An experimental setup for investigation of thermal oscillation induced by dryout in printed circuit steam generator

Jin Su Kwon[a], Doh Hyeon Kim[a] Jeong Ik Lee[a,*], Sang Ji Kim[b]
[a]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong Yuseong-gu,Daejeon 305-701, Republic of Korea*

[b]*Korea Atomic Energy Research Institute*
150 Dukjin-dong, Yuseong-gu, Daejon 305-353, Republic of Korea

[*]*Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

The demand for a compact heat exchanger technology has been increased for Small Modular Reactors (SMR). A printed circuit steam generators (PCSG) is a kind of printed circuit heat exchanger (PCHE) designed for the steam generator application. The schematic diagram of the PCHE is shown in Figure 1. This concept of heat exchanger has been investigated for the steam generator in SMART, a small-sized integral-type PWR developed at KAERI in Korea [1]. The outstanding structural integrity of a PCSG comes from the nature of the manufacturing process. PCSG is fabricated by stacking multiple chemical-etched plates and diffusion bonding together under high temperature and pressure conditions. PCHEs generally have 0.5 to 4 mm semi-circular channel diameter, which can provide a large heat transfer area.

The PCSG is a once-through steam generator. Thus, a PCSG experiences various boiling regimes; nucleate boiling, dryout, and dispersed flow film boiling regimes as shown in Figure 2 [2]. The dryout occurs where the liquid film in contact with the heated wall disappears and enters the dispersed flow film boiling region. The movement of dryout front, which is unstable in nature, induces a transition in boiling regimes between nucleate boiling and dispersed film boiling regimes [3]. It is expected to induce considerable wall temperature oscillation that can potentially cause thermal fatigue. This can impact the component lifetime due to cyclic thermal stresses. Therefore, thermal oscillations induced by dryout have to be studied to assess the component integrity and service lifetime.

This type of oscillation was studied in a shell and tube steam generators in the past [4, 5]. Most previous studies have been conducted on typical tubing having diameter greater than 8 mm and researches on micro tubes are very limited. Hence, the frequency of wall temperature oscillation at the dryout front in the semi-circular micro channel should be studied through experiments. The purpose of this research is to design an experimental facility including a test section.

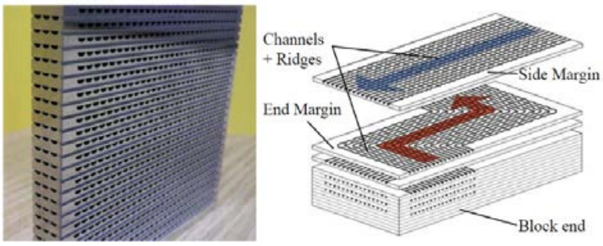

Figure 1. Schematic diagram of the PCHE block

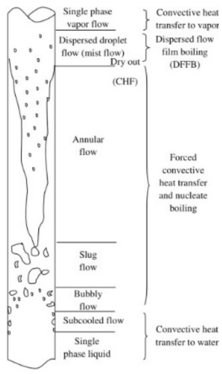

Figure 2. Boiling regimes inside once through steam generator tube [2]

2. Setup for the thermal oscillation experiments

2.1 Main loop

Figure 3 shows the schematic diagram of the experimental facility for the thermal oscillation induced by dryout. The key target of the experimental facility design is having capability as follows: (1) to produce and cool the steam under a few atmospheric pressures, (2) to control the experimental parameters such as heat flux and mass flux at the test section. Deionized water is used for the working fluid as a simulant of the pressurized water used in the steam generator. The facility is a flow loop made up of the test section with the heater, inventory tank, cooler, pump, and various instrument devices. The heat into the system is supplied from the preheater and rectifier, respectively. Rectifier, which converts 220 V alternating current into direct current, can transmit the direct current up to 3000 A with voltage up to 10 V to the test section. An immersion heater is used for preheater to maintain the inlet conditions of the test section. With two means of heat source, the water becomes superheated steam inside the test section while experiencing the nucleate boiling, dryout, and post-dryout heat transfer regimes.

