ORGINAL RESEARCH ARTICLE

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 these 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 the Natural Circulation Flow Map (NCFM) investigation in the 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 has proved the good design of NCP during normal operation in comparing typical PWRs operations in high power cases.

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

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. The 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 is 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.

Materials and methods

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 have been presented in Table 1. Fig. 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 Steam Generator (SG). The coolant turns to the core entrance by the down-comer after cooling through the SG. The other components of Nuscale reactor along with flow pass line are shown in Fig. 1.

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Table 12. 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 (ft2)	Approximately 18,000
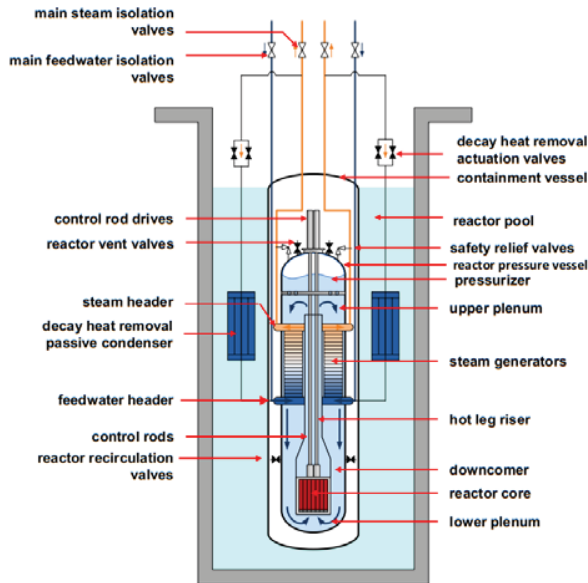
Figure 2. The primary loop component and safety-related systems [4]

Natural Circulation Phenomena

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. The 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]. The NC flow regimes are illustrated in Fig. 2 that white areas indicate the flow regimes, and the shadowed areas show transition regions.

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.
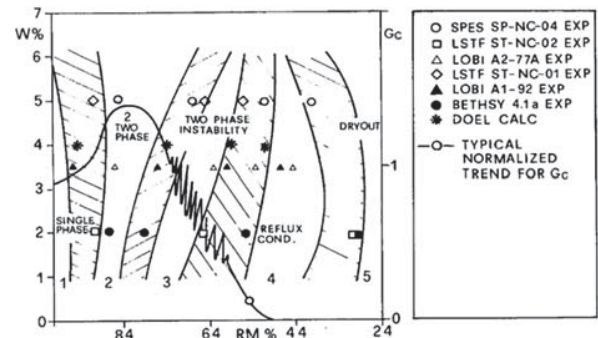

Figure 2. Characterization of NC flow regimes based on experimental data and system code calculations in PWR systems [1]

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.

The NCFM diagram proposed by D'Auria et al. [1] has been shown in Fig. 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. Generally, whatever the points have been located at the higher positions show a better natural circulation performance (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,
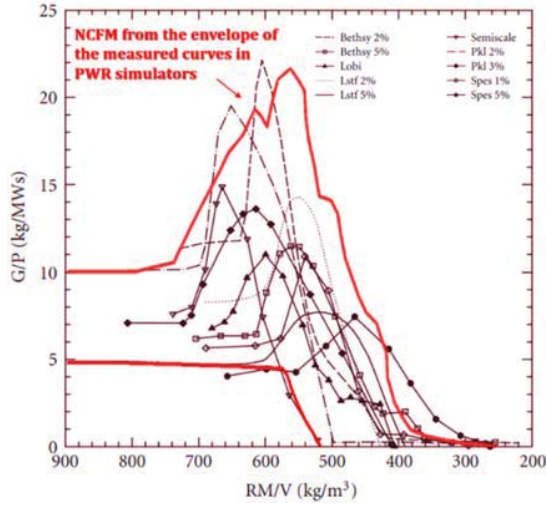
respectively.

