High Temperature Operational Experiences of Helium Experimental Loop

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1. Introduction

A Very High Temperature gas-cooled Reactor (VHTR) can produce the high temperature heat above 850℃, so its application include not only high efficient electricity but also industrial heat supply such as hydrogen production, steam reforming, and other industrial processes [1, 2]. The development of high temperature components of VHTR is very important because of its higher operation temperature than that of a common light water reactor and high pressure industrial process.

The development of high temperature components requires the large helium loop. Many countries have high temperature helium loops or a plan for its construction. Table 1 shows various international state-of-the-art [3-9] of high temperature and high pressure gas loops.

TABLE 1 State-of-the-Art of Helium Loops

Loop Name (Country)	Heated Power [MW]	Mass Velocity [kg/s]	Design P &T [MPa/℃]	Status
EVA II [3] (Germany)	10	4	4/950	dismantlement
HHV (Germany)	100	200	5/850	dismantlement
CT-1383[4] (Russia)	0	95	4.9/345	dismantlement
KVK[3] (Germany)	10	3	4/1000	dismantlement
ST-1312[4] (Russia)	15	4	5/965	dismantlement
HENDEL[5] (Japan)	10	4	4/950	dismantlement
HTF-HTTU (RSA)	0.5	0.5	10/1600	rest
HTF-HPTU (RSA)	0.1	2.8	5/35	rest
HELITE[6] (France)	1.2	0.4	10/950	interrupt
HELOKA[7] (Germany)	3~8	1.8~5.5	10/700	operation
CTF[8] (USA)	15~50	10~20	-/950	delay
ETF-HT[9] (China)	10	3.8	7/750	operation
HELP (Korea)	0.6	0.5	9/1000	operation

Korea Atomic Energy Research Institute (KAERI) has constructed and operated gas loops to develop the high temperature compact heat exchangers in a nuclear hydrogen production system. At present, KAERI is operating a small-scale gas loop [10, 11] for feasibility tests of a laboratory-scale process heat exchanger and a very high temperature Helium Experimental LooP (HELP) [12] for verification tests of the bench-scale intermediate heat exchanger in its component-level environment.

Figure 1 shows HELP assembled with its key components. The design [10] and operation experience [11] with a small-scale gas loop provide the basic information for the design, construction and provide the basic information for the design, construction and operation of HELP. This paper presents the design, specification and operation experiences of HELP.

Figure 1 Whole View of HELP

2. Helium Experimental Loop (HELP)

The primary goal of HELP is to maintain the component-level operation condition for the verification tests of bench-scale key components for nuclear hydrogen production system. The size was designed for the verification test of a 150kW-intermediate heat exchanger or the simulation test in a 1/6 scaled down fuel block. The loop consists of the primary loop and the secondary loop. The primary loop and the secondary loop simulate VHTR and intermediate loop in nuclear hydrogen production system, respectively. The loops were designed to withstand the maximum temperature of 1000°C, the maximum pressure of 9.0 MPa, and the normal mass velocity of 0.5 kg/sec. The working fluid is helium as the actual coolant of VHTR. 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 gas-bearing circulator, a passive venting system and gas filters. The secondary loop has the same system configuration as the primary loop except a high temperature heater. Two loops share a helium supply system, a helium purification system and the water loop for a cooling tower as Figure 2.

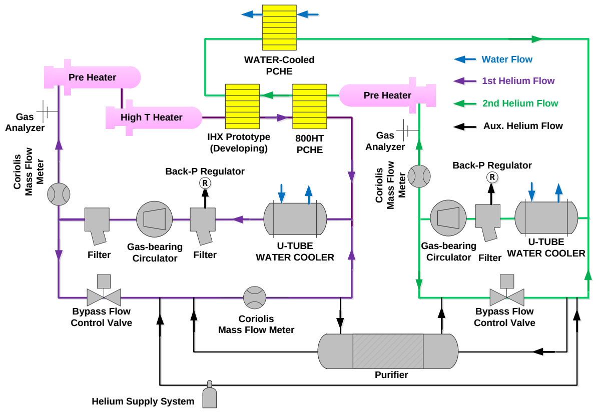

Figure 2 Schematic Diagram of HELP

The design outlet temperature of the preheater and the high temperature heater are 500℃ and 1000℃, respectively. The maximum power of the heaters is 300 kW. The heated materials of the pre-heater and the high temperature heater are Inconel-600 and C/C composite whose design temperature is 850℃ and 1600℃. The heated elements are designed with a 3-phase Y-connection. The detail design was explained in Hong et al.[13] and Yoon et al.[14]. Figure 3 shows the schematic diagram of the high temperature heater in HELP. The heater power is controlled by 3 phase SCR control. After the 3-years operation, the liner of the preheater and the heated elements of a high temperature heater were modified to absorb the thermal expansion difference among vessel, liner and heated elements.