For the experimental conditions, inlet temperatures of the test section are fixed to 40 °C and outlet temperature is up to 190 °C. The operating pressure is one to five times of atmospheric pressure. The superheated steam passing through the test section merges with the water in the bypass line and it is condensed back to water in the cooler and flows into the inventory tank. Bypass line, which is placed at the outlet of the pump and inlet of the test section, is installed to have better controllability of mass flow rate in the test section. Moreover, constant flow rate between 1 to 50 ccm injected into the test section is supplied through a flow rate controller, which is shown in Figure 4. In order to prevent the occurrence of two-phase flow instability caused by the rapid volume expansion, a throttle valve and check valve are placed at the inlet and outlet of the test section, respectively. The flow loop is constructed with 1/2-inch tube with stainless steel 304 except for test section. The working fluid heated in the heater section is cooled by water at room temperature in the cooler. The loop is designed to operate at pressure up to 8 bar.

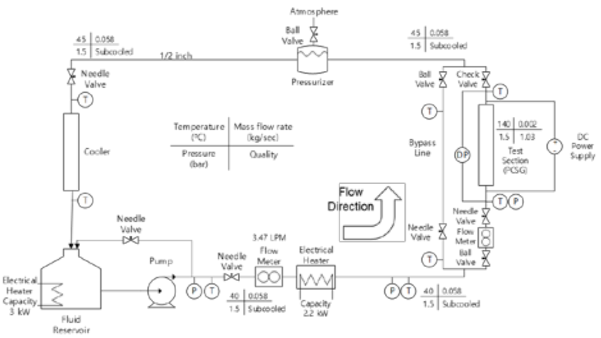

Figure 3. Schematic diagram of the experimental facility

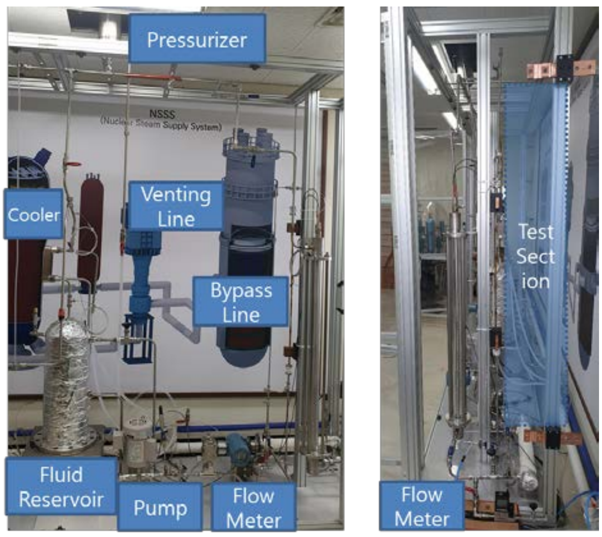

Figure 4. Pictures of the experimental facility: front view(left), side view (right)

2.2 Test section

As shown in Figure 5, the test section consists of three parts: (1) resistance heating section, (2) visualization window and (3) clamp. To facilitate the sophisticated measurement of experimental parameters, the test section has only one semi-circular flow channel in the middle. To produce the superheated steam in the flow channel, the rectifier supplies the DC current to the resistance heating section. The dimension of the heating section is determined by considering the electrical resistivity and structural stability. When the cross-section is wide, electrical resistivity is decreased, and thus, the current is increased under the same electrical potential difference, which leads to a high heat generation by the Joule's law. On the other hand, the heat loss can be larger due to larger heat transfer area and fixing between resistance heating section and visualization window becomes difficult. The height is set to 1.5 meters considering the test section buckling and acceptable wall temperatures. The semi-circular shaped flow channel and diameter of 2 mm are derived from the optimized PCSG geometry. One difference in the test section from the typical PCSG flow channel is that 0.16 mm diameter optical fiber is placed at the middle-edge of flow channel. It enables the optical fiber sensor to measure the wall temperature oscillations directly. The graphite seals are installed symmetrically with respect to the flow channel between the heating section and visualization window since leakage can cause significant measurement error of the flow rate. With the purpose of the visual observation of dryout instability, the visualization window made of ceramic glasses having a thickness of 5 mm is attached to the heating section. After the experiments, the visual observations of the hydraulic phenomena will be used to validate the measurement of thermal oscillation frequency. The resistance heating section and visualization window are physically bonded by the customized aluminum clamp with bolt. A ceramic fiber dielectric sheets capable of withstanding up to 1600 Celsius degrees are placed between the resistance heating section and the clamp to prevent electrical flow to the clamp. The electric resistivity of graphite is about 8 times higher than that of nichrome so most of the direct current flows into the nichrome section. It indicates that Joule heating mainly occurs at the resistance heating section, not at the graphite seals. The reason why the rubber or Teflon is not used at the connections is due to the wall temperature that can be increased up to 550 °C when dryout occurs in the flow channel. Such a high temperature environment can cause deformation of rubber-like materials so that graphite is chosen as the seal material.

