High Temperature Helium Heater for 800°C Steam Supply to a Lab-scale HTE Device

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1. Introduction

A Lab-scale helium loop for simulating a VHTR (Very High Temperature Gas Cooled Reactor) is now under constructing at the Korea Atomic Energy Research Institute. The Lab-scale helium loop will be connected to 30kW capacity "High Temperature Electrolysis (HTE) system" as a function of high-temperature steam supply to the HTE device (Figure 1). A *high-temperature heater* (HTH) heating the 4.0MPa helium up to 1000°C is one of key components in the Lab-scale helium loop. The HTH uses a non-metal heating element which can withstand temperatures in excess of 2000°C in an oxygen and moisture free environment. In this study, we discuss the design methodology for a high-temperature heater that has the following operating conditions:

Power,	55 kW
Design pressure,	6.0 MPa
Outlet temperature,	1000 °C
Flow rate (helium, max.),	1.0 kg/min

The HTH design output are validated by the thermal-hydraulic analyses using GAMMA+ code [1].

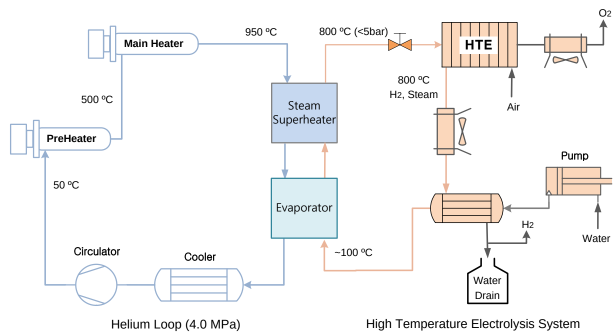


Fig. 1. Layout of a helium loop connected to HTE system

The heat loss of the HTH depends upon the thickness of the internal insulation. If we fix the cross-sectional geometry of HTH, we can obtain the necessary amount of heat loss through the following relationship of energy balance.

Heat transfer by conduction to outer wall of HTH
= Heat loss by convection & radiation to air

2. Design requirements

Three aspects of the mechanical design of the HTH are considered to arrive at the following mechanical requirements: fluid-induced vibration, sound-induced vibration, and thermal stress analysis. The fluid induced vibration and the acoustic vibration were simply checked by the method proposed by Hong, et al.[3]. Thermal stresses are generated for all of the HTH components (liner, vessel, heater, spacers, connector) which expand against adjacent structural supports. Below 450°C, creep and creep rupture effects are usually negligible under high pressure conditions for steels and stainless steels [4].

The design requirement of HTH design are listed in Table 1 that satisfies the various design requirements. The maximum operating temperature (MOT) of the heating element is the primary factor in the HTH design which depends on the MOT of an internal insulator, a liner and a heating element that form the flow channel of HTH. For example, a super Kaowool (internal insulator material) has the MOT of 1650°C. Keeping the flow regime turbulent in the HTH flow channel has great benefit in reducing the size of HTH.

Table 1. Design requirement of HTH

Item	Design Requirement
Helium outlet T	$\leq$ 1000 °C
FIV	$U/(fD) < 22$
AV	$U \ll 1739$m/s
Temperature limit (Material)	- Heater element < 1500 °C - Ceramic Liner < 1300 °C - Insulator < 1200 °C - Vessel (Alloy) < 450 °C - Vessel (304SS) < 360 °C

3. High temperature heater

Helium heating system in the lab-scale helium loop of the Figure 1, composed of two heaters; preheater and main heater. The preheater heats helium gas up to 500°C helium and supply to the inlet of the main heater. The main heater is a high temperature heater (HTH) which is heating the 500°C helium up to 1000°C helium.

Figure 2 shows the vertical and cross-sectional views of the internal of HTH. The stainless-steel vessel of the HTH heater is internally insulated by Kaowool ceramic fiber to protect the vessel from the 1000°C helium. A Corundum liner provides a robust separation between the insulator and the flow channel. The material of heater array is a Carbon Fiber Composite (CFC) that can withstand over 2000°C in the oxygen and moisture free environment. The heater array is electrically insulated from each other by Boron-Nitride (BN) ceramic spacers of which is equally spaced vertically 600mm between rods.

4. Steady-state T/H analysis

Thermal performance for the HTH is predicted with sophisticated design tools, GAMMA+ code. A brief description of GAMMA+ model for the HTH is as follows;

- Lumped model
  - Four heater is lumped to one heater
  - Axial nodes : 22 cells
  - Radial nodes: 17 cells (heater 5, liner 2, insulator 10, vessel 5)
- Heat transfer model
  - Radiation : view factor model (two zones)
  - Insulator: effective thermal conductivity

$$\lambda_{eff} = 0.0196 + 4.70 \times 10^{-4} T(K) \qquad (1)$$

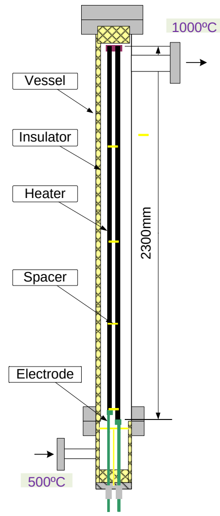
The operating condition is focused on the helium loop for 800°C steam supply to a 30kW HTE device. The steady-state GAMMA+ results are listed in Table 2 and represented to Figure 3 and 4, respectively.

