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Preliminary Design of a Primary Hot Gas Duct Based on a Heat Balance Model

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1. Introduction

Very High Temperature Gas Cooled Reactor (VHTR) has been selected as a high energy heat source for a nuclear hydrogen generation. The VHTR can produce hydrogen from heat and water by using a thermo-chemical process or from heat, water, and natural gas by steam reformer technology. The nuclear hydrogen system being researched at KAERI is planning to produce hydrogen by using nuclear energy and a thermo-chemical process. Helium gas is the choice for the coolant of the nuclear hydrogen system since it is an inert gas, with no affinity to a chemical or nuclear activity, therefore a radioactivity transport in the primary circuit of the nuclear hydrogen system is minimal under a normal operation. Moreover, its gaseous nature avoids problems related to a phase change and water-metal reactions and therefore improves its safety. In this study, a preliminary hot gas duct design of the nuclear hydrogen system has been undertaken based on a heat balance model.

2. Nuclear Hydrogen System

The schematic nuclear hydrogen system is shown in Fig. 1. According to Fig. 1, two HGDs and an IHX are needed. One of the HGDs, which is called a primary HGD, is located between the reactor pressure vessel and the IHX. The other HGD, which is called a secondary HGD, is located between the IHX and SO_3 decomposer. The HGD structure of the nuclear hydrogen system is tentatively considered as a horizontal coaxial double-tube structure as shown in Figs. 2 and 3 which provides a passage for the hot and cold helium gas. In this study, a preliminary design for the primary HGD of the nuclear hydrogen system is carried out based on both the tentative design configuration as shown in Table 1 (1) and a heat balance model (2). By passing through the nuclear hydrogen system reactor core, the hot helium gas is conveyed via the liner tube of the horizontal HGD to the IHX. After being cooled down, the cold helium gas is returned to the lower section of the reactor pressure vessel via a passage between the coaxial inner tube and the pressure vessel of the primary HGD.

Table 1 Tentative Design Configuration

Power [MW_{th}]	200
Pressure boundary of a primary HGD [MPa]	~ 7.0
Inlet/Outlet temperature of helium [℃]	~ 490/950

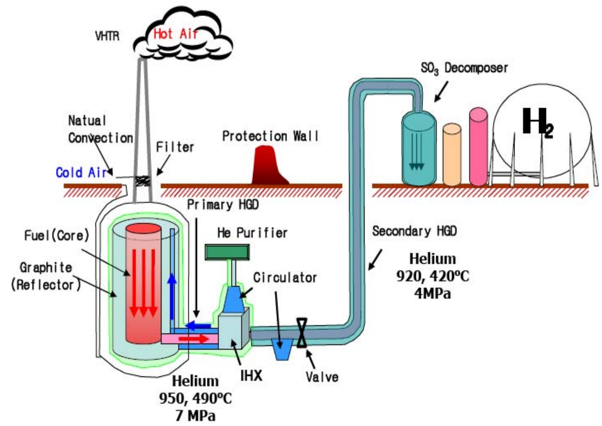

Fig. 1 Nuclear Hydrogen System

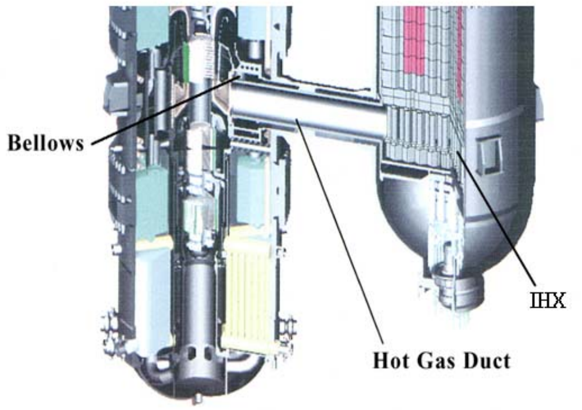

Fig. 2 Position of the primary HGD

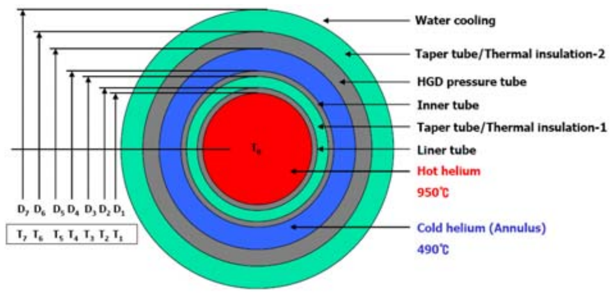

Fig. 3 Cross-section of the primary HGD and its design parameters

3. Heat Balance Model of the Primary HGD

The heat balance model of the primary HGD is shown in Fig. 3, which D_i and T_i represent the diameter and temperature of each part, respectively. The heat balance of the system is defined as following equations.

