Preliminary Study on the Concept of Boiling Condensing Reactor for Natural Circulation PWR Type SMR

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1. Introduction

Recently, the small modular reactor (SMR) is being actively developed in many countries. There are many types of reactor being developed and some land based water-cooled SMRs are close to the commercialization stage [1]. Safety is more emphasized in SMRs and some PWR type SMRs adopted natural circulation for full power operation to fundamentally eliminate the hazards associated with reactor coolant pumps. However, the size of the reactor pressure vessel (RPV) becomes considerably larger since it requires a high riser to provide natural circulation driving head. This is undesirable in the current trend pursuing a compact design. Therefore, in this paper, the authors propose the concept of a boiling condensing reactor (BCR) that allows in-core boiling in a PWR type natural circulation reactor. By allowing boiling in the reactor core, it is expected that the height of RPV can be greatly reduced due to the improvement of thermal driving head.

2. Concept of Boiling Condensing Reactor

2.1 Natural Circulation Based Integral PWR

PWR type is expected to lead the early commercialization of SMRs. Modularization and compactness are emphasized in SMRs, and therefore many institutions have been developing an integral type PWR in which the steam generator is placed in the reactor pressure vessel. This study also targets the integral type PWR. Fig. 1 shows the reactor pressure vessel of NuScale (USA) and CAREM (Argentina) which are representative full power natural circulation based integral PWR [2,3]. NuScale is under the final phase of the U.S NRC review and CAREM is under construction of a prototype.

To reduce the thermal center difference, some of PWR type single-phase natural circulation reactors, including CAREM, use flashing which refers to the partial evaporation when a saturated liquid undergoes depressurization while rising to the steam generator. Therefore, buoyancy is improved due to the phase change of primary coolant in the riser. Although the buoyancy can be increased, the size of RPV cannot be effectively reduced since the density difference is not maximized at the thermal center.

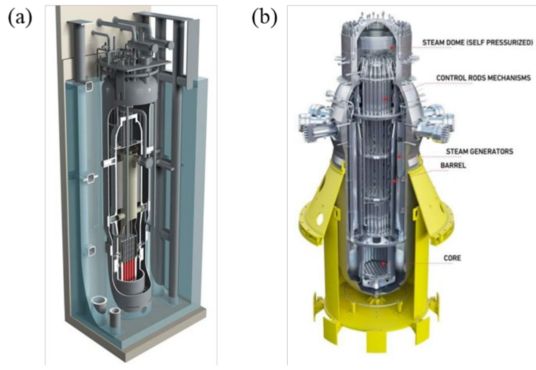

Fig. 1. (a) NuScale (b) CAREM

Table I summarizes some of major technical parameters of integral PWR type SMRs being developed in various countries including CAREM, NuScale, and ACP100 (China) [1]. As can be seen from the table, when natural circulation is adopted, the RPV height becomes very high compared to the reactor capacity. In order to develop a competitive SMRs in the future, the size of RPV needs to be reduced when considering modular production and transportability.

Table I: Technical parameters of integral PWR type SMRs [1]

	CAREM (CNEA, Argentina)	NuScale (NuScale Power, USA)	ACP100 (CNNC, China)
Reactor type	Integral PWR		
Thermal power [MWt]	100	160	385
Electrical capacity [MWe]	~30	50	125
Primary circulation	**Natural circulation**	**Natural circulation**	**Forced circulation**
System pressure [MPa]	12.25	12.8	15
Core inlet/exit temperatures [°C]	284/326	258/314	286.5/319.5
RPV height/diameter [m]	**11/3.2**	**17.8/3.0**	**10/3.35**

2.2 Boiling Condensing Reactor

For the development of a safe and compact PWR type SMR, the concept of BCR is suggested. Fig. 2 shows the conceptual diagram of primary system of BCR. The BCR is basically a PWR-based concept that allows boiling in the reactor core. Although the boiling of coolant occurs at the core, the radioactivity issues of the turbine building are the same as that of the general PWR since it adopts an indirect cycle unlike BWR. The quality at the upper core is expected to be between 0.0 and 0.2 since there is no need to produce dry saturated steam. The thermal driving head can be dramatically increased because the vapor density is 7-9 times smaller than that of liquid at the operating pressure of the PWR. In addition, since there is no need for a depressurization component at the riser, it is expected that a highly effective natural circulation reactor cooling system can be achieved.