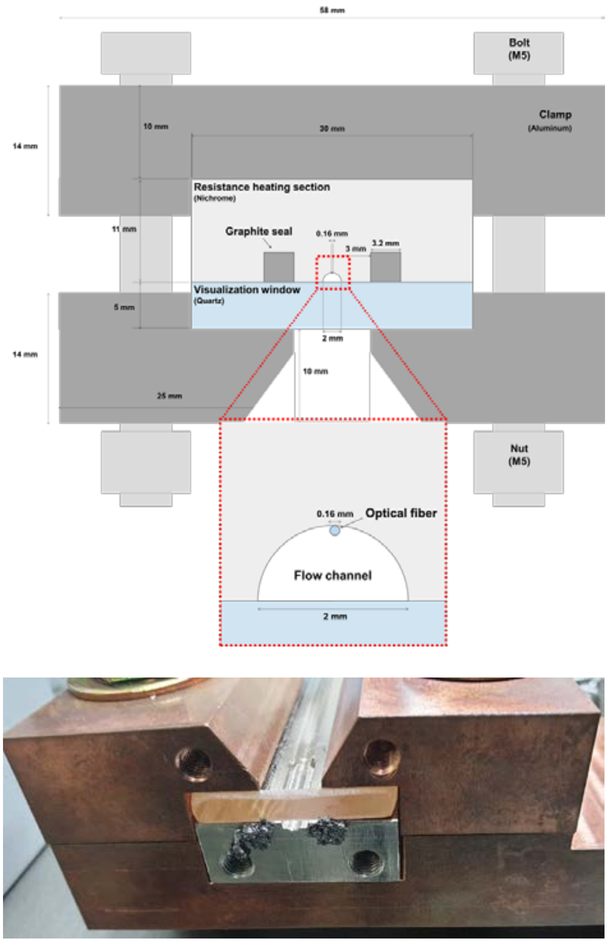

Figure 5. Cross section of the test section

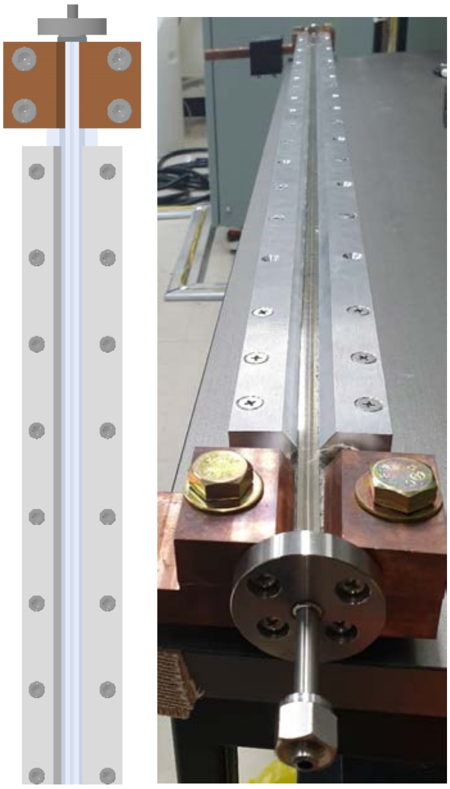

Figure 6. Front view of the test section

2.3 Installation the optical fiber into the facility

The period of the thermal oscillation induced by dryout can be obtained by measuring the wall temperature oscillation near the dryout front. In the previous researches, wall temperature was measured using thermocouples by placing them very densely. For instance, thermocouples are spaced 5 mm apart in the flow direction at the expected dryout occurrence point [6]. Such a traditional method limits experimental conditions due to a fixed place where dryout occurs. In addition, the uncertainty of frequency measurements can be increased with the difficulty in predicting the location of dryout occurrence. In order to resolve the abovementioned problems, a novel concept of temperature measurement system is introduced. The fiber optic sensing system can acquire the distributed temperature along a single strand of thin optical fiber, which is called a distributed temperature sensor (DTS) [7]. The detailed description of this instrument device is stated in previous study [7, 8].