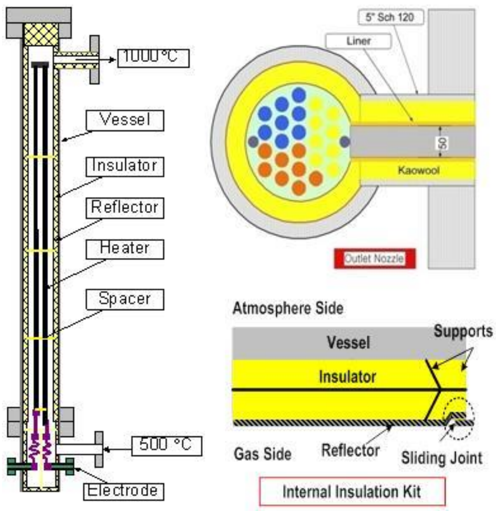

Figure 3 Schematic Diagram of High Temperature Heater

Gas-bearing type is selected as the circulator of HELP not to use the oil which is the source of C/C composite oxidation at the high temperature. Figure 4 shows the gas-bearing circulator. Its design pressure, design mass velocity, and compression ratio are 9.0 MPa, 0.5 kg/s (@4 MPa), and 1.04, respectively. The high speed squirrel-cage induction motor and internal water cooling jacket is selected for higher operation temperature than that of the circulator in the small-scale nitrogen loop [11]. A gas filter is installed at the inlet of the circulator to prevent solid particle ingress to the circulator internals. Especially, a gas filter is also installed at the outlet of the circulator to prevent metal particle from the circulator to the high temperature heater, because there is a probability that a eutectic alloy is formed by the metal particles from the gas bearing circulator and molybdenum liner in the high temperature heater.

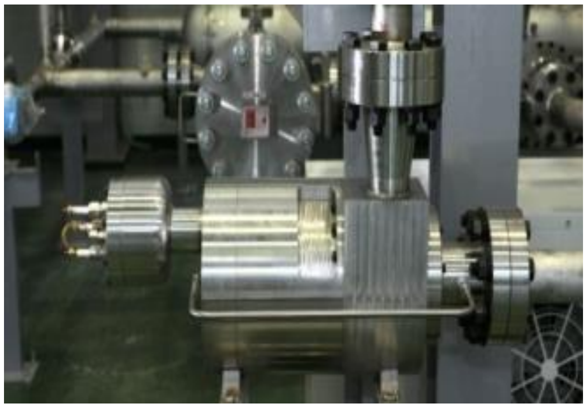

Figure 4 Gas Bearing Circulator

Hot gas duct is a hot gas flow channel to minimize the heat loss by an internal thermal insulator. In this loop, the hot gas duct links the outlet of a high-temperature heater and the inlet of the intermediate heat exchanger prototype. Its design pressure and temperature are 9 MPa and 1000℃, respectively. The hot gas duct, in common with the pre-heater and the high temperature heater, has an internal insulator and a liner to prevent direct contact between the pressurized stainless 304 pipe and the hot gas, and the dust ingress to the flow channel. The Kaowool insulator was installed around the liner. The insulator in a high temperature heater and a hot gas duct was baked and hardened to minimize the dust generation at the high temperature condition. The liner is made of alumina because it has a relatively short length and a small temperature gradient to the high temperature heater. The stopper of the liner outlet limits the axial movement by the frictional shear force between the hot gas flow and liner. The free end of the liner inlet enables the thermal expansion absorption of the liner and the insulator. The pressurized pipe has the same geometrical size as the outlet of the high temperature heater. The inner diameter of the liner is 60 mm. Its length is 1.0 m. The insulator thickness was determined to maintain the vessel temperature below 450℃ like the heaters. A thermal analysis showed that the external pipe temperature was 322℃, and the heat loss through the hot gas duct was 2.32 kW/m. The external surface of the hot gas duct also colored in Cr-oxide paint to maintain a high emissivity above 0.8.

HELP has two helium-to-helium printed circuit heat exchangers. One is an 800HT PCHE and the other is an alloy617 PCHE. The 800HT PCHE is designed to make the operation condition for the verification test of the alloy617 fabricated in the future. Table 2 shows the design specification of the 800HT PCHE. In the present, the 800HT PCHE is installed at the helium-helium option for the high-temperature performance test of a high-temperature heater in HELP.

