Preliminary Design of Refueling Decay Heat Removal System Steam-water Separator for the PGSFR

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1. Introduction

The Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) is a pool-type sodium-cooled fast reactor which has thermal power of 392 MW.

For refueling and reloading of the nuclear fuel, the Main Steam and Feedwater System (MSFS) provides sufficient cooling to Primary Heat Transfer System (PHTS) until the temperature of the refueling operation is reached, and cooling through the MSFS is stopped and the Refueling Decay Heat Removal System (RDHRS) operates to keep the reactor temperature at 200 °C for refueling and reloading of the nuclear fuel in the reactor pool during the refueling operation of the plant.

2. Design Requirements of the RDHRS

The RDHRS consists of two independent loops with the same structure and is designed to maintain the temperature of the PHTS at 200 °C, which is the temperature of the reactor at the refueling operation by removing 2.1 MWt of decay heat, which is about 0.5% of the rated power per loop, during the refueling and reloading operation of the plant.

Each loop of the RDHRS consists of one steam generator, one separator, two refueling recirculation pumps and two air-cooled condensers, and the residual heat is removed by forming a recirculation loop as shown in Fig. 1. The RDHRS piping is diverted from the piping at the upstream of the main steam isolation valve and connected to the separator, and diverted from the pipe at the downstream of the feedwater isolation valve and connected to the refueling recirculation pump.

In other words, saturated steam from the exit of the steam generator tube enters the separator and the separated vapor moves to the air-cooled condenser, and the separated water enters the separator storage tank. Vapors pass through an air-cooled condenser and condensed water enters a separator storage tank and mixes with water separated by a separator.

The water in the storage tank is transported by the refueling recirculation pump to the inlet of the steam generator tube, and circulated through the RDHRS flow path.

3. Separator Types and Selection

There are horizontal and vertical types of separators. Usually, vertical type is used for low flow rate, high Vapor/Liquid ratio and horizontal type is used for high flow rate, low Vapor/Liquid ratio.

The separator is designed to take into account the speed of the saturated fluid and the speed of the vapor. The information of the steam generator tube side outlet is shown in Table 1.

Table 1: Information of Steam Generator Tube Side Outlet in the Refueling Operation Mode [6]

Temperature (°C)	180
Pressure (MPa)	1.003
Total Flowrate (kg/s)	37.5
Steam Flowrate (kg/s)	1.68
Water Flowrate (kg/s)	35.82
Quality	0.0447

Since the quality is low and flow rates are relatively high, a horizontal separator was selected.

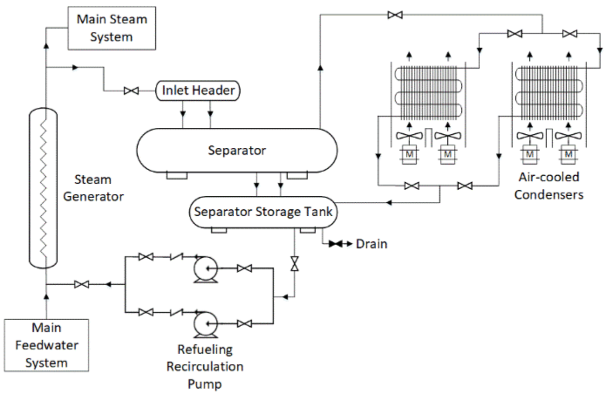

Fig. 1. Schematic Diagram of the PGSFR RDHRS

4. Calculations

4.1. Terminal Velocity

Water droplets in the saturated steam passing through the inside of a horizontal separator are separated from the vapor if the gravity acting on the water particle is greater than drag force of the vapor. Performing a force balance of the liquid droplet disengagement provides the necessary relationship.

These forces can be expressed in the following expressions.

$$F_D = \frac{\left(\frac{\pi}{8} C_d D_P^2 U_V^2 \rho_g\right)}{g} \quad (1)$$

$$F_G = \frac{M_P(\rho_l - \rho_g)g}{g\rho_g} \quad (2)$$

F_D is drag force, F_G is gravity force, C_d is drag coefficient, D_P is the diameter of the water particle, U_V is the velocity of the gas, and M_P is the mass of the water droplet. Subscript l and g means liquid and gas, respectively.