Placing an optical fiber on the wall of a semicircle flow channel with a diameter of 2 mm is one of the issues to be solved for test section design. Using an epoxy may cause a significant change on the flow channel geometry when controlling the amount of epoxy fails. In addition, it cannot be restored to its original state after using the epoxy since the fiber optic cable and the test section are strongly bonded. A mechanical method using spot welding was used to fix the optical fiber to the heating wall in this study. The principle is to place the optical fiber between the thin stainless-steel sheet and the flow channel at the 3 locations (inlet, center, and outlet) of the test section along the flow direction, and they are spot welded to limit the movement of the optical fiber. The conceptual diagram is shown in Figure 7. By using this mechanical method, it is expected that optical fiber can measure the wall temperatures stably and be easily detachable.

The other issue is maintaining the water-tightness between the flow loop and optical fiber. In general, welding, gasket, and lock fitting are used to prevent leakage. Since the optical fiber is fragile, welding is not a proper method. In addition, gasket and lock fitting cannot be applied due to its small diameter of 0.155 mm. To overcome these problems, a sealant with a clay-like texture was used in this experiment. This sealant consists of a hardener and base resin as shown in Figure 7. As the sealant is mixed by hand, the two contrasting colors of components blend into one color to indicate complete mixing and it turns rock hard in a few minutes. As shown in Figure 8, it fills the joints between the pipe and the optical fiber while enduring eight atmospheric pressure.

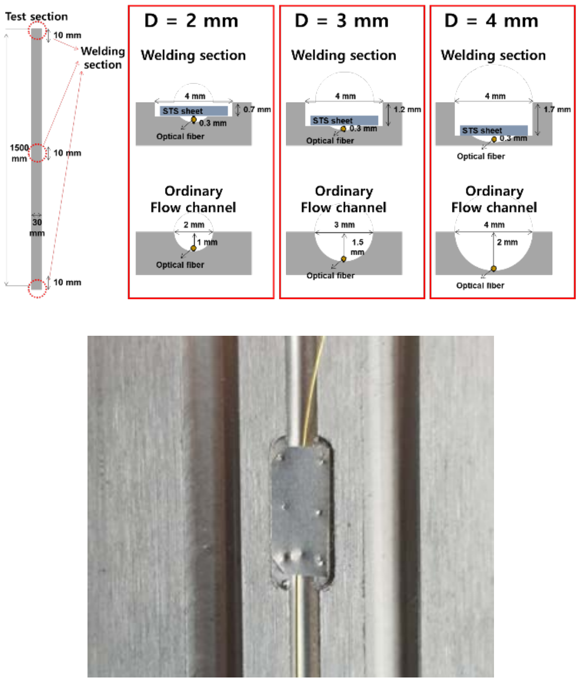

Figure 7. Conceptual diagram of welding section (up) and picture of the welding section (bottom)

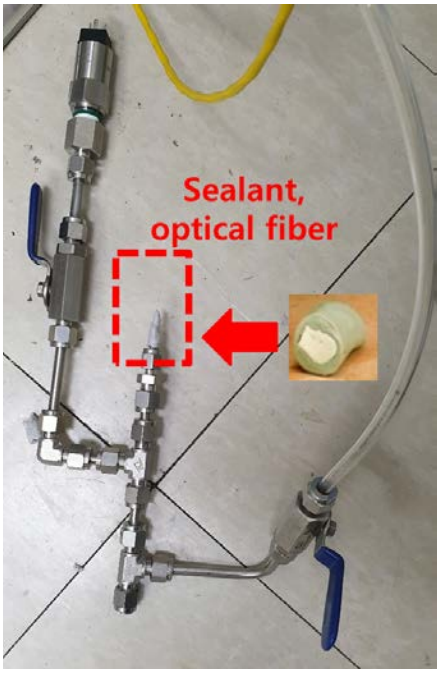

Figure 8. Sealant with optical fiber

3. Summary and Future Works

A PCHE for the steam generator application has been considered for the future PWR type SMRs. If an SMR produces superheated steam, dryout will occur in the steam generator, and thermal fatigue induced by dryout in PCSG is not evaluated in detail previously. Hence, an experiment was planned to understand the phenomena. Experimental apparatus including the test section was designed with the novel concept of temperature measurement system. For further works, the test will be conducted and then major parameters related to thermal oscillation induced by dryout will be analyzed.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government (Ministry of Science and ICT) (NRF-2020M2A8A4023945)

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