Hydraulic Design Methodology of Safety Depressurization System for HTGR

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1. Introduction

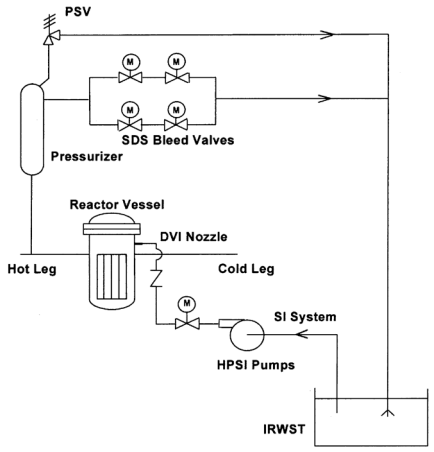
The Safety Depressurization System (SDS) of a High-Temperature Gas-cooled Reactor (HTGR), which utilizes helium as a coolant, is simpler than that of a Pressurized Water Reactor (PWR). This difference arises from the distinct reactor coolants and design-basis accidents associated with each type. In a PWR, the SDS is connected to the pressurizer system. In contrast, the HTGR-SDS piping connects to the primary helium side of the steam generator and shares piping with both the Helium Purification System (HPS) and the Helium Supply and Transfer System (HSTS), which provides pressurization functions [1]. While the design-basis accident for a PWR-SDS is a complete loss of feedwater to the secondary system [2], the design-basis accident for an HTGR-SDS is a "steam generator tube rupture"; in this scenario, the helium coolant released through the SDS passes through filters to remove radioactive isotopes before being discharged into the atmosphere [1].

The primary reason for the simplicity of the HTGR-SDS components compared to those of a PWR lies in the differing response to core uncover following an accident (Figure 1). In a PWR, core uncover resulting from the loss of water coolant is a critical issue; conversely, in a gas-cooled HTGR, core uncover is not a significant concern, whereas the oxidation of core structures is the primary focus. Although the discharge of helium coolant leads to a rise in fuel temperature, the reactor is designed to ensure that this temperature does not reach the threshold for fuel failure. However, the HTGR-SDS must rapidly relieve overpressure during a design-basis accident to minimize the oxidation of internal graphite structures caused by potential steam ingress.

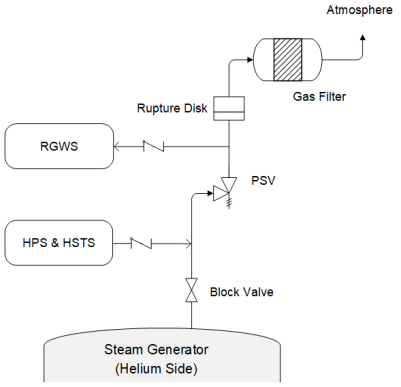
Meanwhile, when the SDS safety valve opens during a design-basis accident, the excessive pressure differential causes "choked flow" at the nozzle within the SDS piping. While determining the Choked Mass Flow Rate (CMFR) is crucial for safe reactor operation, the SDS piping shares lines with the HPS and HSTS systems; therefore, optimal design efforts are also required to minimize noise and vibration in the piping used during normal operation.

2. Configuration of SDS System

Since helium recharging is not required for the HTGR-SDS following a design-basis accident, components found in the PWR-SDS, such as bleed valve, sparger, and safety injection system, are unnecessary (Figure 1).



(a) PWR SDS (YGN 3/4)



(b) HTGR SDS (MHTGR-350)

Fig. 1. Configuration of SDS System

The HTGR-SDS is configured with two identical SDS units interlocked so that one is always operational. For both SDS units, the connection runs from the helium circulator outlet (where primary coolant pressure is highest during normal operation) to the top of the steam generator vessel. Each SDS features a series of components connected upward from the nozzle at the top of the steam generator vessel in the following order: a block valve, a pressure safety valve (PSV), and a rupture disk. Following a design-basis accident, overpressure discharge flows through the PSV; if the downstream rupture disk remains intact, the discharge is routed to the Radioactive Gaseous Waste System (RGWS), whereas if the rupture disk bursts, it is released into the atmosphere after passing through a gas filter that removes radioactive isotopes. While some SDS designs place the rupture disk

upstream of the PSV [3], KOSHA guidelines [4] mandate that it be located downstream of the PSV.

