Very High Temperature Test of Alloy617 Compact Heat Exchanger in Helium Experimental Loop

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1. Introduction

Since the outlet temperature of the Very High Temperature gas-cooled Reactor(VHTR) is above 850℃, its application range can be extended to non-electric application including hydrogen production, steam-methane reforming, and other industrial processes[1,2]. Its higher operational temperature than that of a common light water reactor requires the development of the high temperature components such as a blower, valves, heat exchangers & others.

Especially, the Intermediate Heat eXchanger (IHX) is a key-challenged high temperature component which determines the efficiency and the economy of VHTR system. Heat generated in the VHTR fuel block is transferred from the VHTR to the intermediate loop through IHX. In the present, the shell-helical tube heat exchanger is generally used as IHX of the helium cooled reactor. Recently, 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 [3]. Mylavarapu et al. [4] fabricated a laboratory scale alloy617 PCHE and experimentally investigated its thermo-hydraulic performance in a High-Temperature Helium Facility (HTHF) at up to 800℃ and 3 MPa.

Korea Atomic Energy Research Institute has developed a high temperature diffusion-bonded compact heat exchanger [5] and operated a very high temperature Helum Experimental LooP (HELP) to verify the performance of the high-temperature heat exchanger at the component level condition [6]. This paper presents the prototype of a bench-scale alloy 617 compact heat exchanger and its very high temperature performance test in HELP.

2. HELP & Alloy617 Compact Heat Exchanger

HELP was constructed in 2011 to maintain the component-level operation condition for the verification tests of bench-scale key components for nuclear hydrogen production system. Its size was designed for the verification test of a 150 kW IHX or the simulation test in a 1/6 scale fuel block [6]. The loop consists of primary loop and secondary loop as shown in Fig. 1.