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

NuScale Steady-state Modeling

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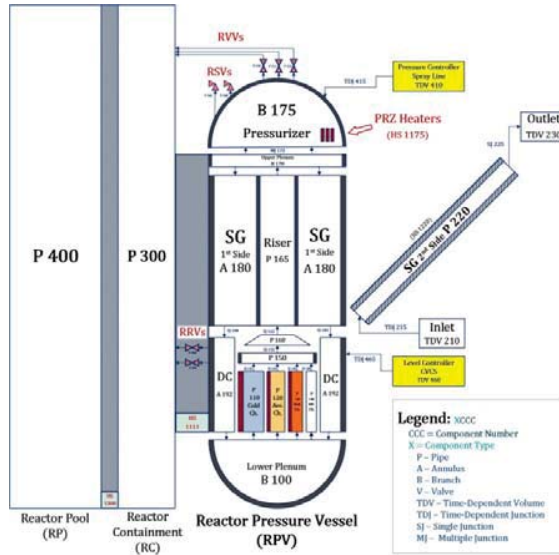

Figure 4. Nodalization of NuScale reactor with RELAP5/Mod3.3

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:

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

P_{FA} indicates the power of the one fuel assemblies while $\bar{P}$ is the average power of the fuel assemblies [12, 13]. 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. Fig. 5 shows the distribution of the K_q in BOC along with core modelling 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.
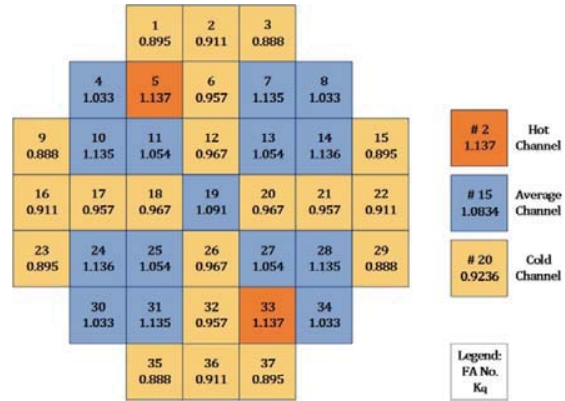

Figure 5. The fuel assemblies' relative radial power (K_q) at BOC with including modeling channels
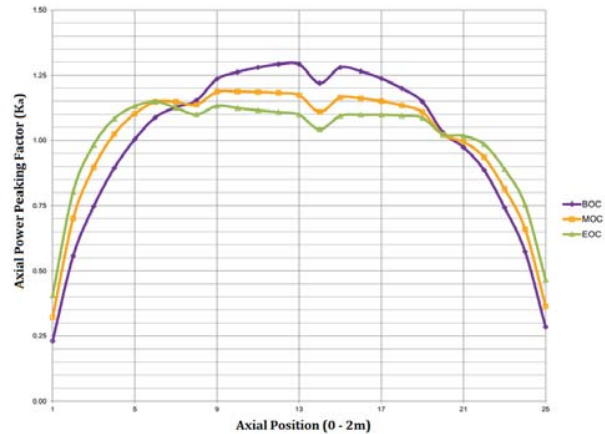

Figure 6. Axial power distribution ($\bar{K}_a$) at beginning, middle, and end of cycle [4]

The axial power distribution ($\bar{K}_a$) at the beginning, middle, and end of the reactor operating cycle are shown in Fig. 6 [4]. The heat generation in each of the nodes (q_n) is defined as:

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

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

Verification of Steady-state Results

This section presents the results of the steady-state simulation. To qualify the nodalization and modelling, 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 modelling errors are in the acceptable error ranges.

Table 2. The verification of resultsduring normal operation

Item	Design value	Model value	Accept-table error %	Model-ling error %
Overall reactor pressure vessel volume (m³)	70.820	70.820	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