The HPS and HSTS connect to the piping between the block valve and the PSV. The RGWS connects to the piping between the PSV and the rupture disk.

3. Design of Pipe Size

3.1 Theory

In accordance with the design criterion [5] stating that the pressure drop in the piping connecting the system and the safety valve must not exceed 2% of the discharge pressure, it is necessary to calculate the pressure drop based on the piping length. The piping length is defined as the distance from the nozzle penetrating the primary heat transport system (S/G upper head) to the safety valve.

The equation for the pressure drop in the pipe is as fol lows [6].

$$\Delta P = f\frac{L}{D}\frac{\rho v^2}{2} = f\frac{L}{2\rho D}\left(\frac{W}{A}\right)^2 \qquad (1)$$

Where, for smooth tube $f = 0.3164Re^{-0.25}$

D Diameter (m)
L Length (m)
W Mass flowrate (kg/s)
A Flow area (m²)

During a design-basis accident, a "choking" phenomenon occurs in the SDS system's connecting piping, where the flow velocity reaches the speed of sound and the flow rate hits its maximum. The Choked Mass Flow Rate (CMFR) of a gas is a function of pressure, temperature, nozzle cross-sectional area, and the specific heat ratio. The formula for the maximum mass flow rate through a one-dimensional isentropic converging nozzle, assuming an ideal gas, is as follows [7].

$$\mathrm{W} = \hat{A}P_o\sqrt{\frac{\gamma}{R_sT_o}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (2)$$

Where,

$\hat{A} = C_v \circ A$: Minimum flow area in a pipe (m^2)
C_v Valve flow coefficient (0.6~0.82)
P_o Upstream stagnation pressure (Pa)
T_o Upstream stagnation temperature (K)
γ Ratio of specific heats (He = 1.667)
R_s Specific gas constant (J/(kg-K), He = 2077).

Equation (2) reveals that the discharge coefficient significantly influences the CMFR and that the range of CMFR corresponding to the minimum and maximum values of the discharge coefficient is quite wide.

3.2 Piping

The inner diameter of the piping influences the relief of overpressure in the heat transport system via helium coolant discharge, while also determining the CMFR of the discharge device. To avoid flow-induced vibration, the helium velocity within the piping must be maintained below 60 m/s [8]. The flow within the piping is categorized into active flow—occurring during helium charging and purification for normal reactor operation—and passive flow—discharged through the PSV during design-basis accident. For the design of the piping inner diameter, the active flow rates selected were the helium purification flow rate (approximately 1% of the reactor's rated flow) and the flow rate required to charge the reactor with helium within one hour. Table I lists the helium velocities in the connecting piping that satisfy the 60 m/s limit for active flow.

The governing flow rate for designing the internal pipe diameter is the CMFR. When choked flow occurs, the pressure drop in the piping connecting the system to the safety valve must not exceed 2% of the relieving pressure; this limit is intended to prevent malfunction or damage caused by valve chattering. Section 4 discusses the design method for determining whether the connecting piping—which already satisfies the requirements for the active flow rate—also meets the criteria for choked flow and the associated pressure drop limits.

3.3 Pressure setpoints for PSV

The “maximum allowable set pressure” of a PSV must be equal to or less than the design pressure or the “maximum allowable operating pressure” of the vessel or equipment being protected. According to KOSHA design guidelines [4], the maximum allowable operating pressure is determined differently depending on whether a single safety valve or two or more safety valves are used. Reactor PSVs are classified as “safety-related” devices and must be configured with two trains in accordance with the concept of defense-in-depth. This configuration accounts for the potential malfunction of one train during an accident, with the design basis assuming that only a single train operates. The PSV opening set pressure is designed at 100% of the vessel's design pressure, based on the assumption of a single-train configuration.

Table II lists the pressure setpoints applied to the PSV design for the MHTG-350. The PSV opening set pressure is 7.22 MPa (100% of the vessel design pressure), and the reseating pressure is 6.68 MPa (92.5% of the design pressure). However, the reseating pressure was set at 6.1 MPa, a value lower than the 6.68 MPa specified in the general safety valve design guidelines. This setting deviates from the KOSHA design guidelines [4]—which typically require safety valve settings to exceed the system operating pressure—and instead

reflects the SDS design methodology aimed at securing sufficient pressure margin for the reactor to ensure safety during design-basis accident.

