Thermal Sizing of Printed Circuit Steam Generator for Integral Reactor

Han-Ok Kang*, Hun Sik Han, Young-In Kim, Keung Koo Kim
Korea Atomic Energy Research Institute, 1045 Daeduk-daero, Yuseong-Gu, Daejeon 305-353, Republic of Korea
**Corresponding author: hanokang@kaeri.re.kr*

1. Introduction

SMART (System-integrated Modular Advanced ReacTor) is a promising advanced small nuclear power reactor. It is an integral type reactor with a sensible mixture of proven technologies and advanced design features. SMART aims at achieving enhanced safety and improved economics; the enhancement of safety and reliability is realized by incorporating inherent safety-improving features and reliable passive safety systems [1]. The improvement in the economics is achieved through a system simplification, component modularization, reduction of construction time, and high plant availability. The standard design approval assures the safety of the SMART system.

The capital cost of the major plant equipment has a significant effect on the overall economics of the nuclear plant. Minimizing the cost of manufacturing of the nuclear plant components is important to reduce the cost of the reactor. It is necessary to reduce the size of the steam generator in order to design a smaller reactor vessel, which is substantial for the overall construction cost, with the required thermal capacity preserved. The Printed Circuit Heat Exchanger is a type of compact heat exchangers that provides high power density along with a low pressure drop and reduced maintenance requirements. This paper describes the approach we used while determining the size of the Printed Circuit Steam Generator (PCSG) and resultant smaller reactor vessel.

2. Application of PCSG into Integral Reactor

2.1 Internal Configuration of Integral Reactor

The reactor assembly of SMART contains its major primary components such as the fuel and core, eight steam generators, a pressurizer, four reactor coolant pumps, and twenty five control rod drive mechanisms in a single pressurized reactor vessel, as shown in Fig. 1.

The integrated arrangement of the reactor vessel assembly enables the large size pipe connections to be removed, which results in an elimination of large break loss of coolant accidents (LBLOCAs). This feature, in turn, becomes a contributing factor for the safety enhancement of SMART. Eight modular-type once-through steam generators consist of helically coiled tubes producing 30 °C superheated steam under normal operating conditions, and a small inventory of the secondary side water sources at the steam generator prohibit a return to power following a steam line break accident. Four reactor coolant pumps with a canned motor, which has no pump seals, inherently prevent a loss of coolant associated with a pump seal failure. Four-channel control rod position indicators contribute to the simplification of the core protection system and to an enhancement of the system reliability.

The large free volume in the top part of the reactor vessel located above the reactor water level is used as a pressurizer region. As the steam volume of a pressurizer is designed to be sufficiently large, a spray is not required for a load maneuvering operation. The primary system pressure is maintained constant due to the large pressurizer steam volume and a heater control.

The reactor coolant forced by reactor coolant pumps installed horizontally at the upper shell of the RPV flows upward through the core, and enters the shell side of the steam generator from the top of them. The secondary side feedwater enters the helically coiled tube side from the bottom of the steam generators and flows upward to remove the heat from the shell side eventually exiting the steam generators in a superheated steam condition. The SMART core is composed of 57 fuel assemblies, the design and performance of which are based on a proven 17x17 array with UO_2 ceramic fuel rods in commercial PWRs.

