Effects of Relative SG Tube Pitches on the Performance Characteristics of a Small Modular Reactor driven by Natural Circulation

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1. Introduction

This research is focused on two key features of SMR: the natural circulation in SMRs adopting pressurized light water reactor and the conceptual design for the SMR without reactor coolant pumps (RCPs). Fig. 1 shows the schematic diagram of the SMR without RCPs.

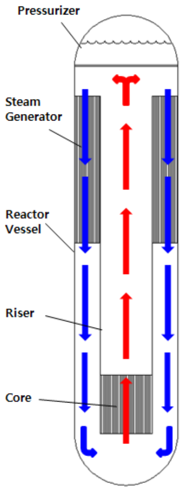


Fig. 1 Schematic diagram for SMRs without RCPs.

In this research, the capacity and basic dimensions for SMRs driven by a natural circulation are preliminarily assumed to determine the SMR configuration for the conceptual design, and each of the pre-set values is explained below. Firstly, the PZR configuration is not considered because it is not included to the main flow of the primary coolant. One of the SMR requirements is that SMR shall carry on the road. Hence, the vehicle geometrical limits are 15 meters for the length, and 3.5 meters for the height, approximately. With these limits for the dimensions of the SMR, RV length is assumed about 13.8 meters and RV diameter about 2.5 meters.

In IAEA definition for SMRs[1], the capacity of electric power is no more than 300 MWe. If the efficiency of SMR power plant is assumed to 33% compared to the commercial power plant, the core power is below 1,000 MWth. In this research, the core power is assumed to 200 MWth arbitrarily during normal operation.

The core configuration for this research adapts the Westinghouse 17x17 array fuel assembly. Therefore, the number of fuel assemblies to generate 200 MWth is 37ea, the core diameter is about 1.75 meters, and the length of the active core is 2.0 meters [3].

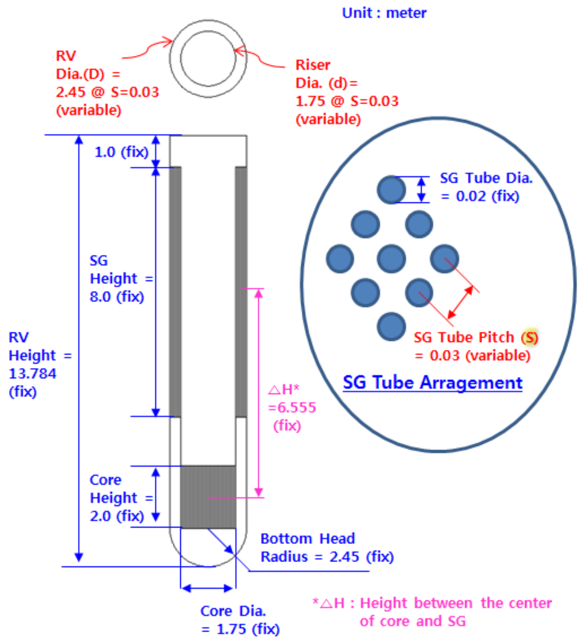


Fig. 2 Schematic diagram for SMRs without RCPs.

The SG whose function supplies the superheated steam in the secondary system is assumed to the straight tube type. The arrangement for SG tubes is located between Riser and RV, and the array of SG tubes is regular triangular like Fig. 2. The primary coolant passes through the outside of tubes, and the heat is transfer to the secondary feedwater. The secondary feedwater passes through the inside of tubes, and the heat from the primary coolant is received to generate the superheated steam. From the preliminary evaluation for the SG sizing, if the hydraulic diameter of SG tubes is assumed to be 20 mm, the evaluation results showed that the SG needs 6,000 tubes with an 8- meter length. In addition, during a normal operation, the SG is assumed to have the heat sink with the same amount of heat from the core to maintain the thermal equilibrium.

From the above preliminary pre-set values, Fig. 2 shows the basic configuration and the dimensions to analyze the SMR's performance for this research.

Here, if the pre-set values are fixed, the RV diameter(D) and Riser diameter(d) depend on the SG tube pitch(S). Above of all, to array the SG tubes with the 20-mm diameter, 8-meter length, and 6,000 numbers, we select the reference array to have a 30-mm tube pitch which is 1.5 times of tube diameter. The reference array of the tube pitch, S=30mm, has the same diameters to the bottom and top of the RV and Riser. And then, for the tube pitches of S=20mm and S=40mm, the RV diameter(D) and Riser diameter(d) can be changed depending on which diameter is fixed.