4. Results and Discussion

4.1 Choked Mass Flow Rate (CMFR)

CMFR is a function of the pipe's inner diameter; once the diameter is specified, the CMFR can be calculated using Equation (2). Equation (2) also reveals that the valve-flow-coefficient C_v significantly influences the CMFR, resulting in a wide range of possible flow rates between the minimum and maximum C_v values. Calculations using Equation (2) with these minimum and maximum coefficients indicate that the CMFR for a pipe with a 67 mm inner diameter falls within the range of 9.0 to 12.3 kg/s (Table III).

Alternatively, the CMFR can be determined based on the speed of sound, independent of Equation (2). The speed of sound at Mach 1 is a function of gas temperature, as shown below.

$$V_{ss} = 331.5 + 0.6T_g \text{ (m/s)} \quad (3)$$

$$W_{ss} = \rho V_{ss} A \quad (4)$$

Where, the T_g is the gas temperature (°C).

Since the speed of sound increases with temperature, the theoretical maximum CMFR is achieved under conditions of maximum gas temperature. For a pipe with an inner diameter of 67 mm, the maximum CMFR calculated using Equation (4) was 9.5 kg/s, a value close to the CMFR calculated using the minimum flow coefficient (9.0 kg/s). An increase in CMFR during a design-basis accident implies a higher discharge rate, which facilitates rapid reduction of reactor overpressure and aids in accident mitigation.

The time required for the PSV to close following the pressure drop after its initial opening was calculated. Since the CMFR represents the maximum rate at which helium is discharged through the PSV, it is possible to determine the time elapsed between the valve opening and closing. Assuming the helium inventory in the heat transport system to be 1,450 kg, half that of the MHTGR-350, the calculated time from valve opening to closing was less than one minute in all cases (Table III). The calculation of the valve closing time did not account for the steam inflow from the steam generator following the design-basis accident; this factor should be considered in future reactor designs.

4.2 Pipe size

Figure 2 illustrates the pressure drop behavior of 300°C helium flowing through pipes with inner diameters of 57 mm and 67 mm—using connection lengths of 0.5 m and 1 m—based on the aforementioned equation. The solid line in the figure represents the 2% pressure drop limit for the connection, which corresponds to 130 kPa relative to the MHTGR-350 operating pressure of 6.48 MPa.

The analysis results indicate that while the CMFR increased with pipe size, the pressure drop decreased. For the 67 mm pipe, the 2% pressure drop limit was met at a length of 0.5 m within the expected choked flow range; meanwhile, the 57 mm pipe satisfied the limit at both 0.5 m and 1 m lengths across the same range (Figure 2). This implies that with smaller pipe inner diameters, the rate of decrease in CMFR has a greater impact than the rate of increase in pressure drop.

A low CMFR results in a reduced discharge rate during a design-basis accident, causing the reactor pressure to decrease slowly, which hinders accident mitigation efforts.

Conversely, a high CMFR can cause the pressure drop in the connecting piping to exceed the limit during a design-basis accident, potentially leading to PSV malfunction; furthermore, shorter connection lengths complicate the layout design of the SDS.

Table I. Helium velocity in the pipe

Hole	**Area**	**T**	**P**	***W***	**Density**	***V***
mm	mm²	℃	MPa	kg/sec	kg/m³	m/sec
57.3	2578	500	6.4	0.4	3.95	39
		50	2	0.4*	2.95	53
66.9	3515	500	6.4	0.4	3.95	29
		50	2	0.4*	2.95	39

* Mass flowrate filing the 1450kg helium within one hour

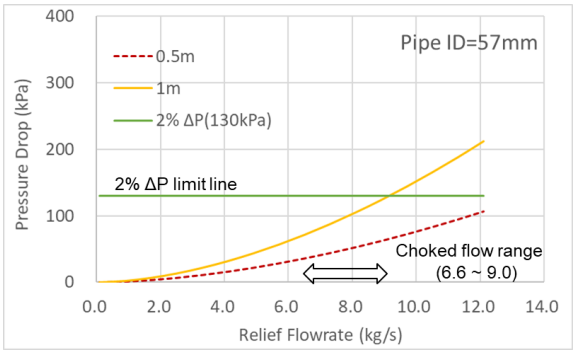
Table II. Pressure setpoint of the MHTGR-350 PSV

