A Preliminary Thermal Analysis and Modeling Study of MSRE Freeze Valve for K-MSR Valve Development

Chan Lee[a*], Dongyeol Yeo[b], Gyeong-Hoi Koo[b]
a) *LWR Fuel Technology Division, Korea Atomic Energy Research Institute*
b) *Advanced SMR Technology Development Division, Korea Atomic Energy Research Institute*
Corresponding author: chanlee@kaeri.re.kr

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1. Introduction

Freeze valve is one of a distinctive instruments of MSR system, which utilizes phase transition of the main coolant (molten salt) to control the flow. Basic configuration of freeze valve is to equip both heating and cooling devices around a throttle to control temperature of the coolant inside the throttle. When the coolant is cooled below freezing point, the valve is closed. Reversely, the valve is open when the coolant is heated above melting point. Pressurized air was utilized as coolant gas, and shaped cartridge heaters were utilized as heating devices in MSRE.

As a part of the K-MSR: Korea-Molten Salt Reactor project, we are now analyzing freeze valve system of the former molten salt reactor experiment (MSRE), operated at ORNL and looking for improve the design. In this study, we have developed and presenting detailed 3D drawings of the MSRE freeze valve and established preliminary thermal models for further CFD study.

2. Methods and Results

2.1 MSRE Freeze Valve Design and Dimensions

In the literatures[1,2], authors stated that they decided to use freeze valves because they were unable to find any other mechanical type valve, reliable enough to use in high-temperature, highly-corrosive environment inside the MSRE main coolant pipes. Freeze valves are slower than ordinary mechanical valves to operate, but was fast enough to control molten salts in the MSR.

Total 12 freeze valves were installed in the MSRE and we classified the valves as two group; passive and active freeze valve. Only one of 12 valve was passive, tagged as FV-103, which was installed under the reactor core and only cooling devices were attached because the decay heat supplies enough heat to thaw open the valve.

Another 11 valves were classified as active freeze valves and we set those valves as a standard model to evaluate.

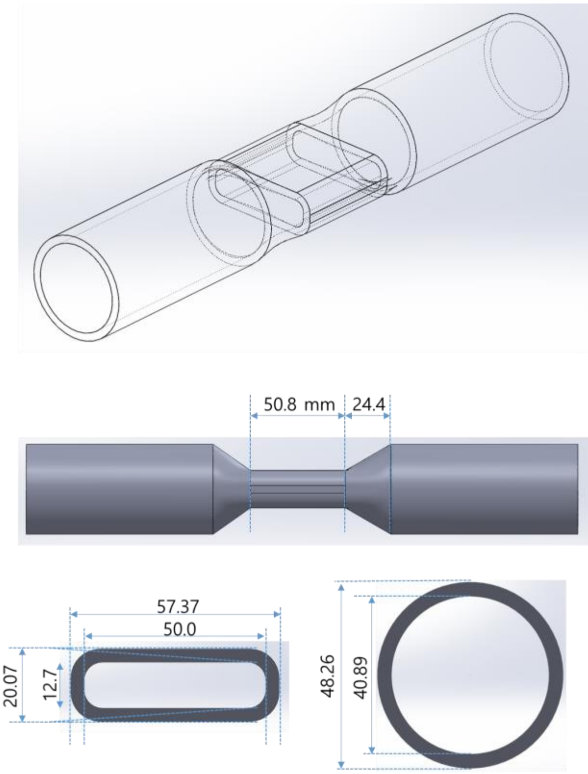

Fig. 1. Essential dimensions and CAD modeling of MSRE freeze valve, excluding cooling shroud.

Fig. 1 shows reconstructed 3D model based on the literature. 38.1 mm schedule 40 Hastelloy-N pipe was cold worked to shape a throttle, inside width of 50 mm and height of 12.7 mm. Transition section between the pipes and throttle was called as “shoulders” and formed to have about 30 ° angle along the pipe axis.

