Fouling Behavior of a Printed Circuit Steam Generator under Simulated Secondary Coolant Conditions of an Integrated Reactor

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1. Introduction

Steam generators (SGs) occupy the largest volume among components constituting a pressurized water reactor (PWR). Particularly, in an integrated reactor, the size of the reactor vessel is determined by the size of the SGs because the SGs are located inside of the reactor vessel, unlike commercial PWRs [1]. Therefore, if heat transfer efficiency can be increased while reducing the size of the SG, the integrated reactor can be further applied in various fields.

Recently, printed circuit heat exchangers have been developed and applied in various industry. They have large surface area to volume ratio and high heat transfer efficiency. However, they have not been applied in the nuclear industry until now. In this regard, a printed circuit steam generator (PCSG) is being developed for application to an integrated reactor in the Korea Atomic Energy Research and Institute (KAERI) [2, 3].

However, in order to commercialize a PCSG, it is necessary to investigate fouling phenomenon that occurs inside the PCSG. Fouling is defined as the accumulation of unwanted impurities on the heat transfer surface [4]. If excessive fouling occurs, heat transfer efficiency will decrease and flow instability will occur in the narrow flow paths of the PCSG, which could be fatal to safety and economic efficiency [5].

Therefore, in this study, fouling phenomenon occurring inside a PCSG was simulated using a water circulation loop system. The morphology, composition, and amount of deposits were analyzed along the length direction of the PCSG.

2. Experimental Methods

2.1. Manufacture of the PCSG

The PCSG was manufactured using a photochemical etching process and a diffusion bonding process. First, flow channels were etched into a 316 stainless steel plate with the dimensions of 84 x 850 x 5mm as shown in Fig. 1. The flow channels were designed to have two symmetric flow passages. Each flow passages consist of a feed water inlet, an orifice, multi-channels, and a steam outlet.

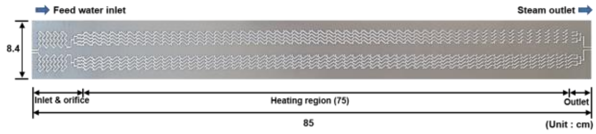

Fig. 1. Image and dimensions of etched flow channels on a 316 stainless steel plate.

A cover plate having the same dimensions and composition was diffusion-bonded onto the channel plate. After bonding, 316 stainless steel tubes were welded to the ends of both the inlet and outlet of the PCSG to allow the coolant to flow smoothly. A schematic diagram of the manufactured PCSG is shown in Fig. 2.

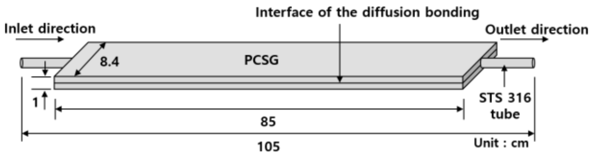

Fig. 2. Schematic image and dimensions of the manufactured PCSG.

2.2. Fouling simulation test

The fouling test was conducted using a water circulation loop system for 500 h. Deionized water was used as a coolant, and $pH_{25\,°C}$ was maintained at about 9.8 using ammonia. The coolant in a make-up tank is heated to about 230 °C through a preheater and fed into the PCSG at a flow rate of 340 mL/min and at 58 bar. At this time, different heat fluxes were applied using electric heaters to the surface of the PCSG. As a result, the subcooled feed water underwent phase transformation inside the PCSG, and came out as superheated steam at 303.5 °C. Finally, the superheated steam is condensed into a single-phase water state in a condenser and enters the makeup tank. This phase transformation was repeated until the test was completed.

To simulate fouling phenomenon under the above phase transformation conditions, a fouling source containing ferrous ions was artificially injected into the coolant at a concentration of 100 ppb.

2.3. Analysis of fouling behavior

After the fouling test, the heating region of the PCSG was cut into ten equal parts. Chemical cleaning was performed for each separate region to dissolve the deposits accumulated inside the PCSG. After chemical cleaning, the amount of iron ions dissolved in the cleaning solution was quantitatively measured using ICP-AES, and the amount of deposits attached to each heating region was calculated.

The morphologies of the deposits was also examined performed using focused ion beam-scanning electron microscopy (FIB-SEM). In addition, the crystal structure of the deposits was analyzed using X-ray diffraction patterns.

3. Results and Discussion

3.1. Characteristic of the deposits

Fig. 3 shows the surface images of the flow channels after the fouling test. The flow channels were completely covered with dark colored deposits. The deposits had a polyhedral shape with various size.

