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Two-Phase Instability Characteristics of Printed Circuit Steam Generator for the Low Pressure Condition

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1. Introduction

The vessel of integral reactor contains its major primary components, so its size is proportional to the required space for the installation of each component. The steam generators take up the largest volume of internal space of reactor vessel and their volumes is substantial for the overall size of reactor vessel. Reduction of installation space for steam generators can lead to much smaller reactor vessel with resultant decrease of overall manufacturing cost for the components.

A PCHE(Printed Circuit Heat Exchanger) is one of the compact types of heat exchangers available as an alternative to conventional 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.

PCSG(Printed Circuit Steam Generator) is a potential candidate to be applied to the integral reactor with its compactness and mechanical robustness. For the introduction of new steam generator, design requirement for the two-phase flow instability should be considered. This paper describes two-phase flow instability characteristics of PCSG for the low pressure condition.

2. Application of PCSG into Integral Reactor

2.1 PCSG for 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[1]. Eight modular-type once-through steam generators consist of helically coiled tubes producing 30 °C superheated steam under normal operating conditions.

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.

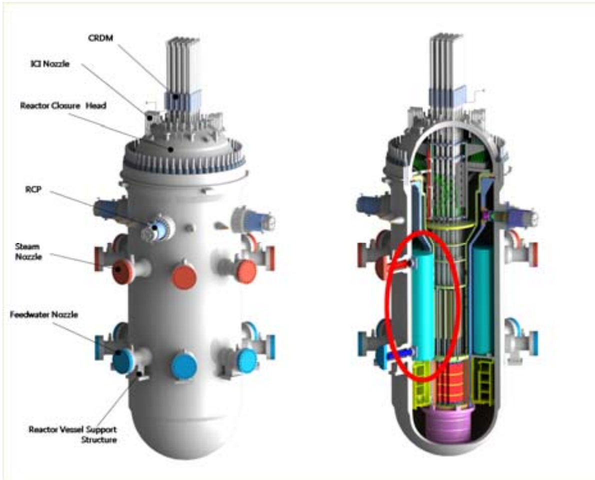

Fig.1. Reactor Vessel of Integral Reactor

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.

A PCHE is one of the compact types of heat exchangers available as an alternative to shell and tube heat exchangers. 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. A typical example of a PCHE block is shown in Fig. 2.

The coolant transfers its thermal energy to secondary feedwater flowing down through the hot side of the PCSG 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

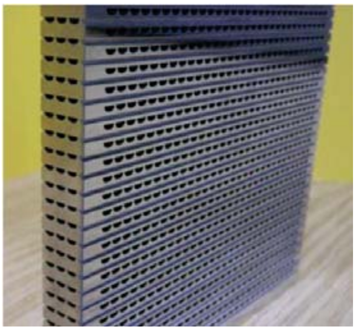

Fig.2 Typical example of PCHE Block [2]

2.2 Two-Phase Instability of PCSG

Two types of instabilities have been observed in the once through steam generators[3]. The first type is Ledinegg instability. This instability can occur only if the hydraulic curve of the boiling channel which means the static relation between the pressure drop and the mass flow rate has a negative slope locally. The second type is an instability between the heated tubes, which can be categorized into a density wave oscillation by considering its generation mechanism. This instability is closely related to the oscillating boundaries of the two-phase region. The flow fluctuation develops due to a delayed outlet pressure change relative to the tube inlet disturbance. It is evident that an increment of the hydraulic resistance of a section with a single-phase fluid through a tube inlet orifice installation leads to a reduction of the relative pressure differential at the two-phase region. The generation mechanism of the density wave oscillation is mainly owing to the delayed response of boiling channel to the inlet perturbation, so interconnection of each channel can reduce the retardation and lead to resultant stabilized flow condition. Cold side flow paths are interconnected to mitigate the two-phase flow instability in the cold side.

3. Experimental Data of Two-Phase Instability in PCSG

3.1 Experimental Setup for PCSG Test

The experimental setup was composed of a closed oil loop and an open water loop for the hot and cold sides, respectively. The PCSG consisted of one cold side plate and two hot side plates, and each plate had 26 micro-wavy channels of 2 mm in width and 0.8 mm in depth with a semi-elliptical cross sectional shape as shown in Fig.3.

Considering that a higher flow rate is required in the hot side compared to the cold side for SMART operation, a double-banking design, which stacks one cold side plate with two hot side plates in a sandwich structure was adopted. The 2-dimensional flow channel design was applied to the cold side plate, while the hot side plates were equipped with 3-dimensional flow channels. In the 2-dimensional flow channel design, the channels are fabricated on only one side of the plate with honeycomb patterns, and thus flow mixing is allowed between the neighboring channels.

The thermal oil heated by a 20 kW electric heater flowed into the hot side of the PCSG, and released thermal energy into the cold side. As the water traveled along the flow path of the PCSG, it absorbed heat from the thermal oil and began to evaporate. The superheated steam was then vented out. Experiments were performed under counter flow conditions, and the experimental data were stored in a data acquisition device with a 1-Hz sampling frequency after reaching a time-periodic quasi steady-state. The parameter ranges were m_c=0.1~0.3 lpm, m_h = 20~25 lpm, and p_{cout} = 2~3 bar.