Flow cross-sectional area of the throttle was about 645 mm^2, while the pipe had about 1313 mm^2. Confined volume inside the throttle, the minimum volume to freeze for closing the valve, was estimated as about 32258 mm^3.

Typically K-type thermocouples were attached on the flat side of the throttle, on the both shoulders, and pipe surfaces about 127 millimeters away from the center of the valve.

Shaped cartridge heater groups were attached to overall surface and shroud to form the coolant path was built around the throttle area with Hastelloy sheets, and.

Finally insulation layers were applied to cover the pipes and peripherals.

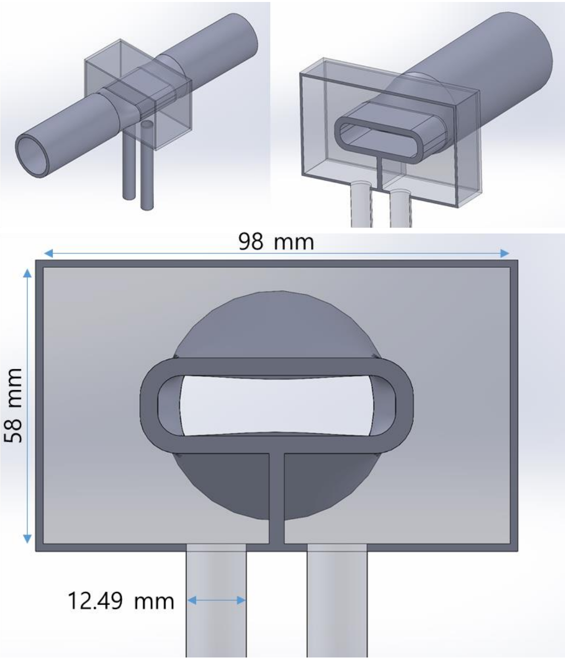

Fig. 2. Essential dimensions and CAD modeling of MSRE freeze valve with cooling shroud

Fig. 2 shows reconstructed 3D model of active freeze valve based on the literature. As each valves in MSRE had their own field modifications fit to the surrounding conditions, geometry and dimensions may differ from actual ones. However, we are going to consider above drawing as a standard model.

Shroud case was formed with thin Hastelloy plates, with about 98 mm width, 58 mm height, and 50.8 mm length to cover the throttle area. Cooling gas inlet and outlet was placed at the bottom side, with half inch pipes.

Since cooling gas was supplied from the cell atmosphere around the valve, composition of the gas differs along the installed location. For example, FV-104 to 106 was supplied with drain tank cell atmosphere of ~95 %N_2 and ~5 % O_2, while FV-107 to 112 was supplied with normal air. Cell temperatures, which is the source of cooling gas and determines supplied cooling gas temperature was maintained below 66 ℃. Coolant gas outlet was placed in opposite side of the inlet, to dump out the used gas nearby zone.

Flow rate of the cooling gas was planned as 2.1 SCMM (Standard Cubic Meters per Minute) at maximum for passive valve, and about 0.4 SCMM for active valves. However in actual operation, standard flow rate for each valves were separately defined to fit individual surrounding conditions.

Heater group, consist of shaped cartridge heaters, were equipped for active valves. Total heating capacity was about 4 kW per valve. This includes heaters not only for the throttle, but also surrounding instruments, e.g., pipes, and siphon pots.

Typical time required to operate, freeze or thaw a valve, was within 15 minutes, as written in the literature.

2.2 Salt Thermal Properties

Thermophysical properties of the molten salts are essential to estimate their phase change behavior. We acquired data of MSRE salt from the literature[3] and utilized for further calculations.

Molten salt of MSRE was based on LiF-BeF_2 and nominal mol fraction (%) was 65 LiF, 29.1 BeF_2, 5 ZrF_4, 0.9 UF_4 for main loop, and 66 LiF, 34 BeF_2 for both coolant loop and flushing salts. We are using coolant loop salt properties for simplicity.