Reactor	**Set point**	**Unit**	**Value**
MHTGR 350	Normal Pressure	MPa	6.48
	Open Pressure		7.07±1%
	Close Pressure		6.01±1%

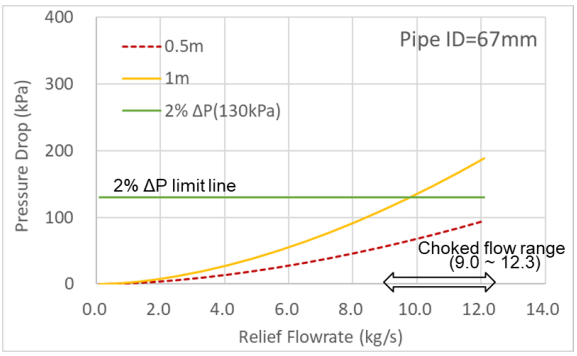
Table III. CMFR and closing time of PRV

Hole	**Area**	C_v	**CMFR**		**Closing time***
			Eq. 2	**Eq. 4**	
mm	mm²	-	kg/s		sec
57.3	2578	0.60	6.6	7.0	37.8
		0.82	9.0	7.0	27.7
66.9	3515	0.60	9.0	9.5	27.7
		0.82	12.3	9.5	20.3

* Condition: 300℃, 6.4MPa helium with 1450kg inventory.



(a) 57mm ID pipe



(b) 67mm ID pipe

Fig. 2. Pressure drop of pipe for the CMFR

5. Summary

The design-basis accident for the HTGR-SDS is a steam generator tube rupture; in this accident, overpressure must be relieved rapidly to minimize the oxidation of internal graphite structures caused by steam ingress.

The SDS for an HTGR which utilizes helium as a coolant is simpler than that of a PWR. This is because, unlike PWRs, where core uncover entails thermal-hydraulic impacts, HTGRs do not require helium injection following a design-basis accident. Consequently, components such as bleed valve, sparger, and safety injection system found in PWR-SDS configuration are unnecessary.

During a design-basis accident, "choking" occurs in the SDS connecting piping as the flow velocity reaches the speed of sound, resulting in a maximum flow rate. This implies that the pipe's inner diameter determines the discharge flow rate; furthermore, the length of the piping between the nozzle and the PSV must be designed so that the pressure drop remains within the 2% limit.

Analysis of choked flow and pressure drop behavior in the connecting pipe revealed that a smaller inner diameter results in reduced choked flow but increased pressure drop.

While reduced choked flow leads to a lower discharge rate, thereby slowing the relief of reactor overpressure, the accompanying decrease in pressure drop allows for a longer connecting pipe, which facilitates the SDS layout design.

Conversely, if the choked flow rate is too high, pressure drop in the connecting pipe during a design-basis accident may exceed the limit, potentially causing PSV malfunction; additionally, the required shortening of the connecting pipe complicates the SDS layout design.

ACKNOWLEDGEMENT

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REFERENCES

[1] HTGR-86-024, "Preliminary Safety Information Document for the Standard MHTGR," October 6, 1986.
[2] Y.M. Kwon, H.S. Lim, J.H. Song, "Design options for safety depressurization system," Nuclear Engineering and Design 179 (1998) 287–296
[3] Patsy L. Hendricks, "General Atomic: Standard safety analysis report (GASSAR-6)," U. S. DOE, 1977.
[4] KOSHA D-18-2020, "안전밸브 등의 배출용량 산정 및 설치 등에 관한 기술지침," 한국산업안전보건 공단, 2020.
[5] 원자력안전위원회고시 제 2016-12 호, "원자로시설의 안전밸브 및 방출밸브에 관한 기준," 2016. 7. 25.
[6] J. P. Holman, "Heat Transfer," 10th edition, McGraw-Hill, Inc. 2010.
[7] V. Babu, "Fundamentals of Gas Dynamics," Second edition, John Wiley & Sons, 2015.
[8] M. Gilbert and R. Katz, "Thermal and Flow Design of Helium-cooled Reactors; Chapter 3, Reactor Core Heat Transfer: Fundamentals," American Nuclear Society, USA, 1984.