As a result, the objective of this research is to ensure the direction for the basic design of SMRs from the numerical analysis to predict the temperature contours and the flow rates driven by a natural circulation for the pressurized light-water SMRs without RCPs when the SMR configuration can be changed by various SG tube pitches inducing the RV diameters and the Riser diameters.

2. Calculation Method

2.1 Governing equations

The governing conservation equations for continuity, momentum, energy, and turbulent(k-ε) model are employed[4].

2.2 Assumptions and boundary conditions

The commercial CFD code 'ANSYS' (Ansys, Inc.)[4] is used to calculate the steady-state heat and mass transfer in the SMR. The working fluid of SMR on this research is the pressurized subcooled water under 15.5MPa of the operating pressure. This research is focused on the single phase. Two-dimensional numerical simulation is constructed in this study because the shape of SMR is axisymmetric. Neglecting the pressurizer, RV top is assumed as a wall. All of the walls are assumed adiabatic. Especially, the core and SG are assumed to be the porous media [2] and to have uniform heat source and heat sink, respectively. The total amount of the heat source in the core and the heat sink in the SG is assumed to be same.

3. Results and Discussion

The computed contours of the velocity vector with the designated SG tube pitches(S=20, 30, and 40 mm) are showed in Fig. 3. As has been expected, the velocity in the porous media such as core and SG is uniform, and near the top and the bottom the velocity decrease sharply due to the change of the flow direction. But, the velocity vectors with non-uniform diameter, S=20mm and S=40mm, have some different characteristics. Especially, the velocity contour of S=40mm in Fig. 3(b) shows that the velocity increases sharply when the hot water passes through the narrower riser than others. This is induced by a coupled effect both a buoyancy force and a flow area contraction. Afterward, we have to improve the design near the intervals changing the diameters using tapping or rounding because the velocity near the non-uniform diameters changes sharply and this velocity change can affect the natural circulation flow rate and locally cause the critical heat flux and departure from nucleate boiling.

Fig. 4 shows the temperature contours. When the natural circulation loop is a steady state and single phase, then the temperature differences is like the following equation.

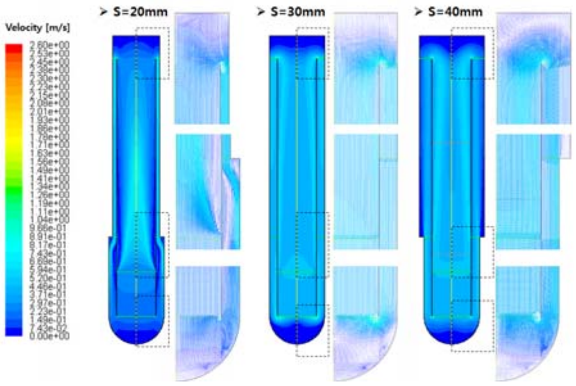
$$\Delta T = \left(\frac{RP^2}{2\rho^2{}_0 \beta g \Delta H C_p{}^2} \right)^{1/3} \qquad (1)$$

Because the S=20mm loops have a larger flow resistance(R) in SG, the temperature differences are the biggest. The calculation results of temperature show that most of the loops have a similar maximum temperature(~304℃) exempt for the S=40mm loop in Fig. 4 (b). The S=40mm loop has the biggest maximum temperature(~315℃) passing through the riser after the core. The minimum temperature difference occurs in the S=30mm loop, and it has the most uniform temperature.

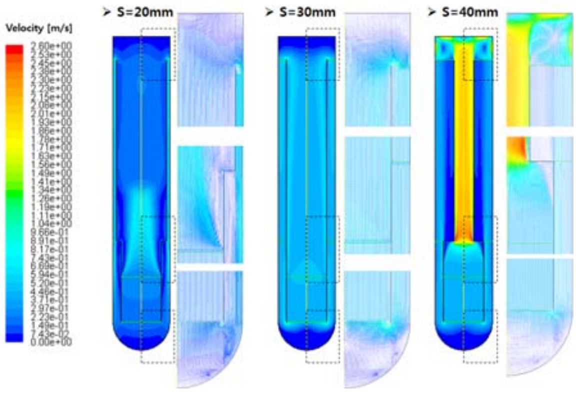
Finally, Eq. (1) can be converted to the mass flow rates like the follow equation.