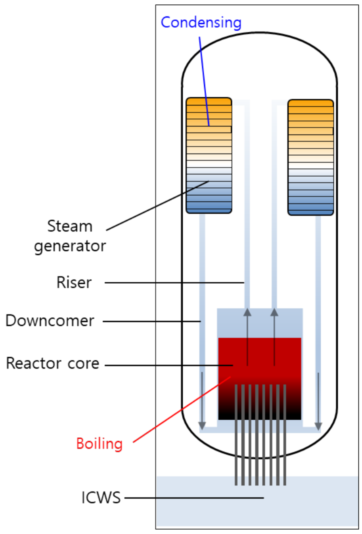

Fig. 2. Conceptual diagram of primary circuit of BCR

Fig. 3 shows the comparison of RPV height of natural circulation nuclear reactors. This is a preliminary result for estimating approximate RPV height. The thermal center difference was calculated for each thermal power, and the height of remaining parts except thermal center length was assumed to be 3.7 m. The reactor coolant conditions of PWR and BWR refer to NuScale in Table I, and ESBWR (Economic Simplified Boiling-Water Reactor) which is designed by GE-Hitachi Nuclear Energy, respectively [4]. Therefore, Fig. 3 shows a rough trend and may differ from other actual reactors depending on the control element driving mechanism (CEDM) or auxiliary components in RPV. For example, KARAT-45, a BWR under development in the Russian Federation, shows an 11 m high RPV since it adopts the top-mounted CEDM. However, Fig. 3 may provide an overview of the RPV height trend with the reactor thermal power of general PWRs and BWRs.

Since the operating pressure of BWR is lower than that of PWR and the density difference between phases is much greater, it is less sensitive to changes in thermal power. The result of BWR corresponds to the extreme case, and considering the BCR concept that allows a little boiling in PWR, the RPV height of BCR will be between PWR and BWR as shown in the figure. Depending on the degree of boiling tolerance, it is expected to be more competitive in the future SMR market where compactness is emphasized.

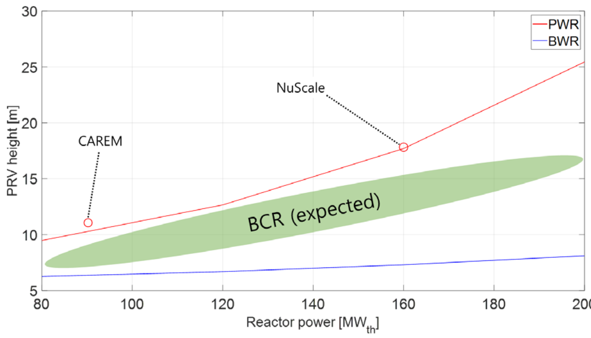

Fig. 3. Comparison of RPV height of natural circulation reactors

In addition to the RPV height, there will be advantages in various aspects. Since the indirect steam cycle is adopted, condensation occurs on the primary side of the steam generator and boiling occurs on the secondary side. Since effective two-phase heat transfer occurs on both sides of the steam generator, there is a possibility that the steam generator can become more compact. It is also possible to achieve self-pressurization and simplify the startup procedure. However, further research seems to be needed as there may be technical and regulatory issues that can arise from allowing in-core boiling.

3. Summary and Further Works

In this paper, the concept of boiling condensing reactor (BCR) is suggested for natural circulation PWR type SMRs. It is a PWR based concept that allows a little boiling in the reactor core. By adopting two phase natural circulation based indirect-cycle reactor, it is expected to be more compact and simplified. In the future, it will be further investigated on the technical aspects of the BCR concept.

ACKNOWLEDGEMENT

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