Parametric study of the fuel salt drain system design of K-MSR

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***Keywords : Molten Salt Reactors; MSR; Molten Salt; Drain Tank; Drainage**

1. Introduction

The drain system is one of the distinguished features of most molten salt reactors (MSR). Many MSR, including the molten salt reactor experiment (MSRE), utilizes the drain tank as an emergency or a normal shutdown system. As freeze plug at the bottom of the core melts, the fuel salt in the active core is drained and eventually reach a subcritical state.

The drain time is thus the key measure of this system. The drain time can be a function of several design parameters including the drain pipe diameter, the angle of the drain line slope, and the drain pipe length.

In this study, we performed the parametric studies of the drain system for the 100-MW_{th} K-MSR (Korea-Molten Salt Reactor) that is being developed in Korea Atomic Energy Research Institute (KAERI). First, an analytical model for the drain system was suggested. Second, the suggested model was validated with the simulation using the system code, GAMMA+. Finally, the parametric studies of the drain system were performed and the values of a few key parameters are determined based on the analysis.

2. Drain System

A 100-MW_{th} molten salt fast reactor (MSFR), K-MSR, is currently being developed by KAERI. One of the fuel salts that is being considered for the MSFR is NaCl-KCl-UCl_3 (42.9-20.3-36.8 mol%). For the drain analysis, the density and the viscosity of the NaCl-KCl-UCl_3 at 605℃ were used as given in Table 1.

Table I: The properties of NaCl-KCl-UCl_3 at 605℃

	Value
Density	3,331 kg/m^3
Viscosity	0.002781 Pa·s

In this study, the whole volume of the FSL was simplified as an equivalent cylindrical tank, as suggested by the authors of [1]. Since the salt volume (V_{FSL}) and the height of the FSL (H_{FSL}) are the key parameters for draining, the diameter of the equivalent FSL tank (FSLT) was determined considering the salt volume as follows, while the height of the tank was maintained.

(1) $$D_{FSL,eq} = \sqrt{\frac{4V_{FSL}}{\pi H_{FSL}}}.$$

The objective of the drain system is to deliver the fuel salt in the FSL to the drain tank for the reactor shutdown. The configuration of the drain line of the MSFR followed that in the MSRE [2]. The drain line is connected at the bottom of the FSL and extended to the bottom of the drain tank. The drain line is slightly sloped to prevent the retention of the residual salt. On the drain line, there are two freeze valves that control the draining procedure. One of them is installed just below the FSL and opened when the draining procedure is initiated. The other valve is located before the drain tank and used to isolate the drain tank from the other lines (e.g. flush salt line).

As a result, the overall configuration of the drain system can be simplified as illustrated in Fig. 1. The form loss pressure drops are expected at several locations including the freeze valves, drain line inlet, drain line outlet, and pipe bends.

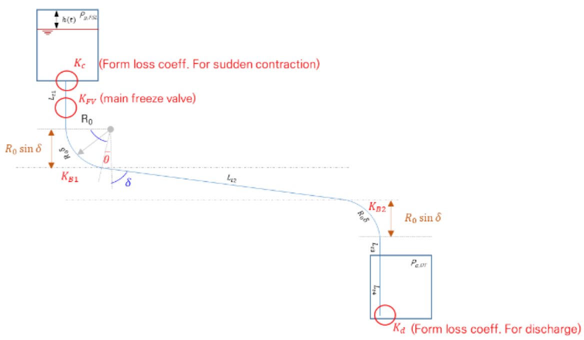

Fig. 1. Schematic diagram of the simple drain system

3. Analytical model

For the parametric study of the drain system, the analytical model suggested by Wang et al. [1] (Wang's model) is used. The Wang's model was derived using the simple geometry where an equivalent FSL tank is connected to a vertical drain pipe. In this model, the time-dependent height from the top of the FSL equivalent tank ($h(t)$) is calculated as follows:

(2) $$\frac{dh(t)}{dt} = \sqrt{\frac{2}{R_B^2-1}\left[g\left(H_t + H_{FSL} - h(t)\right) - \frac{(p_B - p_A)}{\rho} - \Sigma\frac{\Delta P}{\rho}\right]},$$

where the subscript t stands for the drain line tube, R_B is the ratio between the cross-sectional area of the FSLT and the tube diameter ($R_B = (D/d)^2$), and p_A and p_B are the pressure at the DT and the FSLT, respectively.

