Concept Development of Boiling Condensing Small Modular Reactor (BCR)

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1. Introduction

Many small modular reactor (SMR) type light water reactors are compact reactors to achieve good modularity, often adopting design approach of putting major components into a single pressure vessel. Its compact design minimizes the risk of loss-of-coolant accident (LOCA). Also, the amount of water required to cool the reactor is small compared to conventional power plants, making it possible to operate the reactor inland. The sizes of reactor components are also small, which are easy to be manufactured and transported. For these advantages, many countries are jumping into the development of SMR. For instance, NuScale has received a design certificate by the US Nuclear Regulatory Commission (NRC), and CAREM of Argentina is currently under construction. Many of the SMRs under development, including NuScale and CAREM, are basically PWRs. Although they are outstanding in terms of safety, their sizes are still too large to be called ‘small’ reactors. To resolve this issue, the concept of Boiling Condensing Small Modular Reactor (BCR), a hybrid of Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR), is newly devised in this paper. Under specific geometry and operating conditions, the height difference between the reactor core and heat exchanger, i.e., the thermal center difference is calculated. Eventually, the height of reactor pressure vessel (RPV) is estimated to check if it is possible to reduce the reactor size with this concept.

2. Characteristics of BCR

2.1. Natural Circulation, Self-pressurized, Integral Type PWR

Many of the SMRs currently under development are natural circulation-based reactors. Instead of using pumps to circulate the coolant, they lean on the buoyancy generated by the density difference between hot fluid and cold fluid to drive the flow. A reactor using such scheme can inherently avoid any risks related to a coolant pump failure. Also, in order to reduce the size of the plant, some SMRs are designed as integral type reactors whose steam generators are integrated inside the RPV.

Following this trend, the BCR proposed in this paper is a natural circulation-based integral type reactor. What makes the BCR stand out is that it maximizes coolant density difference so as to improve circulation capacity. This will be dealt in more detail in the next part. Not only has BCR got ridden of coolant pumps, but also there is no pressurizer inside the RPV. Using the boiling and condensing power, it is able to self-regulate the system pressure without any pressurizer [1]. Thus, the system of BCR is expected to be quite simple.

2.2. Hybrid of PWR and BWR

BCR is basically in the form of PWR in that the coolant system is divided into primary and secondary sides. It is well known that this kind of configuration protects coolant pipes and turbine from being contaminated by radioactive materials during operation.

In natural circulation based PWRs, small degree of boiling inside the core is allowed, so-called flashing, to increase the coolant density difference. However, this is not enough to replace coolant pumps, requiring long risers. This eventually increases the size of RPV, which limits the competency of SMR in terms of transportability and economic feasibility. To enhance the circulation of coolant without increasing the RPV height, BCR allows much more boiling inside the reactor core to maximize buoyancy. The flow quality at the core exit is expected to be 0.2~0.3, a bit lower than that of a typical BWR. From the preliminary study on the concept of BCR, the RPV height was expected to be higher than BWR but lower than PWR [2]. Fig.1 shows a rough prediction of BCR’s height at various thermal powers, compared to natural circulation PWR and BWR, based on the calculation of thermal center difference.

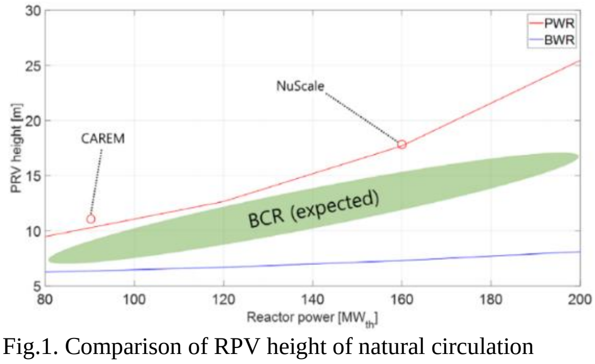

Fig.1. Comparison of RPV height of natural circulation reactors [2]

2.3. Enhanced Heat Transfer in the Heat Exchanger

Several studies have reported that heat transfer in the heat exchanger can be enhanced if helical-shaped tubes are used. [3,4] Hence, some integral type PWRs are choosing helical coil tubes so that their sizes are minimized. However, since helical coil is difficult to be manufactured or maintained, a heat exchanger composed of thousands of such tubes can face substantial technical challenges in production, operation and maintenance.