Investigation of the NCP in NuScale Reactor

The NCFM 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 the previous section, G/P vs. RM/V values of a reactor show NCP in operational cases.At the NCFM envelope diagram, the very left side of the diagram represents the single-phase NC, and by moving toward the right side, two-phase NC with the maximum in NC flowrate, siphon-condensation oscillation NC,

reflux-condensing NC, and dry-out regimes are experienced. Within all points of the map between two boundaries, NC is enough to remove core decay power (low power cases). For decay powers, the upper curve can be considered the best NCP measured in PWR geometry. Generally, whatever the points have been located at the higher positions show a better NCP. For high power NC (not decay power), the G/P ratio is usually located lower than the bottom boundary, and the closer to the envelope indicates the better NCP. For comparison between two high power cases NCP by using the NCFM, each one has an upper position, has a better NCP [1]. According to the previous works, several code runs have been performed to demonstrate the possibility of operating the NPP at different core powers in NC without dry-out occurrence. These operational cases are summarized for a PWR in Table 3. The study was carried out by utilizing a qualified PWR NPP nodalization suitable for the RELAP5 code. All the reported data related to conditions where core power equals SG removed power. The void content in the loop predominantly affects the NC core flowrate. The mass inventory in the primary loop and the upper plenum void values also reported in Table 3 give an idea of the loop's void content. At limit values for core flowrate, i.e., close to the dry-out condition, the non-linear relationship is calculated between core flowrate and core power. A complex relationship also links core flowrate and the SG conditions, including pressure and feedwater temperature. Boundary conditions in the primary and secondary system have been varied to this aim, e.g., cases 21, 23, and 25 in Table 3. The NCFM is derived for low values of core power (decay heat) but appears useful for high power values (20% power of a typical PWR, case 3 in Table 3, which has been placed lower than the bottom boundary with a single-phase NC). Also, case 2 shows single-phase NC in low powers (3% power of a typical PWR) placed near the upper boundary.

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 Fig. 7, this point is located just below the lower boundary in the NCFM diagram. Therefore, this diagram shows that the reactor has a suitable design in single-phase operation modein comparing typical PWRs operations in high power cases that are shown in Fig. 8. In other words, the 20% PWR power is a high-power condition, and a comparison between these points and the NuScale G/P value shows the better NCP of NuScale than a typical PWR design. Shift-up in NCP is demonstrated in Fig. 8.
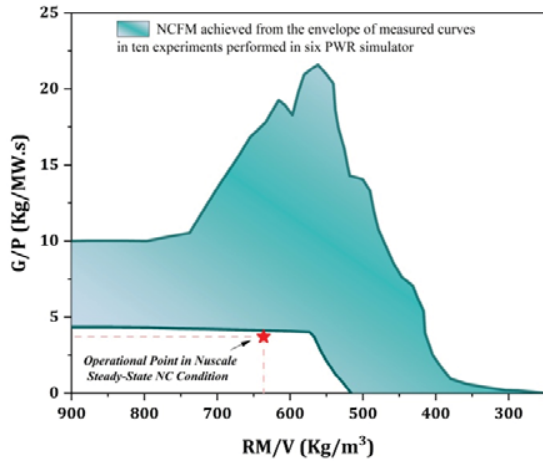
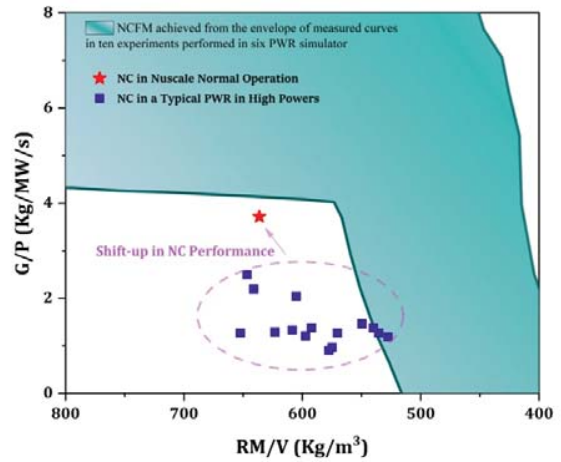**Figure 7.** The NuScale steady-state operational point in the NCFM diagram

Figure 8. The NuScale steady-state operational point comparison with a PWR high power operational cases.

