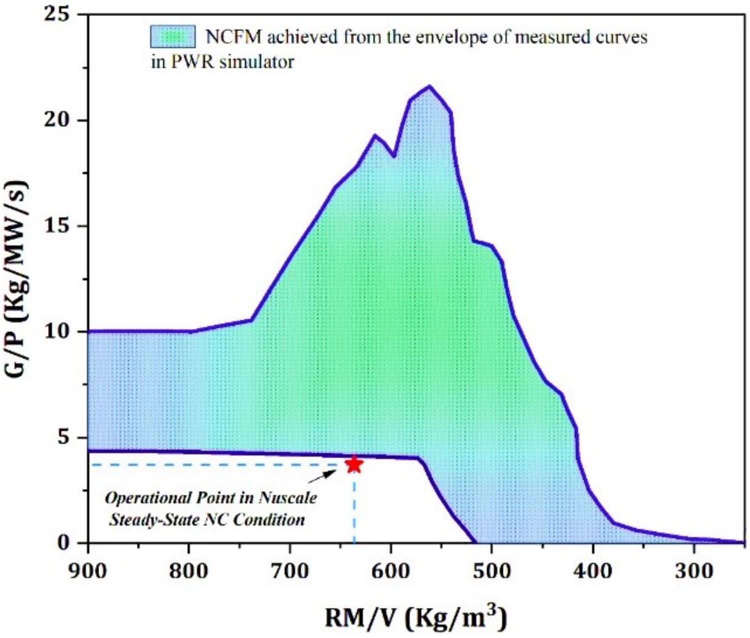

Figure7: The NuScale steady-state operational point in the NCFM diagram.

In this paper, after extracting the steady-state results, the Nuscale operating NCP in steady-state is evaluated with calculations inside RELAP5 code. According to Figure 7, this point is located just below the lower boundary in NCFM diagram. Therefore, this diagram shows that the reactor has a suitable design in single-phase operation mode.

4. Conclusion

Natural Circulation (NC) besides the passive safety systems, could be used as the primary coolant main drive mechanism at the normal operation condition. Several Small Modular Reactors (SMRs) have been proposed to use NC main drive flow mechanism. As mentioned in the article, the NCFM engineering tool has been directly derived from the analysis of experimental data. In this study, the use of the NCFM has been extended to the NuScale reactor during normal operation. Comparison between the attained results and designers' data showed that the differences are in the acceptable range for the steady-state condition. Then the NC of NuSclae design was established and mapped on NCFM envelope. The evaluation of NC of NuSclae showed the proper NC performance of this reactor and proved the good design of NuScale NC during normal operation. Also, the NCFM shows its capability to judge the NCP very well.

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