Moreover, its complex geometry makes it arduous to precisely analyze the thermal hydraulics of the fluid.

In the case of BCR's heat exchanger, boiling occurs on the secondary side and condensing occurs on the primary side. Thus, the heat transfer coefficient between the two systems is expected to be quite large. This implies that a straight tube based shell-and-tube type heat exchanger can provide enough heat transfer area within a small volume.

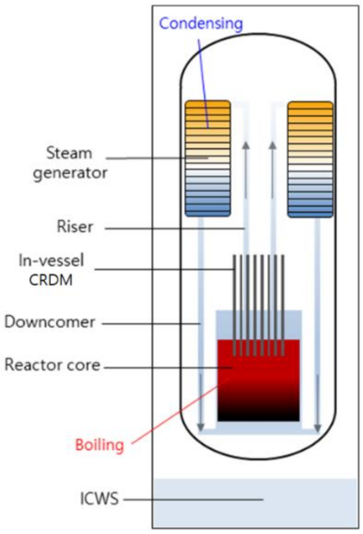

Fig. 2. Schematic design of RPV of BCR [2]

3. Estimation of Thermal Center Difference

3.1. Design of BCR

The main goal of this study is to roughly estimate the RPV height based on the thermal center difference. Under steady-state in a natural circulation-based reactor, the buoyancy-generated pressure head should be balanced by pressure drop around the primary circuit. To put that into equation,

$$\left(\rho_{cold\ leg} - \rho_{hot\ leg}\right) g \Delta H = \Delta p_{core} + \Delta p_{SG} \quad (1)$$

Note that the frictional pressure drops across external components such as riser, downcomer, etc. have been neglected. To obtain the thermal center difference (ΔH), some basic geometrical parameters and general operating conditions were established in advance.

The general operating conditions of BCR are summarized in Table. 1. With the electrical power output fixed at 170 MWe and assuming that the thermal efficiency is 35%, the thermal output was estimated as 485.7 MWt. Other parameters, system pressure and core inlet/outlet temperature, followed those of a typical BWR. As BCR is a natural circulation-based reactor, the primary reference model was ESBWR designed by GE-Hitachi Nuclear Energy, which is also a BWR relying on natural circulation [5].

Table. 1. General operating conditions

Electrical output [MWe]	170
Thermal output [MWt]	485.7
System pressure [kPa]	7171
Core inlet/outlet temperature [°C]	278/287.6
Core exit quality	0.2
Core mass flow rate [kg/s]	1274.7

In order to calculate the pressure loss in the core and the steam generator, the geometry of each component must be determined. The necessary parameters are summarized in Table. 2. Again, the configuration and geometry of fuel rods followed that of ESBWR, since BCR allows in-core boiling. However, considering the thermal power rating, the number of fuel assemblies was adjusted from 1132 in ESBWR to 150 in BCR. Finally, the core mass flow rate was estimated by dividing the thermal output by the enthalpy difference between core inlet and outlet.

For the steam generator, its tube geometry follows that of shell-and-tube type steam generator. The number of steam generators per RPV and the tube length was determined by referring to NuScale design [6]. Also, the number of tubes per steam generator was reduced to 3000, considering the amount of heat transfer.