ΔP in equation (2) is the pressure drops occurring due to the friction or the form losses, which are generally expressed as follows:

(3) $\Delta P = K \times \frac{1}{2}\rho u^2$,

where u is the velocity at the FSLT or the drain line tube depending on the location where pressure loss occurs. K is the friction or the form loss coefficient, which are calculated using the expressions or the values in Table II. In the present analysis, the form loss due to the freeze valve was assumed fully open and did not contribute to the pressure drop.

Table II: The friction and form loss coefficients

Types	Expressions or values for K	Ref.
Friction	$4\left(\frac{16}{Re} + \frac{0.0076\left(\frac{3170}{Re}\right)^{0.165}}{1+\left(\frac{3170}{Re}\right)^{7.0}}\right)\left(\frac{L}{D}\right)$, where $Re = \rho u D/\mu$	[1]
Pipe inlet	$0.5(1 - R_B^{-1})$	[3]
Bend	$0.0175\lambda\delta R_0/D_t$, where λ depends on Re and obtained from the curve in [3]. For example, $\lambda = 0.045$ at Re=200,000.	[3]
Pipe discharge	1.0	[3]

In the original paper by Wang, the drain pipe is assumed installed vertically, hence the height of the tube (H_t) was same as the length of the tube (L_t). In this paper, the height and the length of the drain line were separately estimated for the configuration given in Figure 1 to model the friction loss more closely to the actual drain system.

4. Comparison with GAMMA+ results

The results from the suggested analytical model were compared with the results from the system code simulation for the verification. For the system code, the GAMMA+ (Gas Multi-component Mixture Analysis+) was used. The GAMMA+ was originally developed for the gas-cooled reactor analysis, but it has recently updated to simulate the advanced reactors including the molten salt reactors [4]. In this study, the stratified flow dynamics model in GAMMA+ was used for the drain simulation. This model solves the mass, momentum, and energy equations for the liquid-gas mixture.

For this simulation, we set the base case design parameters for the drain system, based on the configuration given in Figure 1. The equivalent diameter of the FSLT was calculated as 2.075 m using Eq. (1). The drain line was sloped by 3° and the length of the sloped drain line was 5 m. The curvature of the pipe bend was assumed three times the diameter of the drain tube. The design parameters for the base case were summarized in Table.

Table III: Base case design parameters for drain system

Parameters	**Values**
V_{FSL}	11.23 m^3
H_{FSL}	3.320 m
$D_{FSL,Eq}$ 1)	2.075 m
$L_{t,1}$, $L_{t,2}$, $L_{t,3}$	0.5 m, 5 m, 0.25 m
D_t	0.127m
R_0	0.381m (=3D_t)
δ	87° (=90° - θ)
θ	3°
H_{DT}	2.7 m
D_{DT}	2.7 m

The calculated salt levels in the FSLT from the analytical model and the GAMMA+ were compared in Fig. 2. The calculated salt levels from the analytical model and the GAMMA+ simulation showed good agreement for the most of the drain period. However, the analytical model underestimated the drain time when compared to the GAMMA+ simulation. The delay of the drain at the later phase is due to the increase of the pressure drop as the flow regime changed from the single-phase flow to the two-phase flow of the liquid salt and the inert gas. As shown in Fig. 3, the void fraction in the drain line increased at the time around where the calculated salt level from the GAMMA+ simulation started to deviate from that calculated from the analytical model.

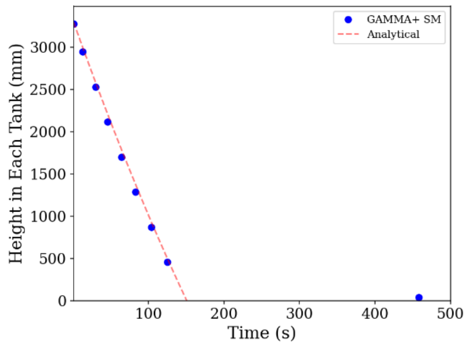

Fig. 2. Comparison with GAMMA+ results

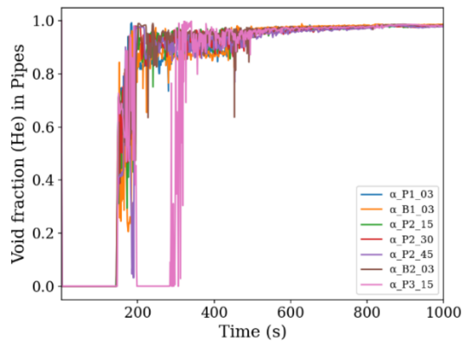

Fig. 3. Void fraction of the Helium in the drain line from the GAMMA+ simulation

Despite of the different predictions of the salt level at the later phase of the salt drain, the agreement between the analytical model and the GAMMA+ simulation results were close enough for the analytical model to be used to investigate the parametric trends. For this reason, we used the suggested analytical model for the parametric studies of the drain system.