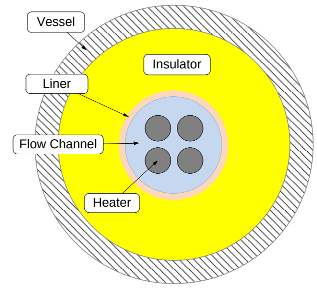
5. Results and discussions

The steady-state GAMMA+ results are listed in Table 2 and represented to Figure 3and 4, respectively. The purpose of the analysis is to analytically verify the design limits of high-temperature components during operation. The main variables are the maximum temperature of the heater and the maximum temperature of the vessel. Table 2 shows the results of predicting the maximum temperature of the heater and vessel according to the flow rate and the area of flow channel(Case-1 & Case-2) with the HTH outlet temperature fixed at 1000°C. It can be seen that the power required to reach the HTH outlet helium temperature up to 1000°C increases as the flow rate increases.

In Case-1, as the flow rate increases, it can be seen from Figure 3-a that the maximum temperature of the heater is different from the expected linear increase. The phenomenon that the maximum temperature of the heater falls at a flow rate of 0.4kg/min can be explained through the Reynolds number graph in Fig. 3-b. Since the flow rate up to 1.0kg/min is smaller than the Reynolds number 2300, which is the standard for sufficiently developed turbulent flow, it is in the laminar flow and mixed flow region, so it shows a nonlinear tendency.

In Case-2 with a small flow area, most of the flow rate belongs to the turbulence region, and as the turbulence is





(b) Cross-sectional view

Main geometric data
- Heater rod dia. 20.2mm
- Heater rod length 2.3m
- Liner dia. 60mm & 75mm
- Vessel OD 114mm
- Heater pitch 25mm

(a) Vertical view

Fig. 2. Vertical and cross-sectional views of a HTH

sufficiently developed, the maximum temperature of the heater tends to converge as shown in Figure 4. This is interpreted because the influence of the mixed flow still remains in the case of the low flow rate region.

In Case-1, the heater maximum temperature requirement (1500°C) was sufficiently satisfied, but the maximum vessel temperature requirement (360 °C) at 1.0 kg/min was not satisfied. The Case-2, with a small flow area, showed overall improved results compared to Case-1. However, at 0.6 kg/min, the vessel maximum temperature requirement was not satisfied.

The maximum temperature of the heater was predicted at a flow rate of 1.0kg/min in Case-1, and the value was 1269.4°C. which is much smaller than the temperature requirement of 1500°C presented in Table 1. It can be seen that the maximum temperature of the vessel was predicted at a flow rate of 1.0kg/min in Case-1, and the value was predicted to 372.9°C larger than stainless-steel temperature requirement of 360°C presented in Table 1. This is the main result obtained from the GAMMA+ analysis that the maximum temperature of the vessel is the main constraint in the design.

Table 3 contains the calculation results to find out the difference between helium gas and nitrogen gas. In Case-1, when nitrogen gas is used, it can be seen that the temperature of the heater increases by about 60°C or more in order to produce the same amount of heat (29.6 kW) as helium. In the case of the vessel, it decreased by 39°C. This is because helium gas is a mixed flow whereas nitrogen gas is a sufficiently developed turbulence flow. In case 2, the temperature of the nitrogen side heater decreased by about 6°C and the vessel also decreased by 41°C despite the turbulent flow on the helium side. This is interpreted because the intensity of the turbulence of the nitrogen gas (Re = 16600) is very large compared to the turbulence of the helium gas (Re = 3580). From the GAMMA+ analysis, it is found that helium gas does not easily generate turbulence compared to nitrogen gas. That is, in order to form a turbulent flow, helium gas requires a relatively small flow area compared to nitrogen gas.