TABLE 2 Design Specification of 800HT PCHE

Items	Hot Side (1st System)	Cold Side (2nd System)
Working Fluid	Helium	Helium
Mass Velocity	0.1 kg/s	0.05 kg/s
Inlet Temperature	750℃	700℃
Outlet Temperature	550℃	300℃
Design Pressure @750℃	3.5 MPa	3.5 MPa

To maximize the heat-transferred area of the PCHE, flow channels in its core matrices were etched in the wavy channels. In addition, one flow channel branches off into two wavy channels and they join the outlet channel. The width and depth of the semielliptical channel are 1.5 mm and 0.7 mm, respectively. The entire 800HT PCHE is composed of 60 stacks of 40 channels per stack, and each system has 30 stacks. The external surface of the PCHE is colored in Cr-oxide green paint to maintain a high emissivity of over 0.9 for visualization of the surface temperature distribution by an infrared camera. There is no insulation in the experiments for the comparison with the structural analysis results.

Kim et al.'s [12] 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. Three tied universal expansion joints are installed to absorb the thermal expansion of the high temperature components, because the yield stress of the alloy617 at the high temperature condition is too small to absorb the elbows of the pipeline to absorb the thermal expansion. The maximum design deformation was determined from ABAQUS analysis on the pipe thermal expansion at the operating condition. Since a tied universal expansion joint can absorb not axial deformation but lateral deformation, the optimum installation position for the tied universal expansion joint were determined with considering the absorption of the later deformation of pipe line. Figure 4 shows the 800HT PCHE, the stainless steel 316L PCHE, and 4 tied universal expansion joints installed in HELP.

Figure 4 800HT PCHE, 316L PCHE and 4 Tied Universal Expansion Joints in HELP

The control of gaseous impurities is necessary to prevent C/C composite heater and metal components from oxidizing at the high temperature condition. The important gaseous impurities are oxygen and steam. Oxygen and steam is Oxygen is removed through the Zr-Al 16 catalyst which commonly applies to helium or hydrogen gas purification in the level of ppb. Steam is adsorbed at the room temperature by GC-532 which is one of the molecular sieves GC-5A. Molecular sieves GC-5A are crystalline and highly porous aluminosilicate beads with pore openings of approximately 5. The purification system is installed at the bypass line to enable the operation temperature to be raised for the high temperature adsorption and catalyst. The design pressure and mass velocity are 6.0 MPa and 100g/m (@4 MPa), respectively. The target impurities are oxygen concentration under 1.0 ppm and absolute humidity under -110℃.

The scalable pressure transmitters produced by Rosemount Inc. were used to measure the pressure and differential pressure in HELP. The helium mass flow rate was measured through U-tube coriolis mass flow meters produced by Micro Motion. There are many K-type thermocouples to measure the temperature at the various positions. Especially, two thermocouples with unequal diameters of 1/16 inch and 1/8 inch are used to correct the radiation bias error for hot gas temperature measurement [15].

Helium temperature is controlled by the heater power control. The system pressure is actively controlled by the helium supply and venting system and passively controlled by the back-pressure regulator. The mass flow rate is controlled by the blower motor rotating speed and the bypass flow control valve. The sliding gate valve was selected to minimize the pressure drop in the valve. Its advantages fit into tight spaces, variable KVS values, excellent leak tightness, optimal flow control and others. Because there is no mass flow meter in the secondary bypass line, the secondary bypass mass flow rate is calculated by the measured pressure drop and the provided valve constant by the vendor.

3. HELP Performance Test Results

The pressure drops were measured between the inlets and outlets of the primary blower and bypass line. The mass flow rates of the main line and bypass line were measured by coriolis flow meters. The system pressure and the temperature at the outlet of the blower were measured to calculate the volumetric flow rate in the blower. In the case of nitrogen, the rotating speed and the system pressure is limited within 300 Hz and 3.0 MPa. Since the thermal conductivity and specific volume of nitrogen were much lower than those of helium, the overheating of the motor might cause the heat-damage of the blower bearing and motor. Figure 5 is the performance curve of a gas-bearing blower in HELP. It shows that blower has enough ability a mass flow rate of 30.0 kg/min and a compressive ratio of 1.04 at 4MPa Helium.