5. Parametric studies

The effects of the design parameters on the drain time were investigated using the suggested analytical model. Unless otherwise mentioned, the design parameters given in Table are used.

5.1. Diameter of drain tubes (D_t)

The effect of the drain line tube diameter was on the drain time was investigated as shown in Fig. 4. The drain time was significantly increased when the diameter of the drain line tube was reduced. In order for the drain time to be within about 10 minutes, the tube diameter should be larger than 3 inches.

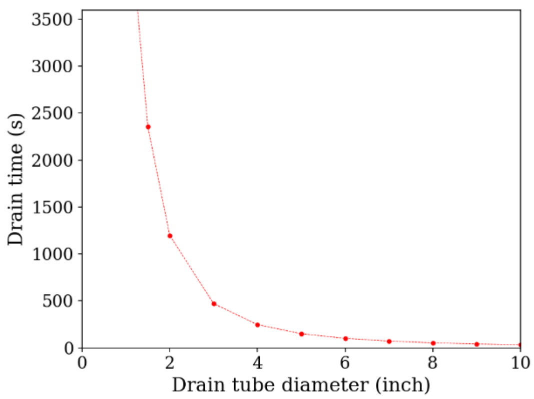

Fig. 4. The effect of the drain line tube diameter on the drain time

5.2. Slope angle of the drain line (θ)

The slope angle of the drain line, on the other hand, only minorly affected the drain time. Increasing the slope from 3 to 25 decreased the drain time only by about 20 seconds, whereas it increased the overall height of the drain line by 1.75 m (Fig. 5). For the maritime applications of the small modular reactors, it is usually beneficial to have a compact size due to the limited space for the reactor installation. Therefore, the small angle of the slope is preferred in this case.

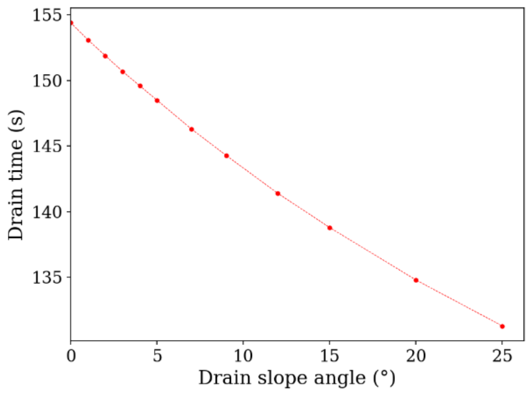

Fig. 5. The effect of the slope angle of the drain line on the drain time

5.3. Length of the drain line

The effect of the sloped drain line length was also investigated as shown in Fig. 6. The effect of the drain line length on the drain time was not negligible; increasing the tube length from 1 m to 20 m increased the drain time only by 25 seconds.

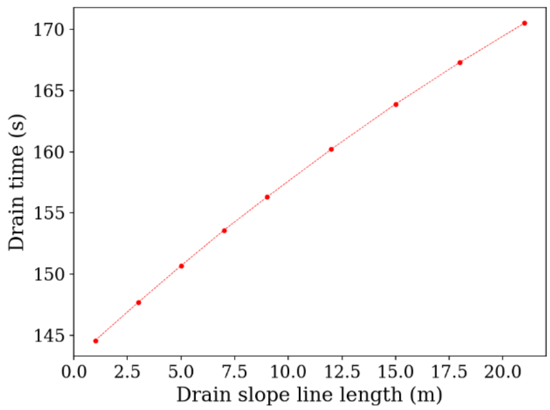

Fig. 6. The effect of the drain line length on the drain time

6. Conclusions

In this study, the parametric studies for the drain system design were performed for a 100-MW_{th} K-MSR. For the parametric studies, the analytical model developed for the simple drain system configuration was suggested. The analytical model can predict the change of the salt level during the drain procedure, and its results were comparable with the results from the system code, GAMMA+.

From the parametric studies using the suggested model, the drain tube diameter was found to be most critical design parameter for the drain system. The time required for the salt draining increased exponentially when the drain tube diameter was decreased below 3 inches. On the other hand, the slope or the length of the drain line has comparatively negligible effect on the drain time. Instead, these parameters increased the overall height of the drain system, which could be undesired for specific small modular reactor (SMR) applications such as the maritime SMRs or the mobile SMRs.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (RS-2023-00259713).

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