Table 3. The NC performance during several operational cases in a typical PWR [1]

No	ID	P MW/%	G (Kg/s)/%	SG PRE MPa	RM KgE5/%	PS PRE MPa	UP T/Tsat K	UP Void -	G/P Kg/sMW	RM/V Kg/m3
1#	KK01	1876/100	9037/100	6.1	1.08/100	15.6	598/618	0.	4.82	647
2^	KK01	56/3.0	520/5.8	8.1*	1.08/100	13.6	577/608	0.	9.28	647
3	KK01	376/20.	930/10.3	6.0*	1.08/100	15.4	615/617	0.	2.47	647
4	KN03	469/25.	1016/11.2	6.0*	1.07/99.1	16.2	620/620	0.10	2.17	641
5	KN04	563/30.	1140/12.6	6.0*	1.01/94.0	16.2	620/620	0.21	2.02	605
6	KN05	938/50.	1370/15.1	6.0*	0.92/85.0	16.2	620/620	0.47	1.46	550
7	KN07	1032/55.	1396/15.4	6.0*	0.90/83.3	16.2	620/620	0.48	1.35	539
8	KN08	1126/60.	1428/15.8	6.0*	0.89/82.9	16.2	620/620	0.49	1.27	536
9	KN09	1219/65.	1450/16.0	6.0*	0.88/82.0	16.2	620/620	0.51	1.19	529
10§	KN10	1313/70.	1490/16.4	6.0*	0.87/80.8	16.2	620/620	0.62	1.13	523
11	KL10	1032/55.	1396/15.4	3.5*	0.99/91.4	16.2	620/620	0.44	1.35	592
12	KL10	1313/70.	1650/18.3	3.5*	0.95/88.2	16.2	620/620	0.49	1.26	571
13§	KL12	1500/80	1492/16.5	3.5*	0.91/84.6	16.2	620/620	0.60	0.99	547
14§	KL11	1688/90.	1523/16.8	3.5*	0.87/80.4	16.2	620/620	0.77	0.90	520
15	LL11	1032/55.	1365/15.1	3.5**	1.01/93.9	16.2	620/620	0.31	1.32	608
16§	LL11	1688/90.	1525/16.9	3.5**	0.93/86.3	16.2	620/620	0.57	0.90	556
17	LL12	1500/80.	1380/15.3	3.5**	0.96/88.8	16.2	620/620	0.49	0.92	575
18	LL13	1032/55.	1300/14.4	2.5**	1.04/96.3	16.2	620/620	0.20	1.26	623
19	LL13	1500/80.	1750/19.4	2.5**	1.00/92.3	16.2	620/620	0.48	1.17	597
20	LL14	1688/90.	1460/16.2	2.5**	0.97/89.4	16.2	620/620	0.50	0.87	578
21§	LL15	1876/100	1587/17.5	2.5**	0.94/86.6	16.2	620/620	0.63	0.85	560
22	HL15	1032/55.	1290/14.3	2.5**	1.09/101.	18.5	631/633	0.01	1.25	652
23§	HL15	1876/100.	1630/18.1	2.5**	0.97/89.3	18.5	633/633	0.58	0.87	578
24	HL16	1032/55.	1295/14.3	2.5+	1.09/101.	18.5	594/633	0.	1.25	652
25§	HL16	1876/100.	1630/18.1	2.5+	0.99/91.4	18.5	633/633	0.50	0.87	590

Nomenclature

ID	Calculation identification	§	Dryout occurrence
G	Core flowrate	#	Nominal working conditions for the system
P	Core Power	^	Reference NC result
PRE	Pressure	*	Feedwater temperature same as in nominal condition
PS	Primary System	**	Feedwater temperature set at 363 K
RM	Mass Inventory in PS	+	Feedwater temperature set at 333 K
T	Fluid Temperature	+	Feedwater flowrate set at 1.3 times the equilibrium value
Tsat	Saturation temperature	UP	Upper Plenum
Void	Void fraction		

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 Natural Circulation Flow Map (NCFM) engineering tool has been directly derived from experimental databases of several thermal-hydraulic test facilities in decay powers or low-powers. 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 the NCFM envelope. The evaluation of NC of the NuSclae reactor showed the better NC performance of this reactorthan typical PWRs design in high-power operational cases. In other words, the NuScale G/P value shows better NC performance than a typical PWR designing high-powers. These results proved the good design of NuScale NC during normal operation.

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