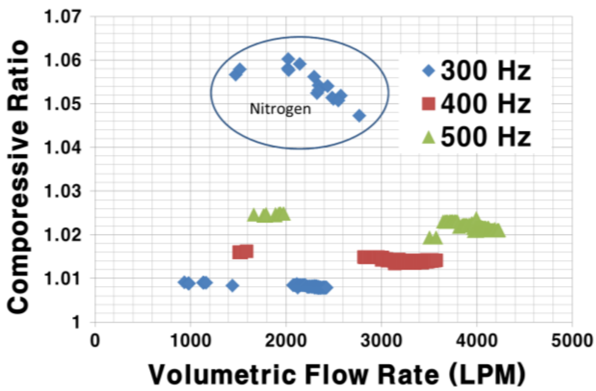

Figure 5 Performance Curve of Blower in HELP

The larger density of nitrogen than helium resulted in the larger pressure drop of nitrogen than helium at the same volumetric flow rate condition. Therefore, compressive ratios of nitrogen in Figure 5 are larger than those of helium. If pressure is corrected at the same density condition of helium, the compressive ratio has the same trend of the helium at 300 Hz condition.

Figure 6 shows the electric current with the voltage of the heaters. The purple line means the current and voltage of the heaters for 300 kW, and their resistance is adequate to electrically generate 300 kW at the laboratory electrical limit of 380V and 800A.

In addition, the heat loss at the heaters in HELP was evaluated from the experimental results. At the same heat capacity and outlet temperature condition, the heat loss at the helium condition was about 8 times as that at the nitrogen condition. The large convective heat transfer coefficient of helium raised the vessel temperature and it resulted in the increased heat loss. Especially, the vessel temperature of the outlet region was much higher than that in nitrogen. Therefore, the water-cooled jacket was added maintain the vessel temperature under the design limit at the high temperature condition as shown in Figure 7.

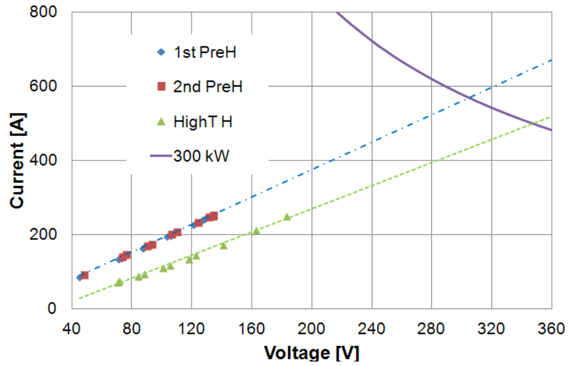

Figure 6 Electrical Performance of Heaters in HELP

Figure 7 Water-cooled Jacket at the Outlet of a High Temperature Heater

Before the replacement of the internal insulator in the hot gas duct, the comparison with the nitrogen heat loss and the helium heat loss at the same heat capacity and outlet temperature condition showed that the heat loss from the hot gas duct was independent on the working fluid. After the replacement of the internal insulator, the heat loss was increased at the same outlet helium temperature condition, because the gap between the hardened insulator and the pressurized vessel resulted in the natural convection in the hot gas duct insulator region and the natural convection increased the effective thermal conductivity of the internal insulator. Table 3 summarizes the experimental results to evaluate the heat loss at the hot gas duct. The high outlet temperature of the high temperature heater increased the heat loss of the hot gas duct. When the outlet temperature of the high temperature heater was 770℃, the heat loss at the hot gas duct was 4.7 kW.

Figure 9 shows the outlet temperature histories of the high temperature heater in the 1st system and the preheater in the 2nd system. The very high temperature condition above 900℃ was stably maintained during 90 minutes at He 2 MPa and 0.6 kg/min. The picture in Figure 8 shows an alloy 617 pipe between the hot gas duct and the 800HT PCHE. It became red-hot because of its inner gas temperature above 900℃.

Table 3. Experimental Results on the Heat Loss at Hot Gas Duct

Replacement of the Insulator	Before		After
Working Fluid	N_2	He	He
Mass Velocity [kg/min]	16.2	2.9	1.65
System P [bar]	28.7	45.3	29.5
Inlet T / Outlet T [℃]	459/454	460/456	460/440
Heat Loss [kW]	1.41	1.13	2.64

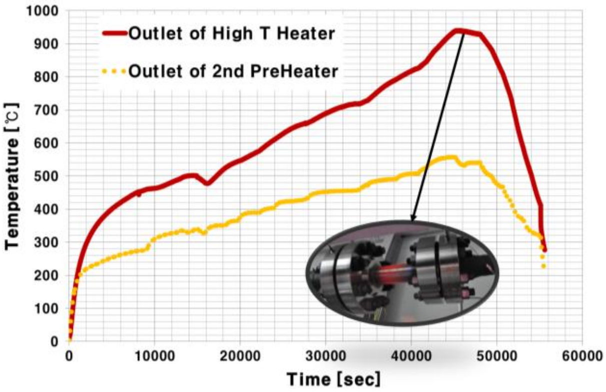

Figure 8 Outlet Temperature Histories of High Temperature Heater and 2^{nd} Pre-Heater

4. Summary

HELP performance test results show that there is no problem in operation of HELP at the very high temperature experimental condition. These experimental results also provide the basic information for very high temperature operation with bench-scale intermediate heat exchanger prototype in HELP. In the future, various heat exchanger tests will give us the experimental data for GAMMA+ validation about transient T/H behavior of the IHX prototype and the optimization of the working fluid in the intermediate loop.