Table. 2. Geometry of reactor core and heat exchanger

Reactor Core	
Fuel rod outside diameter [mm]	11.2
Fuel rod-to-rod pitch [mm]	14.37
Fuel rod length [m]	3.5
Number of fuel rods per assembly	81
Number of fuel assemblies	150
Number of spacer grids	2
Steam Generator	
Type	Shell-and-tube
Number of heat exchangers	2
Number of tubes per HX	3000
Tube length [m]	3.5
Tube outside diameter [mm]	19.05
Tube-to-tube pitch [mm]	25.4

3.2. Core pressure drop

The core pressure drop is divided into frictional pressure drop and minor head loss. First, the frictional pressure drop ($\Delta p_{f,core}$) was estimated using Eq. (2).

$$\Delta p_{f,core} = \frac{f_{lo} G_m^2}{2 D_e \rho_l} \left[(z_{OSB} - z_{in}) + \int_{z_{OSB}}^{z_{out}} \phi_{lo}^2 \, dz \right] \quad (2)$$

Starting from the point of onset of nucleate boiling (z_{OSB}), the coolant becomes two-phase. In this region, a proper two-phase multiplier (ϕ_{lo}^2) must be multiplied to the pressure drop equation. For simplicity, homogeneous equilibrium model (HEM) was adopted for the two-phase multiplier. The integration of ϕ_{lo}^2 along the fuel rod was performed based on the assumption that axial power distribution inside the core is sinusoidal. For the friction factor along the subchannels (f_{lo}), Cheng and Todreas correlation was selected.

Other than frictional pressure drop, minor head losses occur at several components such as spacer grids, inlet and outlet. These minor head losses are obtained by putting proper loss coefficients (K) and two-phase multipliers into Eq. (3). Especially for spacer grids, the loss coefficient was determined by de Stordeur's model.

$$\Delta p_{form} = \sum_i \left(\phi_{lo}^2 K \frac{G_m^2}{2\rho_l} \right)_i \quad (3)$$

3.3. Steam generator pressure drop

For the frictional pressure drop in the primary side of the heat exchanger, Eq. (2) was utilized again. The primary side flows downward through the shell side of the steam generator, while the secondary side flows upward through the tube side. Hence, the two-phase multiplier profile was deduced from the temperature profile for counterflow. Also, the friction factor along the shell side was obtained by using the Cheng and Todreas correlation again.

3.4. Results

The pressure drop calculation results are summarized in Table. 3. The total pressure drop around the primary side was estimated to be 30.72 kPa. Taking this to be equal to buoyancy-generated pressure head, the thermal center difference should be 5.22 m.

The last step is to guess the height of RPV. By roughly assuming that the height of remaining parts of RPV besides thermal center difference is 3.5~4.0 m, the height of BCR's RPV should be 8.72~9.22 m, which is quite smaller than expected. This is because the frictional and form losses around other components, such as riser, downcomer and plenums, had been ignored. More accurate calculation of total pressure drop would be possible after further elaboration on the design of BCR. However, this result does imply that it is possible to reduce the reactor size with BCR concept.

Table. 3. Pressure drop calculation results (Unit: [kPa])

Core	Friction	9.41
	Spacer grids	1.06
	Inlet & Outlet	3.96
Heat Exchanger	Friction	16.30
Total pressure drop		30.72

4. Summary and Further Works

In this study, the concept and design of Boiling Condensing Reactor (BCR) was devised. BCR is a natural circulation-based, self-pressurized, integral type reactor. Its design bares the desirable characteristics of both PWR and BWR. Based on that, the height of RPV was estimated to be approximately 9 m for 170 MWe class SMR. Compared to the NuScale whose RPV height is about 17.7 m and the electrical output per power module is 50 MWe, a BCR produces more than 3 times of electrical energy in almost half the size. However, since this was a rough estimation based on thermal hydraulic analysis only, there are many aspects to be further investigated.

To transfer large amount of heat through short steam generator tubes, the amount of heat transferred per unit area is expected be much higher than that of typical PWR steam generators. On the basis of precise heat transfer analysis and material testing, whether the conventional shell-and-tube type heat exchanger can withstand this condition should be unraveled.

As a BCR is a new concept, a new mechanism for controlling reactor power can be developed. Also, further studies should verify whether in-vessel control rod driving mechanism (CRDM) can be applied to this type of reactor.

Acknowledgement

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