Thermal-Hydraulic Sensitivity of Intermediate Loop Parameters for Nuclear Hydrogen System

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1. Introduction

The Very High Temperature gas-cooled Reactor (VHTR) is one of the advanced Generation IV (Gen-IV) reactor concepts especially for application to nuclear hydrogen production [1]. As shown in Fig. 1, the heat generated from the VHTR system is transferred to intermediate loop (red line, left in Fig. 1) through Intermediate Heat Exchanger (IHX). The intermediate loop transports VHTR heat to a Sulfur-Iodine (SI) hydrogen production system through Process Heat Exchanger (PHX) (blue line, right in Fig. 1).

To alleviate safety interference between the reactor and hydrogen production systems, certain level of safety distance should be provided by the intermediate loop. Since the intermediate loop performance affects overall nuclear hydrogen system efficiency, it is required to optimize its design and operating parameters. In this study, thermal-hydraulic sensitivity of the intermediate loop parameters with various coolant options has been examined by using MARS-GCR code [2].

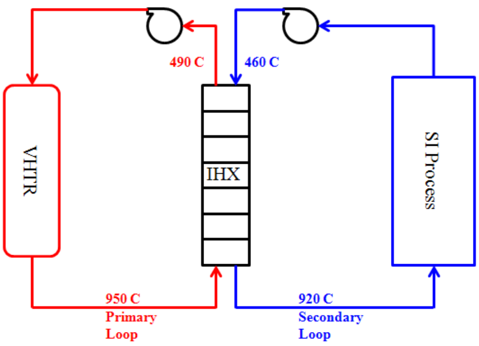


Fig. 1. Simplified schematic diagram of nuclear hydrogen production system.

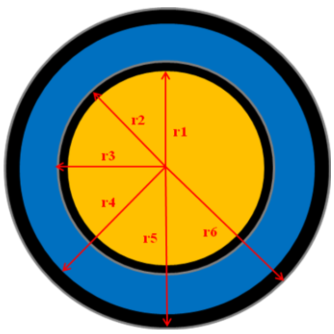
2. Analysis Methods and Results

MARS-GCR code was used to model and analyze the intermediate loop performance. As coolant options, the helium (He), carbon dioxide (CO_2), nitrogen (N_2), and He-N_2 and He-CO_2 gas mixtures were screened. Operating and design parameters of the intermediate loop were represented by reference boundary conditions. Simulations were performed for the heat loss, pressure drop and subsequent circulator work for a given safety distance.

2.1 Operating Conditions of Intermediate Loop

As shown in Fig. 1, 950°C of hot helium from a 600 MWth VHTR returns to the reactor at 490°C after transferring heat to the intermediate loop. Assuming 30°C of mean temperature difference across the IHX and PHX, the hot and cold side temperatures of the intermediate loop are considered to be 920°C and 460°C.

Mass flow rates (W) of the intermediate loop are determined by coolant thermal properties of each He, N_2, CO_2 and gas mixtures by using the relationship, $Q = W \cdot C_p \cdot \Delta T$. Sensitivity parameters selected are the loop operating pressure (30, 50 and 70 bars), the safety distance (100, 200, 400 and 800 m) and the concentric loop piping dimension which is shown in Fig. 2. Table 1 and Table 2 summarize the case studies performed in this study.



Materials	Dia. (m)
Coolant (Hot gas)	0.45120
In617	0.52740
Insulator (Kaowool)	0.54010
Coolant (Cold gas)	0.70375
SA508	0.84345
Insulator (Kaowool)	0.85615

Fig. 2. Reference Concentric Intermediate Loop Piping - hot gas (yellow), cold gas (blue), insulator (black).

Table 1. Reference cases for various coolants at 70 bar,

Coolant	MW (g/mol)	ρ (kg/m³)	C_p (kJ/kg·K)	γ (C_p/C_v)	Mass flow (kg/s)
He	4.002	4.5429	5.1900	1.6630	251.32
CO_2	44.01	50.370	1.1732	1.2248	1111.79
N_2	28.01	31.256	1.1192	1.3779	1165.43
He-N_2 (90:10)	6.404	7.2511	3.4045	1.6131	383.12
He-CO_2 (20:80)	36.01	40.961	1.2550	1.2504	1039.32

Table 2. Case Studies for various conditions.