$$
\begin{aligned}
Q &= q \bullet \pi \bullet D_7 \\
&= h_{He-Hot} \bullet \pi \bullet D_1 \bullet (T_0 - T_1) \\
&= \frac{2\pi\, k_{Liner\ tube}}{\ln(D_2/D_1)} \bullet (T_1 - T_2) \\
&= \frac{2\pi\, k_{Insulation-1}}{\ln(D_3/D_2)} \bullet (T_2 - T_3) \\
&= \frac{2\pi\, k_{Inner\ tube}}{\ln(D_4/D_3)} \bullet (T_3 - T_4) \\
&= h_{He-Cold} \bullet \pi \bullet D_4 \bullet (T_4 - T_5) \\
&= \frac{2\pi\, k_{HGD\ press.tube}}{\ln(D_6/D_5)} \bullet (T_5 - T_6) \\
&= \frac{2\pi\, k_{Insulation-2}}{\ln(D_7/D_6)} \bullet (T_6 - T_7) \\
&= h_{water} \bullet \pi \bullet D_7 \bullet (T_7 - T_{water})
\end{aligned}
\qquad (1)
$$

where
Q : heat flux per unit length
$h_{He\text{-}Hot}$: heat transfer coefficient at the inside surface of the liner
$h_{He\text{-}Cold}$: heat transfer coefficient at the outside surface of the inner tube
h_{water} : heat transfer coefficient at the surface of the insulation-2
$k_{Liner\ tube}$: thermal conductivity of liner
$k_{Insulation\text{-}1}$: effective thermal conductivity of the insulation-1
$k_{Inner\ tube}$: thermal conductivity of the inner tube
$k_{HGD\ press.\ tube}$: thermal conductivity of the HGD pressure tube
$k_{Insulation\text{-}2}$: effective thermal conductivity of the insulation-2

The heat transfer coefficient (h) is obtained from the modified Dittus-Boelter model (3) as follows.

$$Nu = 0.021\ \mathrm{Re}^{0.8}\ \mathrm{Pr}^{0.4} \qquad (2)$$

4. Preliminary Design of the Primary HGD

In order to design the primary HGD of a 200MWth-class nuclear hydrogen system based on the heat balance model, we suppose some assumptions as follows.
- A heat flux per unit length is assumed as 25.53 kW/m.
- The effective heat conductivity of the thermal insulations is obtained from the empirical equation (4) as follows.

$$h = 0.35 + 0.0003 \bullet T \qquad (\mathrm{W/m℃}) \qquad (3)$$

From the equation (1)~(3), the design values of the primary HGD are obtained and shown in Table 2. Strength evaluation results based on design values in Table 2 are shown in Table 3 using the HTR-10 design concept (4).

Table 2 Preliminary design values of the primary HGD

i	T_i(℃)	D_i(m)	Thickness (mm)	Remark
1	950	0.772		
2	947	0.786	7	Liner tube
3	497	0.828	120	Thermal insulation-1
4	493	1.046	10	Inner tube
5	488	1.316	135	Annulus
6	473	1.446	65	HGD pressure tube
7	50	1.686	120	Thermal insulation-2

Table 3 Strength Evaluation Results

Item	Design Options	Results
Strength evaluation of the liner tube [MPa]	$\sigma_1^{acc} = 14.0$	11.0
Strength evaluation of the inner tube [MPa]	$\sigma_4^{acc} = 165.0$	10.3
Taper tube (small dia. end)		
- Max. nominal stress (S_1)	1.5 S_3=14 MPa	0.46
- Mean shear stress (t_1)	1.33x0.6S_3=7.4 MPa	0.29
Taper tube(large dia. end)		
- Max. nominal stress (S_2)	1.5 S_3=14 MPa	0.43
- mean shear stress (t_2)	1.33x0.6S_3=7.4 MPa	0.18
HGD pressure vessel tube		
- Max. nominal stress	S_1=72 MPa	70.9

5. Conclusion

Indirect cycle gas cooled reactors that produce heat at temperatures in the order of 950℃ are being considered in the nuclear hydrogen system at KAERI. Design values of the primary HGD for the nuclear hydrogen system are obtained based on a heat balance model. Preliminary strength evaluation results for the primary HGD design values showed that the geometric dimensions of the primary HGD would be acceptable for the design requirements.

Acknowledgements

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