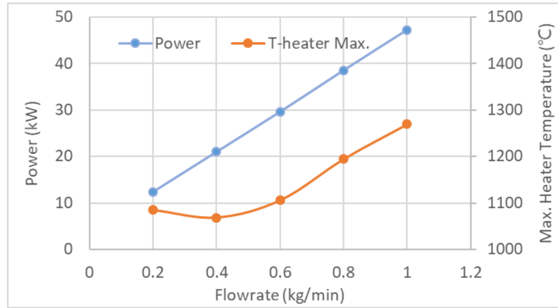
Table 2. Results of steady-state GAMMA+ analysis (pressure: 3.0MPa, HTH inlet/outlet temp.: 500/1000°C)

Flowrate (kg/min)	Reynolds No.(outlet)	Power (kW)	T-heater Max. (℃)	T-vessel Max. (℃)	Heat loss (kW)
Case 1 (flow area = 0.003161 m²)					
0.2	533	12.4	1084.9	338.5	3.76
0.4	1070	21.0	1068.7	335.3	3.59
0.6	1580	29.6	1105.9	340.9	3.68
0.8	2100	38.5	1194.5	360.0	3.94
1.0	2310	47.2	1269.4	372.9	4.23
Case 2 (flow area = 0.001571 m²)					
0.2	1060.0	12.4	1057.2	333.8	3.54
0.4	2330.0	21.3	1142.0	348.5	3.84
0.6	3580.0	30.2	1252.4	368.2	4.32
0.8	4290.0	38.8	1231.1	358.2	4.18
1.0	5370.0	47.3	1232.2	354.8	4.12

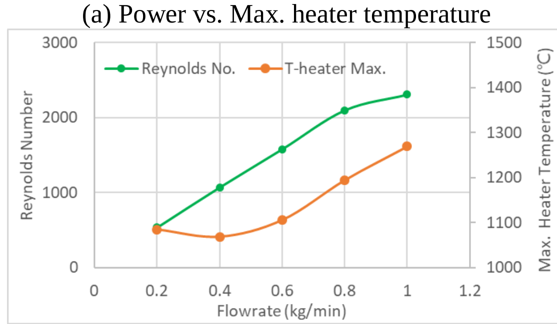
Table 3. T/H differences between helium and nitrogen (pressure: 3.0MPa, HTH inlet/outlet temp.: 500/1000°C)

Parameter	Unit	Case 1		Case 2	
		He	N2	He	N2
T-heater Max.	℃	1106	1166	1252	1246
T-vessel Max.	℃	341	302	368	317
Heat loss	kW	3.68	2.83	4.32	3.16
Flowrate	kg/min	0.6	2.8	0.6	2.8
Reynolds No.	-	1580	8360	3580	16600
Power	kW	29.6	29.6	30.2	30.2

Note: effective thermal conductivity of N2 insulator is assumed by air insulator one.

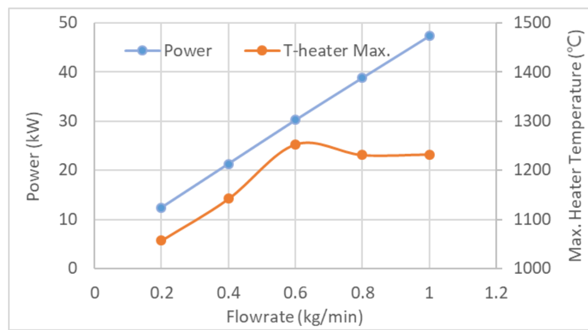


(a) Power vs. Max. heater temperature

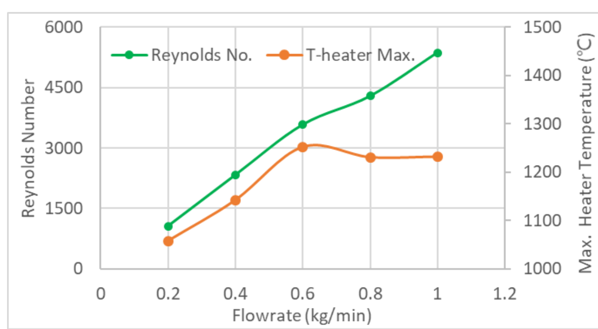


(b) Reynolds number vs. Max. heater temperature

Fig. 3. Case-1 results of steady-state GAMMA+ analysis (pressure: 3.0MPa, HTH inlet/outlet temp.: 500/1000°C)



(a) Power vs. Max. heater temperature



(b) Reynolds number vs. Max. heater temperature

Fig. 4. Case-2 results of steady-state GAMMA+ analysis (pressure: 3.0MPa, HTH inlet/outlet temp.: 500/1000°C)

6. Conclusions

A high-temperature heater (HTH) heating the 4.0MPa helium up to 1000°C is one of key components in the Lab-scale helium loop that will be connected to 30kW capacity HTE system as a function of high-temperature steam supply to the HTE device. Thermal performance of the main heater is validated by a GAMMA+ analyses.

As a result of the GAMMA+ analysis, it is found that helium gas does not easily generate turbulence compared to nitrogen gas. That is, in order to form a turbulent flow, helium gas requires a relatively small flow area compared to nitrogen gas. The normal operation of the 30kW HTE helium heater was 3.0MPa and 0.4kg/min, which was interpreted as satisfying all design requirements in case 2. From the GAMMA+ analyses, it is found that the vessel temperature is the main constraint of HTH operation.

ACKNOWLEDGEMENTS

This study is supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (NRF-2021M2D4A2046777)

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