Table.1 Experimental Conditions

Hot side		Cold side		
Flow rate [LPM]	T_inlet [^{o}C]	Flow rate [LPM]	P_outlet [bar]	T_inlet [^{o}C]
25 25	≥190	0.1 0.2 0.3	2 3	70

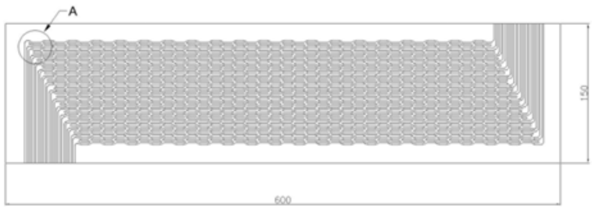

Fig. 3 Flow channel configuration for cold side

3.2 Experimental Results

Two-phase flow generally tends to fluctuate with larger amplitude for the low flow rate condition, which is mainly due to increasing pressure drop in the two-phase region. While the pressure drop in the sub-cooled region instantly reacts to the inlet flow perturbation, the downstream pressure drops from the two-phase region react to the inlet flow perturbation with some time delay owing to the perturbed bubble density transportation. As the inlet flow rate increases, this effect is reduced and the flow is stabilized. Fig. 4 shows the normalized flow fluctuation amplitude for the different flow rates in the cold side. The flow rate oscillates with having constant period for the low flow condition. As the flow rate increases, the oscillation amplitude rapidly decreases and stabilized flow is achieved. The normalized pressure drops show irregular fluctuation compared to those of flow oscillation for the low flow rate condition, which may come from outlet throttling valve. Similar to those of flow rates, the fluctuating amplitude of pressure drop decrease with the increment of flow rate.

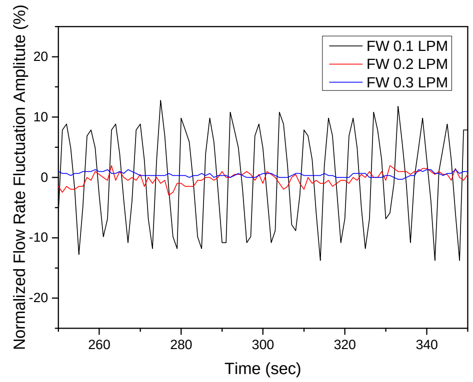

Fig. 4 Normalized flow fluctuation amplitude

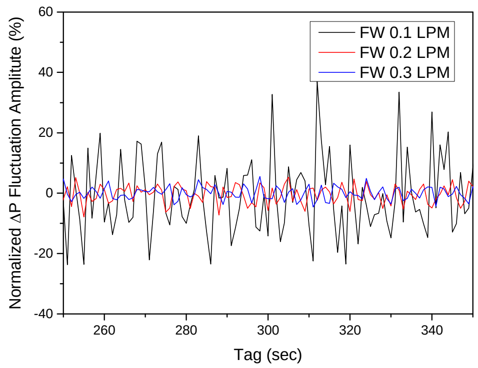

Fig. 5 Normalized ΔP fluctuation amplitude

The fluctuating behavior can be judged more intuitively if the results are displayed through the standard deviation as shown the Fig. 6 and Fig. 7. The flow rate standard deviations have large values at the low flow rate condition. The values rapidly decrease to the two-phase noise level as the flow rate increases. The standard deviations for the pressure drop also decrease to the two-phase noise level as the flow rate increases but not rapidly like those of flow rate. The standard deviations show larger value for the case of PCSG without inlet orificing, which results from the stabilizing function of the orificing at the sub-cooled region.

4. Conclusions

PCSG is a potential candidate to be applied to the integral reactor with its compactness and mechanical robustness. Interconnecting flow path was developed to mitigate the two-phase flow instability in the cold side. The flow characteristics of two-phase flow instability at the PCSG is examined experimentally in this study. The results show that the fluctuation amplitudes rapidly decrease with increment of flow rate.

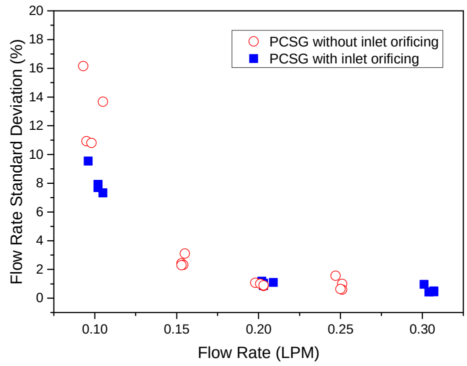

Fig. 6 Standard deviation of flow fluctuation

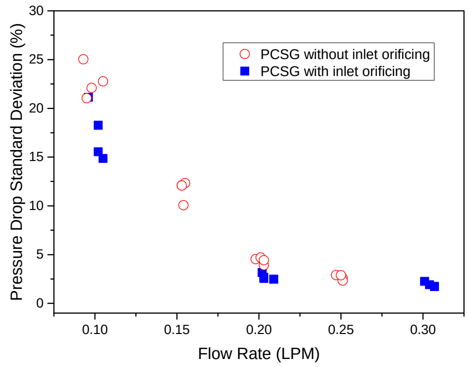

Fig. 7 Standard deviation of flow fluctuation

Acknowledgements

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