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REFERENCES

1. J. H. CHANG, Y. W. KIM, K. Y. LEE, Y. W. LEE and W. J. LEE, "A Study of a Nuclear Hydrogen Production Demonstration Plant," *Nuclear Engineering and Technology*, **39,** *1*, 9 (2007).
2. W. J. LEE, Y. W. KIM, and J. H. CHANG "Perspectives of Nuclear Heat and Hydrogen," *Nuclear Engineering and Technology*, **41,** *4*, 419 (2009).
3. R. HARTH, W. JANSING, and H. TEUBNER, "Experience Gained from the EVA II and KVK Operation," *Nuclear Engineering and Design*, **121,** *2*, 173 (1990).
4. V. F. GOLOVKO, I. V. DMITRIEVA, N. G. KODOCHIGOV, "Approaches to Experimental Validation of High-Temperature Gas-Cooled Reactor Components" *7th International Topical Meeting on High Temperature Reactor Technology*, paper 017, Prague, Czech Republic, (2010).
5. Y. INAGAKI, K. KUNITOMI, and M. FUTAKAWA, I. IKUO, Y. KAJI, "R&D on High Temperature Components," *Nuclear Engineering and Design*, **233,** *1-3*, 211 (2004).
6. A. BERJON ET AL., "Overview of the CEA Program in High Temperature Gas Cooled System Technology," *GLOBAL 2003*, New Orleans, Louisiana, USA (2003).
7. B. E. GHIDERSA, M. IONESCU-BUJOR, G. JANESCHITZ, "Helium Loop Karlsruhe (HELOKA): A Valuable Tool for Testing and Qualifying ITER Components and their He Cooling Circuits," *Fusion Engineering and Design*, **81**, *8-14*, 1471 (2006).
8. V. J. BALLS, D. S. DUNCAN, S. L. AUSTAD, "The Component Test Facility: A National Use Facility for Testing of High Temperature Gas-Cooled Reactor (HTGR) Components and Systems," *4th International Topical Meeting on High Temperature Reactor Technology, HTR2008-58250*, Washington, DC, USA (2008).
9. Z. Y. ZHANG, M. D. YANG, H. L. BO, R. Q. DUAN, and H. Y. ZHU, "Description and Operational Experiences of The Engineering Test Facility - Helium Technology (ETF-HT)", *8th International Topical Meeting on High Temperature Reactor Technology*, HTR2014-61192, Weihai, China (2014).
10. S. D. HONG, J. H. KIM, C. S. KIM, Y. W. KIM, W. J. LEE, and J. H. CHANG, "Development of a Compact Nuclear Hydrogen Coupled Components (CHNCC) Test Loop," *ANS Embedded Topical Meeting: ST-NH2*, 215, Boston, MA, USA (2007).
11. C. S. KIM, D. U. SEO, T. H. YOO, and S. D. HONG, "Performance Test of Nitrogen Loop with Hybrid Heat Exchanger for SO_3 Decomposition of Nuclear Hydrogen Production," *Proceedings of ICAPP '11*, paper 11454, Nice, France (2011).
12. C. S. KIM, J. S. CHAE, and S. D. HONG, "Performance Test of Very High Temperature Helium Loop", *Proceedings of ICAPP 2013*, KF028, Jeju, Korea (2013).
13. S. D. HONG, C. YOON, H. S. LIM, Y. W. KIM, and J. H. CHANG, "The Design and Analytical Validation of a C/C Composite Helium Heater for a

VHTR Simulated Experimental Loop," *Transactions of the Korean Nuclear Society Autumn Meeting*, Gyeongju, Korea (2009).

14. C. YOON, S. D. HONG, J. M. NOH, Y. W. KIM, and J. H. CHANG, "CFD Analysis for Simulating Very-High-Temperature Reactor by Designing Experimental Loop," *KSME Journal B*, **34**, *5*, 553 (2010).
15. C. S. KIM, S. D. HONG, D. U. SEO, and Y. W. KIM, "Temperature Measurement with Radiation Correction for Very High Temperature Gas," *14th International Heat Transfer Conference*, IHTC14-23074, Washington, D.C., USA (2010).