$$\dot{m} = \left(\frac{2\rho^2{}_0 \beta g \Delta H P}{C_p R} \right)^{1/3} \qquad (2)$$

The mass flow rates driven by the natural circulation are the performance index for SMRs without RCPs. Fig. 5 shows the mass flow rates with the core power. From these results, we suggest that the diameters of the reactor coolant passage keep as uniform as possible if the more uniform temperature distribution and larger mass flow rate are required. In addition, the calculation results in Fig. 5 have a good agreement with the theoretical equation Eq. (2).

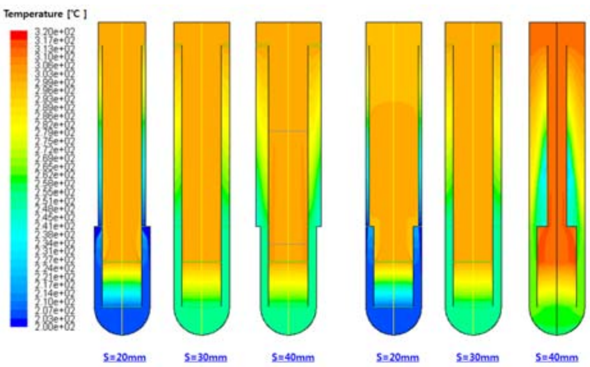


(a)



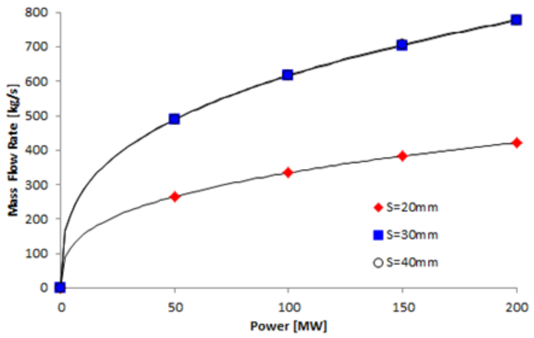
(b)

Fig. 3 Velocity vector contours
(a) when Riser diameter is constant
(b) when RV diameter is constant

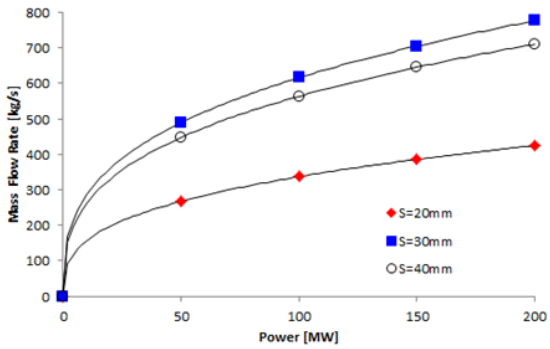


(a) (b)

Fig. 4 Temperature contours
(a) when Riser diameter is constant
(b) when RV diameter is constant



(a)



(b)

Fig. 5 Mass flow rates with core power
(a) when Riser diameter is constant
(b) when RV diameter is constant

4. Conclusion

The present work carries out numerical simulations to get an insight for the effects of the diameters of the reactor vessel and riser using the parameters such as the steam generator tube pitches. To sum up, the calculation results show a good agreement with the theoretical equation and the uniform diameter loop has a more uniform temperature distribution and larger mass flow rate

REFERENCES

[1] International Atomic Energy Agency, "Status of small and medium sized reactor designs", http://aris.iaea.org, 2012.

[2] Jin Yan, Kun Yuan, Emre Tatli, David Huegel, Zeses Karoutas, "CFD PREDICTION OF PRESSURE DROP FOR THE INLET REGION OF A PWR FUEL", Proceedings of the 3rd CFD for Nuclear Reactor Safety Workshop, Bethesda, Maryland, USA, 2010 Sep. 14-16

[3] Westinghouse, "Standard PWR Nuclear Fuel Assembly (17×17)", http://syeilendrapramuditya.wordpress.com/2009/04/14/standard-pwr-nuclear-fuel-assembly-17x17-technical-specification

[4] Ansys software. ANSYS 14.5 User's guide. Ansys Incorporated, http://www.ansys.com, 2013.