Table 1 shows essential properties and approximations based on literatures. We estimated bulk heat in/outs and phase change behaviors of the freeze valves.

Table 1: Essential thermophysical properties for MSRE molten salt

	Approximated value (temperature in K)	Data available over temperature span (K)
Viscosity (cP)	$-1e\text{-}6T^3+0.003T^2-2.8188T+891.11$	650-1000
Thermal conductivity (W/m-K)	1	-
Solidus Temperature (K)	633	-
Liquidus Temperature (K)	728	-
Density (kg/m^3)	-0.42T + 2328.7	650-1000
Heat capacity (J/kg·K)	1.15162T+917.25 (solid) 2394 (liquid)	480-1000
Molecular mass (g/mol)	33.1038	-
Heat of fusion (J/kg)	449400	-

2.3 Estimated Operation Performances

Table 2: Reference molten salt temperatures in MSRE

Alias	Temperature (˚F)	Temperature (K)
Energetic (reactor fuel outlet)	1225	936
Exhausted (HX outlet)	1175	908
Thawed	1100	866
Frozen	750	672
Well Frozen	650	616

We estimated required heat to freeze or thaw a valve, based on the above information. Table 2 shows several reference temperature value based on the literature and individually named.

"Energetic" is the steady-state temperature of main coolant at reactor outlet, and valves near the core can reach around this temperature (~922 K) at the initial cooling process. "Exhausted" is the steady-state temperature of main coolant at heat exchanger outlet, placed for a reference point.

"Thawed" is a target temperature when thawing a frozen valve, ranging 811 to 866 K. Heaters were turned on until reach this temperature to thaw open the valve.

"Frozen" is a target temperature when freezing a thawed valve. Cooling gas was turned on at high flow rate until reach this temperature, then set to low flow rate to slow down the cooling process. When the temperature reach "well frozen", then cooling gas was turned off to avoid to grow excessive frozen plug.

We can note "frozen" temperature is no lower than solidus, which means the salt was not completely solidified at that point. This is possibly because of unique characteristics of MSRE valve operation.

Unlike typical usage of mechanical valve system, freeze valve itself is not suddenly stopping the flow. Flow of the molten salt should be stopped before freezing the valve, as freezing process takes time. In this operating situation, "actually half-frozen" state may be already good as the frozen state.

Table 3: Heat required for operation of MSRE freeze valve

	Freezing mode	Thawing mode
Initial Temperature (K)	922	616
Target Temperature (K)	672	866
Δ Heat (kJ)	534	584

Based on the above data, we estimated minimum required amount of heat/cooling for the freeze valve operation. Only the throttle part was considered into calculation, including Hastelloy pipe and enclosed molten salt inside.

Heat amount to operate the valve differs in about 10 % between freezing and thawing mode despite the same temperature change (250 K). This is partly because of density changes of the salt, affecting initial enclosed mass, and partly because of nonlinear heat capacity change of the salt.

To operate the valve within 15 minutes as written in the literature, average cooling rate should be above 594 W and required heat transfer coefficient is between 129-227 $W/m^2 \cdot K$. In thawing mode, average heating rate should be above 649 W. Result of the calculation seems within feasible range.

Above calculation is not highly accurate since actual freeze valve operation also involves heating/cooling of nearby structures including shoulders, pipes, siphon pots, and insulators. Also, target temperature of the freezing mode is between solidus and liquidus temperature and results inaccurate calculation with simple linear approximations of thermophysical properties.

However we can estimate minimum energy to operate freeze valves and can use as a reference value for newly devised freeze valve designs in future.

3. Conclusions

We have studied documents of MSRE designs and operations to analyze the freeze valve dimensions and thermal models. Until now, we have reconstructed active freeze valve in 3D drawings and established preliminary thermal models for further study.

We are going to proceed into CFD analysis of MSRE freeze valve, for both further analyze the MSRE valve design and confirm our research methodology utilizing CFD, then analyze our new original freeze valve using similar methodology to evaluate the design.

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