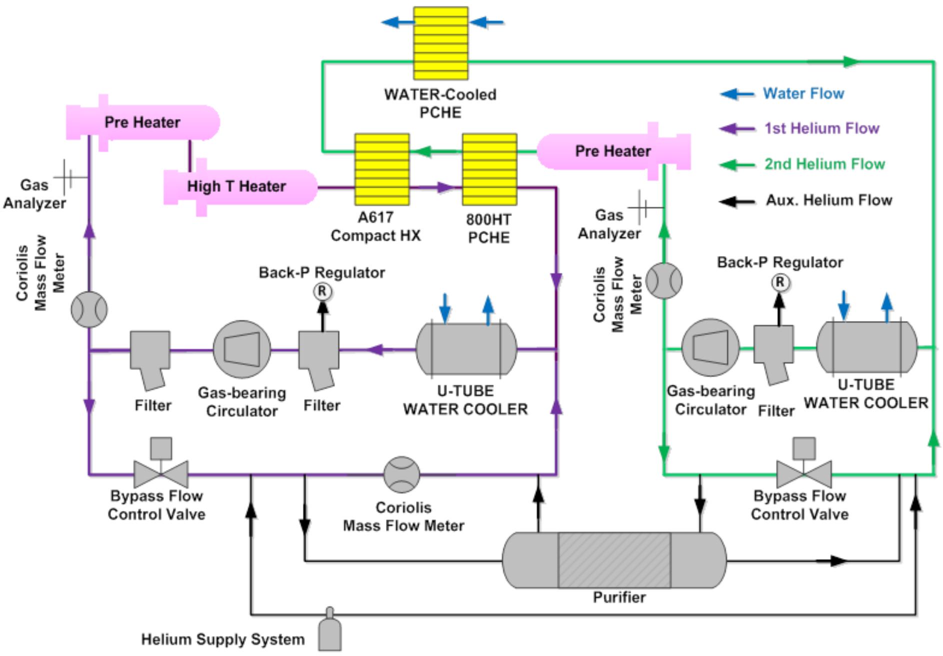

Fig. 1. P&ID of Helium Experimental Loop

The primary loop and the secondary loop simulate VHTR and intermediate loop in nuclear hydrogen production system, respectively. Its high temperature heater in the primary system was designed to withstand a maximum outlet temperature of 1000℃. Its design pressure is 9.0 MPa. The maximum mass velocity & compressive ratio of the blower is 0.5 kg/s and 1.04 at 4.0 MPa helium condition, respectively. The standard working fluid of HELP is helium as the actual coolant of VHTR, but nitrogen can be used in the low pressure condition. The primary loop is composed of a preheater, a high-temperature heater, a hot gas duct, intermediate heat exchangers, a water-cooled U-tube heat exchanger, a passive venting system and gas filters. The secondary loop has the same system configuration as the primary loop except a high-temperature heater and a gas filter at the outlet of the blower. A water-cooled PCHE to cool down the hot gas from the outlet of the intermediate heat exchanger is added in the secondary loop. Two loops share a helium supply system, a helium purification system for oxygen and humidity removal, and a water loop for a cooling tower as shown in Fig. 1. The test results [7, 8] for HELP since 2012 showed its operational performance at the very high temperature condition above 900℃.

KAERI developed the diffusion bonding process condition to fabricate the prototype of Alloy617 compact heat exchanger [9]. In the following diffusion bonding condition, the tensile strength was measured to meet the requirement of alloy617 tensile strength of ASME Sec. IX QW15.

Bonding Pressure: 14.5 MPa
Bonding Temperature: 1220℃
Bonding Time: 4 hours
Furnace Vacuum: 0.001 Pa

Based on the above condition, KAERI fabricated the bench-scale alloy617 heat exchanger. In the case of PCHE, the chemical etching method is widely used to fabricate the channel. Since there is no domestic etching facility for the alloy617 large plate, the flow channels were fabricated by MCT machine. Fig. 2 shows the stack design with the flow channel. Table 1 shows the design specification of the Alloy617 compact heat exchanger.

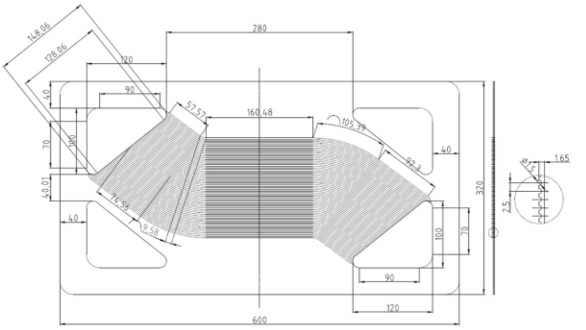

Fig. 2. Stack of Alloy617 Compact Heat Exchanger

Table 1 Design Information of Alloy617 Compact HX

Heat Exchanger volume [m^3]	0.0411648
Total # of Stacks	42(1^{st})/42(2^{nd})
# of Channel per Stack	61
Channel Diameter [mm]	1.5
Flow Length [m]	0.425
Compactness	0.0660
Design P & T	900℃, 2.5 MPa (~1000hr)

Fig. 3 shows the alloy617 compact heat exchanger, and the 800HT PCHE installed in HELP. As shown in Fig. 2, the alloy617 compact heat exchanger has very large volume of the inlet & outlet plenum relatively to the gas flow heat capacity. The 800HT PCHE also had the very large volume of the inlet & outlet plenum [7]. The thick thickness of the plenums, the flanges, and the nozzles was required to withstand the high temperature and the high pressure operation. To accelerate the temperature rising speed in the connection between the alloy617 and the 800HT heat exchangers, the electric furnaces with thermal insulator were installed on their external surfaces. To avoid the high temperature damage of the thermocouple connector, no insulator was installed on all the flanges.

Fig. 3 Alloy617 Compact Heat Exchanger & 800HT Printed Circuit Heat Exchanger in HELP

3. Experimental Results

Kim et al.'s [10] experimental results show that the thermal stress was large enough to result in a plastic windingness of the nozzles of the STS 316L PCHE at the high temperature condition. In the very high temperature condition, thermal stress has to be considered to maintain the integrity of the heat exchanger. Therefore, the temperature difference between inlet & outlet is determined to maintain the total stress below the alloy617 yield strength dependent on the temperature condition [10]. To conservatively estimate the thermal stress, it was assumed that the inlet & outlet plenums temperatures are equal to the inlet and the outlet temperatures of each system. Based on the thermal stress analysis results, the very high temperature operation condition is as follows;

1^{st} system: Inlet T (900℃), Outlet T (650℃)
2^{nd} system: Outlet T (870 ℃), Inlet T (620℃)

Fig. 4 shows the inlet & outlet temperature histories of the 1st system and 2nd system in the alloy617 compact heat exchanger. The very high temperature condition above 900℃ was stable maintained during 4000 sec at 23 bar and 1.0 kg/min. Fig. 5 shows alloy617 heat exchanger during the very high temperature operation. The inlet of the 1st system and the outlet of 2nd system became red-hot because of its high temperature.

