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Experimental Study on Stainless Steel 316L Printed Circuit Heat Exchanger at High Temperature and High Pressure Gas Environments

C. S. Kim*, S. D. Hong, M. H. Kim
Nuclear Hydrogen Project, Korea Atomic Energy Research Institute
Daeduk-daero 1045, Yuseong-gu, Daejeon, Korea, 305-353
**Corresponding author: kcs1230@kaeri.re.kr*

1. Introduction

The development of high-temperature components in a Very High Temperature gas-cooled Reactor (VHTR) is very important since its operation temperature and pressure are higher than those of common light water reactors or industrial plants. In particular, the Intermediate Heat Exchanger (IHX) is a key-challenged high temperature component in VHTR components. A Printed Circuit Heat Exchanger (PCHE) is one of the candidates for the IHX in a VHTR, because its operation temperature and pressure are larger than any other compact heat exchanger types. Mylavarapu et al. [1] fabricated a laboratory scale Alloy 617 PCHE and experimentally investigated its thermo-hydraulic performance in a High-Temperature Helium Facility (HTHF) up to 800℃ and 3 MPa.

The Korea Atomic Energy Research Institute has developed a high-temperature PCHE for a VHTR [2] and operated a very high temperature Helium Experimental LooP (HELP) to verify the performance of the high-temperature heat exchanger at the component-level [3].

In this study, the experimental data include the surface temperature distribution, the pressure drops, and the thermal expansion displacements. The measuring instruments are installed to measure these parameters during the performance test of the stainless steel 316L PCHE.

2. Experimental Setup

The primary goal of HELP is to maintain the component-level operation condition for the verification tests of scale-down key components in a nuclear hydrogen production system. Its size was designed for a verification test of a 150 kW IHX. The loop consists of primary and secondary loops. They are designed to withstand a maximum temperature of 1000℃ [2]. Presently, a stainless steel PCHE is installed as a gas-gas option for a high-temperature performance test of HELP and the feasibility tests of the instruments for the heat exchangers.

The stainless steel 316L PCHE is a straight-channel type to minimize the pressure drop. Its external surface of the PCHE is colored in Cr-oxide paint to maintain a high emissivity of over 0.9 for the visible surface temperature distribution by an infrared camera. The outer surface of PCHE is not insulated to compare the measured surface temperature distribution with the thermal stress analysis results [4]. A differential pressure transmitter manufactured by Rosemount Inc. is used to measure a differential pressure between the inlet and outlet of the PCHE. The helium mass velocity is measured, using a Coriolis mass flow-meter. Thermocouples with two different diameters of 1/16 inch and 1/8 inch are used to compensate a radiation bias of temperature at gas temperature measurement. A laser displacement sensor is used to evaluate the thermal expansion between the inlet and outlet of the primary side of the PCHE. The distance measurement by the laser displacement sensor is based on the optical triangulation principle. Fig. 1 summarizes a Cr-oxide painted stainless steel PCHE with a laser displacement sensor.

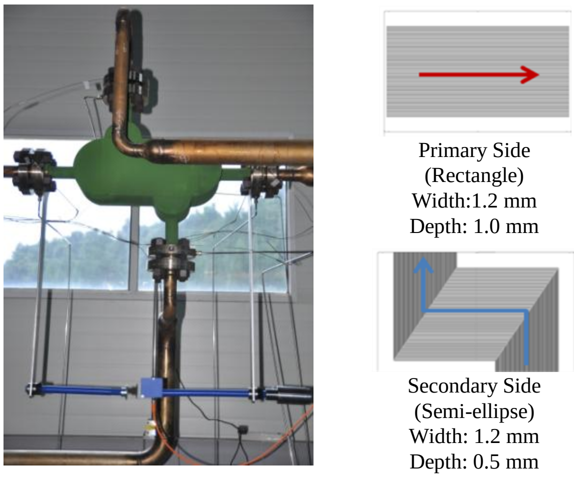


Fig. 1. Stainless Steel 316L PCHE

3. Results & Discussion

Fig. 2 shows two kinds of pressure drops in PCHE; (i) dimensionless total pressure drop and (ii) core-frictional pressure drop. The total pressure drop is measured using a differential pressure gauge. The frictional pressure drop is calculated by the uniform mass flow distribution and the Fanning friction factor recommended from Hesselgreaves [5]. In the primary side, the core-friction pressure drop is less than 50% of the total pressure drop. Therefore, the flow maldistribution in the channels must be considered to quantify the core-frictional pressure drop. On the contrary, the core-frictional pressure drop is the governing pressure drop in the secondary system. The flow maldistribution effect of the secondary side will be much lower than that of the primary side.