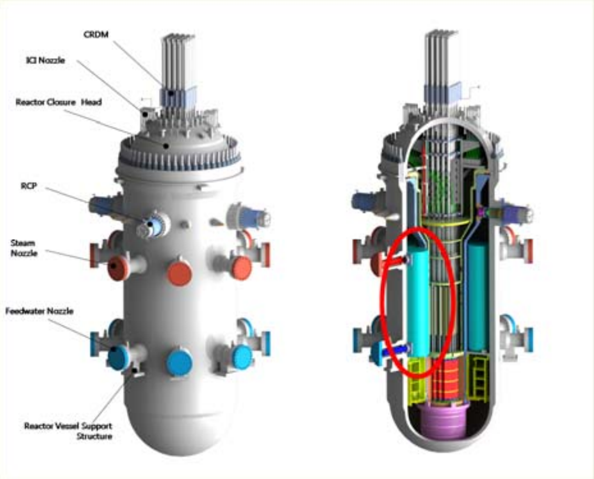

Fig.1. Reactor Vessel of Integral Reactor

2.2 Thermal Sizing of PCSG for Integral Reactor

A PCHE is one of the compact types of heat exchangers available as an alternative to shell and tube heat exchangers. Its name is derived from the procedure used to manufacture the flat metal plates that form the core of the heat exchanger, which is done by chemical milling. These plates are then stacked and diffusion bonded, converting the plates into a solid metal block containing precisely engineered fluid flow passages. These channels are typically semicircular in the cross section with a depth of 1.5 mm to 3 mm. PCHEs are typically built from stainless steels and can operate at temperatures from cryogenic to 800 °C. A typical example of a PCHE block is shown in Fig. 2.

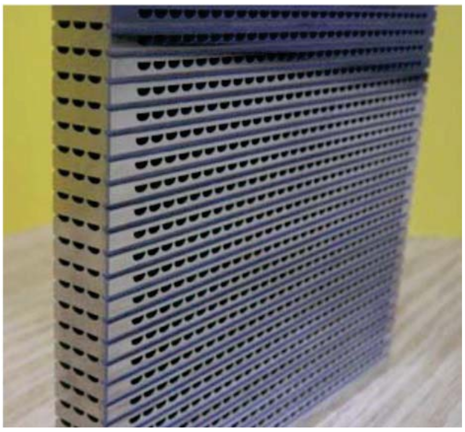

Fig.2 Typical example of PCHE Block [2]

PCHE is made up of diffusion bonded plates with chemically etched flow paths. The plates are bonded togehter in sequence of hot/cold plates. There is a counter-current flow between the hot and cold plates. The thermal design of the heat exchanger is required to determine the size and effectiveness of PCSG.

A single channel is modeld for each hot and cold side and the heat transfer is calculated between them. The result is scaled to the total number of channels in the PCSG. The coolant transfers its thermal energy to secondary feedwater flowing down through the hot side of the channel. Even though the flow channels are usually semicircular in the cross section, the two plates are comibined into one flow passage to accomodate the large flow rate of the coolant, and thus the flow channels of the coolant are circular in the cross section. The flow area of the primary flow path is twice that of the secondary flow path. The feedwater entering into the PCSG with subcooled condition begins to boil with heat tranfer from the primary side, and exits the steam generator with superheated condition. Consequently, the secondary side of the flow path consists of three regions: subcooled, two-phase, and superheated regions. The primary and secondary single-phase heat transfer coefficients are calculated by the Gnielinski correlation which has been experimentally validated for a small diameter and velocity conditions of PCSG [3]. The Chen correlation is used for the two-phase heat transfer. Table 1 shows a comparion of the thermal hydraulic paramters of the new PCSG and former helical once-through steam generator. The overall volume can be reduced significantly by introducing the PCSG.

4. Conclusions

Thermal hydraulic and geometric parameters for the PCSG were studied. The results show that the overall volume of the steam generator can be significantly reduced. On the basis of this calculation, we can design a smaller reactor vessel with the PCSG.

Acknowledgements

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Table. 1 Comparison of thermal hydraulic parameters of PCSG with Helical SG

Parameters	Helical	PCSG	
Power	41.25	27.5	MW
Number	8	12	#
Primary Side			
Mass flow rate	261	174	kg/sec
Inlet temperature	323	323	°C
Outlet temperature	294.5	294.5	°C
Inlet Pressure	15	15	MPa
Pressure drop	55	191	kPa
Secondary Side			
Mass flow rate	20.1	13.4	kg/sec
Inlet temperature	200	200	°C
Outlet temperature	290.5	290.5	°C
Steam Pressure	5.2	5.2	MPa
Pressure drop	170	119	kPa
Overall HTC			
subcooled	2109	6106	W/m2K
two-phase	3508	9138	W/m2K
superheated	1283	5208	W/m2K
Geometry			
Volume	8.58	0.66	m3
Height	6	1.5	m3
Surface area density	37.8	108	m2/m3
Power density	4.8	41.7	MW/m3