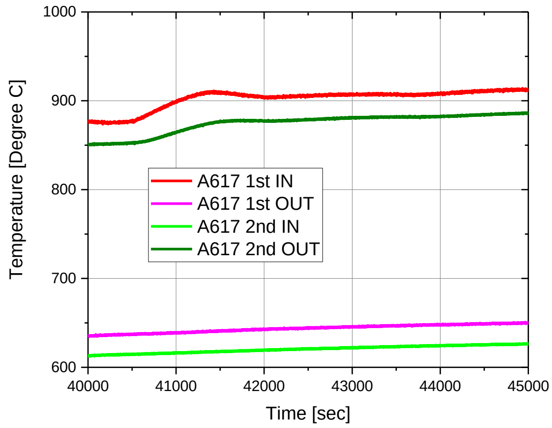

Fig. 4 Temperature Histories of Inlet & Outlet Temperatures of Alloy617 Heat Exchanger

Fig.5 Alloy617 Compact Heat Exchanger during Very High Temperature Condition

Since all the Reynolds number in the channel of the compact heat exchanger are under 400, the Nusselt number is 4.089 referenced from Hesselgreaves [11]. Mylayarapu et al.[4]'s results showed that Nusselt number is constant at the laminar flow region with low Reynolds number under 500. At all the experimental condition, the difference of the average Reynolds number between 1st system and 2nd system were smaller than 3% of the arithmetical mean Reynolds number of two systems. The effective heat transferred length can be calculated as the following equation.

$$L_{eff} = \frac{Q_1 + Q_2}{2\Delta T_{lm} P n_{ch}} \frac{h_1 h_2}{h_1 + h_2} \tag{1}$$

Figure 6 shows that the effective heat transferred length is closed to the flow length. The low Reynolds number decreases the effective heat transferred length. It means that the wall conduction heat transfer in the counter current heat exchanger decreases the correction factor of the alloy617 compact heat exchanger [12].

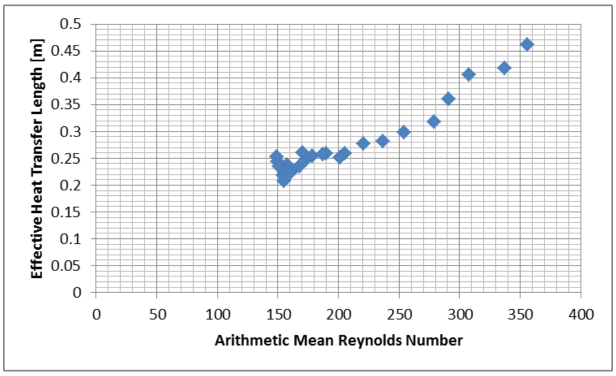

Fig. 6 Effective Heat Transfer Length according to Arithmetic Mean Reynolds number

4. Summary

These test results show that there is no problem in operation of HELP at the very high temperature experimental condition and the alloy617 compact heat exchanger can be operated in the very high temperature condition above 850℃. In the future, the high temperature structural analysis will be studied to estimate the thermal stress during transient and thermal shock condition. The conditions and evaluation standard for the alloy 617 diffusion bonding will be minutely studied to fabricate the large-scale PCHE for the high temperature condition.

NOMENCLATURE

h	convective heat transfer coefficient [W/m^2K]
L_{eff}	effective heat transfer length
n_{ch}	total number of channel at each system
P	heated perimeter of the channel
ΔT_{lm}	log mean temperature difference
Q	exchanged energy in the system

Subscript

1	1st system
2	2nd system

ACKNOWLEDGMENTS

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