$$C_p = \Delta p\left(\frac{\rho u^2}{2}\right)^{-1} \tag{1}$$

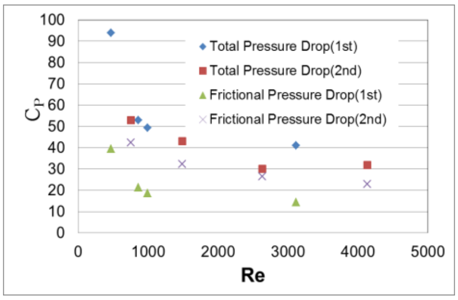
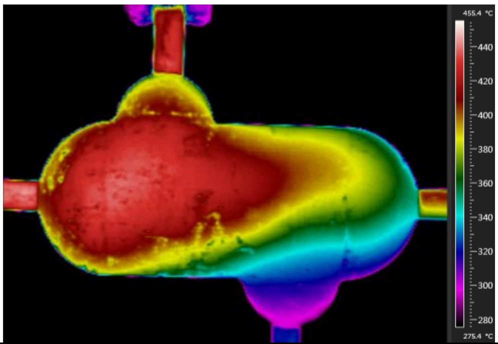


Fig. 2 Dimensionless Pressure Drop

Fig. 3 shows the surface temperature distribution on PCHE under the experimental condition. Since this PCHE is a hybrid type with a trapezoidal counter-current region and two triangular cross-flow sections, the surface temperature distribution shows a raindrop shape of the hot zone leaning towards the outlet of the secondary side.



Primary Side (He)	Secondary Side (He)
3.89 MPa, 0.092 kg/s	3.28 MPa, 0.047 kg/s
Inlet/Outlet (456/379℃)	Inlet/Outlet (328/441℃)

Fig. 3 External Surface Temperature Distribution

Fig. 4 shows the thermal expansion displacement between the inlet and outlet flanges of the primary side with the average temperature. The average temperature is calculated based on the arithmetic mean temperature of the inlet and outlet temperatures of both the primary and secondary sides. The effect of the flow induced vibration is negligible because the standard deviation of the measured distance was 5 μm at the cold flow condition. Considering the measured thermal deformation and the stainless steel thermal expansion coefficient of 1.7~1.8 X 10^{-5} $K^{-1}m^{-1}$, the elbows of the pipe line connected with PCHE absorbed the thermal expansion of PCHE at the relatively low temperature (< 200℃). The sudden rise of deformation rate from 400℃ is most likely due to the distortion of the inlet and outlet ports. The distortion of the ports is induced by the thermal stress as a result of temperature gradient (shown in Fig. 3).

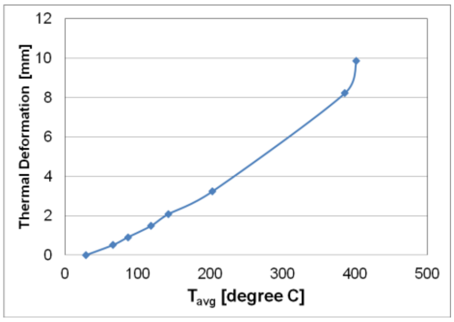


Fig. 4 Thermal Deformation between the Inlet and Outlet Flanges of Primary Side

The heating rate over the cooling rate in the PCHE is about 0.8, which is calculated from the experimental results. Since there is no insulation on the PCHE, the exchanged energy could not be quantified from the experimental results.

4. Conclusion

The measured pressure drops in the PCHE shows that the flow maldistribution must be required to quantify the pressure drop in the primary side. Thermal deformation of PCHE was measured at the experimental condition. The temperature gradient at the primary outlet region caused the port distortion. The elbows of the pipeline can absorb the thermal expansion of the PCHE, but the port distortion must be considered to quantify the thermal deformation at the future alloy 617 PCHE test.

ACKNOWLEDGEMENTS

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