When the velocity of the gas is small enough to reach a certain speed, the water droplets will escape from the gas and this speed is called the terminal velocity (U_T) of the gas. Equating Eqs. (1), (2) results in,

$$U_T = \sqrt{\frac{4gD_P(\rho_l - \rho_g)}{3C_d\rho_g}} \tag{3}$$

The design of separator starts from obtaining this terminal velocity and determine the geometric shape of the gas area inside the separator.

C_d is a function of the target geometry and gas area Reynolds number (Re) and has the relationship shown in Fig. 2 to the circular water droplets.

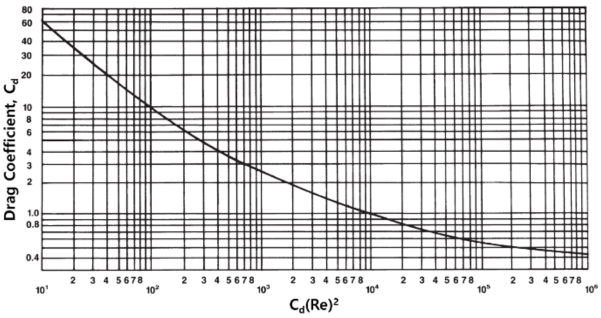

Fig. 2. Drag Coefficient of Rigid Spheres [1]

The abscissa ($C_d(Re)^2$) of Fig. 2 is given by:

$$C_d(Re)^2 = \frac{(0.95)(10^8)\rho_g D_P^3(\rho_l - \rho_g)}{\mu^2} \tag{4}$$

The gas viscosity (μ) at 180°C is 0.015025 cP. Typical particle size is various as shown in Fig. 3 and determination of D_p is necessary in detailed design procedure. As this study is preliminary design, D_p is assumed to be 100 micron.

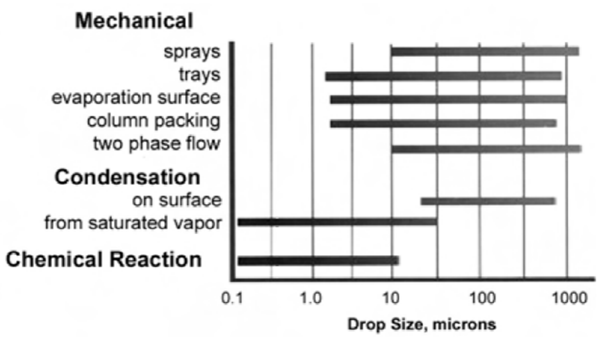

Fig. 3. Typical Particle Size Distribution Ranges from Entrainment caused by Various Mechanisms [1]

Calculated C_d and U_T is 5.12 and 0.686 ft/s respectively. The terminal velocity of the steam area required for 100 micron-sized water droplets to be separated from the vapor is not more than 0.686 ft/s. For conservative design, 0.75 times the terminal velocity is typically set to the final speed of the gas (U_V) [2] and the size of the separator is determined based on it.

4.2. Determining of Surge and Holdup

The design of the separator requires definitions of Holdup and Surge. Holdup is defined as the time it takes to reduce the liquid level from normal level (NLL) to low liquid level (LLL) while maintaining a normal outlet flow without feed makeup during operation. The opposite concept, Surge, is the time it takes for the liquid level to rise from NLL to high liquid level (HLL) while maintaining a normal feed without any outlet flow during operation.

Since regulatory requirements for Holdup and Surge have not been established, we assumed that a five-minute of Holdup/Surge time which is generally used in the industrial field.

The required Holdup/Surge volume (V) for a required Holdup/Surge time is as follows.

$$V = \mathrm{T} \times \frac{W_L}{\rho} \tag{5}$$

W_L is liquid mass flowrate, T is Holdup/Surge time respectively.

4.3. Diameter and Length of the Separator

The cross-sectional area of the horizontal separator is divided into the liquid area (A_{LLL}, A_H, A_S) and the gas area (A_V) as shown in Fig. 4. First, obtain the diameter (D) of the separator and set the LLL.