	Conditions
Coolant	He, CO_2, N_2, He-N_2 mixture and He-CO_2 mixture
Pressure	30, 50 and 70 bar
Safety Distance	100, 200, 400 and 800 m
Pipe Diameter	Reference dimension, 60 and 70% of the reference

2.2 MARS-GCR Modeling of Intermediate Loop

Nodalization of the intermediate loop for MARS-GCR analysis is shown in Fig. 3. Concentric loop piping is modeled using PIPE component consisting of 20 hydrodynamic volumes. Hot coolant flows along the inner side of concentric pipe, while cold coolant flows along the outer annulus. Since the thermal performance of the heat exchangers is predetermined, inlets and outlets of the heat exchangers are modeled as source and sink boundary conditions.

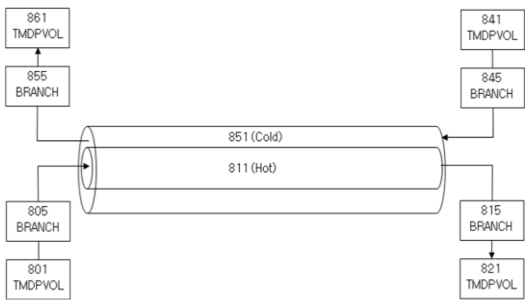


Fig. 3. The MARS-GCR modeling of Intermediate Loop

To analyze environmental heat loss, heat conduction and transfer across the inner and outer pipes are modeled. Total loop pressure drop is calculated by summing those in the loop piping and heat exchangers. Pressure drop in the heat exchangers is estimated by relation equation, $\Delta P = K \cdot \rho \cdot v^2/2$ [3].

Finally, the circulator work is calculated by following equation [4];

$$W_{cir} = \frac{1}{\eta_{cir}} \dot{m} C_p T_{inlet} \left[\left(\frac{P_{out}}{P_{in}} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]$$

where

W_{cir} : circulator work (MWth)
η_{cir} : efficiency of the circulator (0.85)
m : mass flow rate (kg/s)
C_p : specific heat at constant pressure (J/kg·K)
T_{inlet} : inlet temperature to the IHX
P_{out} and P_{in} : outlet and inlet pressure of circulator
γ : specific heat ratio (C_p/C_v)

2.3 Analysis Results

Environmental heat loss, pressure drop and circulator work were analyzed for various operating conditions, piping dimension and safety distances for each candidate coolants, He, N_2, CO_2 and gas mixtures of He-CO_2 and He-N_2. Environmental heat loss is proportional to the safety distance and piping dimension, however, it is estimated negligible.

It was found that the circulator work is the major factor affecting on the overall hydrogen production efficiency. Circulator work increases with the safety distance, and decreases with operating pressure and loop piping diameter. Fig. 4 shows the effect of coolant selection on the circulator work for reference case. In this result, coolant can be ranked in the order of CO_2, He, then He-CO_2 mixture and so on.

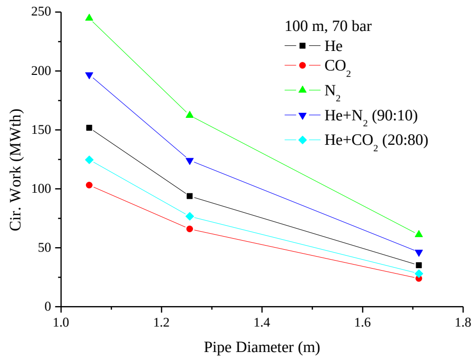


Fig.4. Circulator works vs. pipe diameters for various coolants at 70 bar and safety distances (100 m).

3. Conclusions

Sensitivity of the intermediate loop parameters has been carried out on its thermal-hydraulic performance. Design and operating parameters considered are the diameter and safety distance of concentric loop piping and the operating pressure. Considered coolants are He, CO_2, N_2, gas mixtures of He-CO_2 and He-N_2.

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Sensitivity results obtained from this study will contribute to optimization and finalization of the intermediate loop design, operating conditions and the coolant selection.

REFERENCES

[1] W.J. Lee, Y.W. Kim and J. Chang, "Perspectives of Nuclear Heat and Hydrogen", NET, Vol. 41, No. 4 (2009)
[2] W.J. Lee and H.N. Lee, "Implementation of the Pure and Mixture Gases Properties in MARS-GCR", KNS Autumn Meeting (2013)
[3] S. Kakaç and H. Liu, "Heat Exchangers Selection, Rating, and Thermal Design, 2nd Ed.", CRC Press (2002).
[4] W.J. Lee, Preliminary Operating Parameters of Nuclear Hydrogen Demonstration System, NHDD_KA_07-RD-BT (2007).