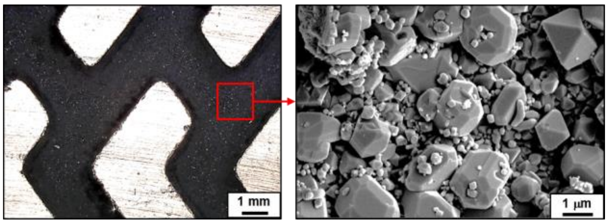

Fig. 3. Surface images of the flow channels after the fouling test.

The deposits that accumulated on the flow channels were collected, and their crystal structure was identified using X-ray diffraction patterns as shown in Fig. 4. The diffraction peaks of the deposits coincided with crystalline magnetite (Fe_3O_4).

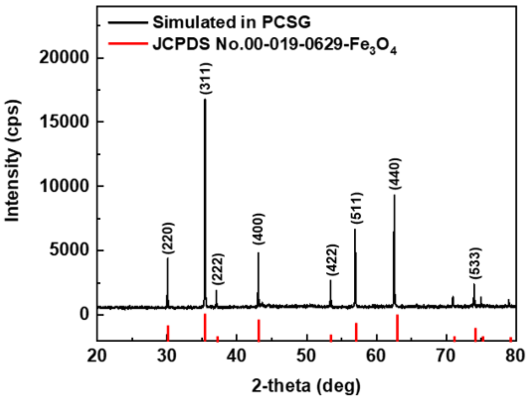

Fig. 4. X-ray diffraction patterns of deposits.

3.2. Amounts of deposits of each heating region

Fig. 5 shows the amounts of deposits per unit area of each heating region. The mass deposited in the first heating region, where the coolant was present as subcooled water was at about 2.28 mg/cm^2.

The amount of deposits was the highest at about 4.3 mg/cm^2 in the initial region where the coolant exists as two-phase of water and steam. The beginning of phase transformation from water to steam means that the coolant attains the saturation boiling condition. As saturation boiling actively and steadily occurs in this region, iron ions in the coolant were continuously precipitated in the form of magnetite, resulting in the most fastest fouling rate per unit area. After that, the deposits rapidly decreased to the end of the heating region. This is because the concentration of fouling source in the feed water was significantly reduced by active saturation boiling in the two-phase initial region.

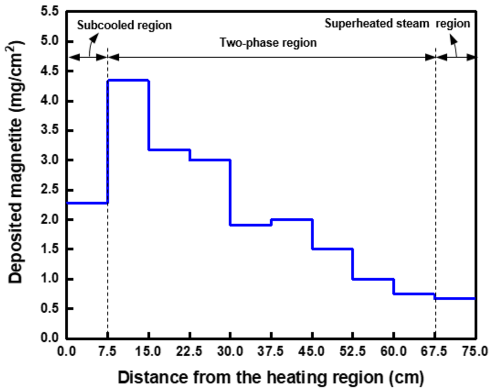

Fig. 5. Amounts of deposits per unit area in each heating region.

4. Conclusions

The fouling behavior on a printed circuit steam generator was investigated using a circulation loop system, and the obtained conclusions were as follows.

(1) Magnetite deposits were formed during the PCSG fouling simulation test. Polyhedral shaped magnetite was densely deposited on the surface of the flow channels.
(2) Among the heating regions of the PCSG, the greatest amounts of deposits were observed in the initial region where phase transformation from water to steam began.
(3) The fouling behavior was decreased after the initial phase transformation region. This means that a large amount of the fouling source has already been consumed in the initial phase transformation region.

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REFERENCES

[1] Z. Liu, J. Fan, Technology readiness assessment of Small Modular Reactor (SMR) designs, Progress in Nuclear Energy, 70, pp. 20-28, 2014.
[2] S.J. Kim, T. Kim, Design methodology and computational fluid analysis for the printed circuit steam generator (PCSG), Journal of mechanical science and technology, Vol. 34, No. 12, pp. 5303-5314, 2020.
[3] H.O. Kang, H.S. Han, Y.I. Kim, Thermal-hydraulic design of a printed-circuit steam generator for integral reactor, The KSFM journal of fluid machinery, Vol. 17, No. 6, pp. 77-83, 2014.
[4] D. Robert, Varrin, Steam generator for nuclear power plants – Chapter 11, Deposit accumulation in PWR Steam generator, Elesvier, pp. 323-363, 2017.
[5] G. Yang, V. Pointeau, E. Tevissen, A. Chagnes, A review on clogging of recirculating steam generators in pressurized water reactors, Progress in nuclear energy, pp. 182-196, 2017.