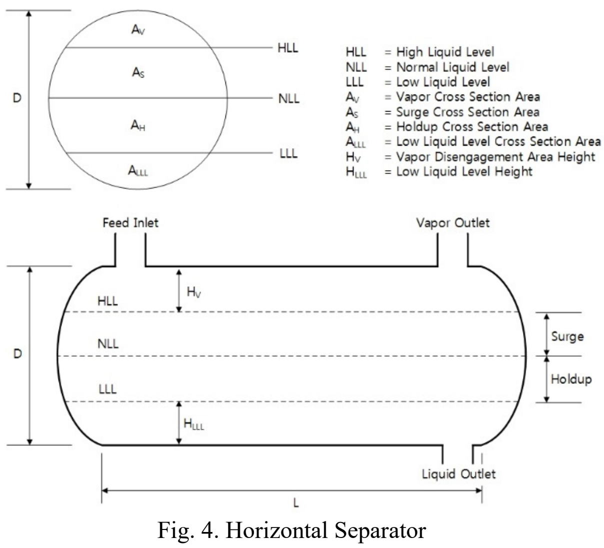

Fig. 4. Horizontal Separator

The NLL and HLL are obtained from Holdup and Surge respectively.

Conservatively, the area from the HLL to the top of the separator is assumed to be the section where the separation takes place (A_V) and the length (L) of the separator is calculated by considering the minimum area required for the separation, considering the Holdup and Surge.

The diameter (D) of the separator can be obtained by using the L/D ratio guideline [2] and Eqn. (6) below. The L/D ratio recommended based on the operating pressure of the RDHRS is 1.5 to 3.0.

$$D = \left(\frac{4(V_H+V_S)}{0.6\pi(L/D)}\right)^{1/3} \quad (6)$$

The ratio of A_{LLL}/A_T and A_V/A_T can be obtained using the conversion formula [2] for H_{LLL}/D and H_V/D.

The minimum length L to satisfy the Holdup/Surge volume can be obtained by using Eqn. (7) below.

$$L = \frac{V_H+V_S}{A_T-A_V-A_{LLL}} \quad (7)$$

The gas entering the separator will pass through the gas area of the A_V with a flow rate of Q_V. Therefore, the horizontal direction speed of the gas can be shown as follows:

$$U_{VA} = \frac{Q_V}{A_V} \quad (8)$$

The time (L/U_{VA}) taken for the gas to pass through the separator area with length L, at the speed of U_{VA} shall be greater than the time taken for the gas entering the separator to travel from the highest point of the gas area to the HLL at the final speed. In this relation, the minimum length of the separator for vapor separation can be shown as:

$$L_{min} = \frac{Q_V}{A_V} \times \frac{H_V}{U_V} \quad (9)$$

Compare L and L_{min} obtained from Eqs. (7) and (9), and determine $L=L_{min}$ when $L<L_{min}$. This simply means providing an extra Holdup/Surge in the separator. If $L<<L_{min}$, increase the height (H_V) of the gas area (A_V) and recalculate.

If $L>>L_{min}$, on the other hand, make H_V smaller and recalculate but H_V shall be greater than 1 ft, the minimum value. In general, the ideal design point is $L>L_{min}$.

If L is obtained check the final L/D is appropriate. Note that this final L/D is different from L/D ratio used in Eqn. (6). Increase D when final L/D>6.0 and decrease D when final L/D<1.5 and recalculate.

When L and D are determined, normal liquid level heights and high liquid level heights can be obtained by Eqn. (10) and the conversion formula [2] for H_{NLL}/D and A_{NLL}/A_T.

$$A_{NLL} = A_{LLL}\frac{V_H}{L} \quad (10)$$

5. Conclusions

Using the methodology of GPSA and Svrcek et al, the specifications of the separator of PGSFR RDHRS are designed as Table 2.

Table 2: Design Parameters of RDHRS Separator

Design Parameter	Value
Vapor Volumetric Flow Rate (m^3/s)	0.33
Liquid Volumetric Flow Rate (m^3/s)	0.04
Vertical Terminal Vapor Velocity (m/s)	0.21
Holdup/Surge Volume (m^3)	12.12
Total Cross-sectional Area (m^2)	4.06
Low Liquid Level Height (m)	0.3
Normal Liquid Level Height (m)	1.08
High Liquid Level Height (m)	1.82
Tank Diameter (m)	2.27
Tank Length (m)	7.67

In this preliminary design, we have chosen values that are sufficiently conservative but detailed design of the PGSFR is carried out in the future, more detailed calculation should be carried out considering the specific design parameter such as arrangement of equipment in the system or installation of mist eliminator pads and inlet diverters inside the separator.

ACKNOWLEDGEMENTS

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