Feasibility Analysis of Density Lock-based Isolation/Drain System for Molten Salt Reactor based on CFD Simulation

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1. Introduction

In the Molten salt reactor (MSR), the freeze plug (or freeze valve) is an important device for reactor safety. The freeze plug is located between the reactor core and the drain tank, where the molten fuel is collected in the unexpected off-normal conditions. In a normal operating condition, the freeze plug blocks isolate the reactor core from the drain tank by freezing molten salt with locally cooling the salt. As a result, the molten salt circulating in the reactor is blocked by the frozen molten salt in the freeze plug from moving into the drain tank and circulates inside the reactor. When a certain off-normal condition including design basis accidents occur, the cooling process in the freeze plug is designed to be terminated and initiate the melting of solidified salt by heating the freeze valve. Therefore, by melting frozen molten salt blocking the move into the drain tank, the molten salt in the reactor core flows down into the drain tank [1]. The freeze valves require about 5 minutes for external heating and 10 minutes for natural heating, and a release time of less than 1000 seconds is recommended before reaching a structural damage temperature of 1200 °C [2,3].

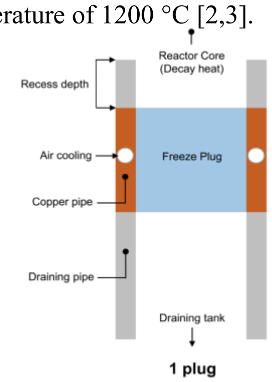

Fig. 1. Vertical cross-section of one-plug freeze plug design [1].

However, freeze plugs have some critical risks due to external control. The freeze plug is necessary to maintain the salt in solid states via external cooling. However, if a malfunction occurs in the cooling system, the undesired drain occurs. Since the freeze plug is located adjacent to the reactor, where the operating temperatures exceed 600~700 °C, there is a potential risk of cooling failure [1]. In addition, there is a risk of damage and maintenance of the freeze plug due to long-term outflow of high temperatures. In the case of the freeze valve, when it contacts over 1200°C, it causes structural damage.

As abovementioned, current concept of the free ze valve in the molten salt reactor has remarkable uncert ainty in the operation. Therefore, an alternative isolation /drain system, which is differentiated from the existing f reeze plug concept, could provide a diversity of MSR sy stem with improving the reliability. In this study, a density lock-based isolation/drain system is proposed and its feasibility is studied with CFD simulation.

2. Conceptual Design of Density Lock-based Molten Salt Drain

2.1. Application of density lock for the MSR

The Fig. 2 is the system layout of density lock application for the MSR. The volume marked with blue color indicates low-temperature (cold) molten salt, and the yellow denotes hot molten salt. The volume remarked by green is internal gas or another low-temperature molten salt (lower temperature than cold salt in the storage tank). The hot molten salt and low-temperature molten salt maintains the density equilibrium because of temperature difference. Therefore, in the contact area between hot and cold molten salt, a boundary is formed, which is density lock. To maintain the density lock, it is necessary to maintain salt temperature in a liquid state, the heat is supplied from the secondary system's residential heat.

The pump output forms the density balance when the density lock generates the driving force, ΔP_{driver}.

(1) $\Delta P_{driver} = (\rho_{cold} - \rho_{hot}) * g * \Delta H + \rho_{reservoir} * g * \Delta H_{reservoir}$

ΔP_{driver} is formed as the driving force to maintain the density lock, resulting from the effects of the buoyant force generated by the density difference between molten salt in the tank and core and the hydrostatic pressure of the molten salt reservoir. For a distinct density boundary to appear and prevent mixing of molten salts, the equilibrium of these two driving forces must occur within the connected pipe.

Figure 3 shows the drain system mechanism of the density lock-based salt during an emergency. In a general situation, step a, the molten salt reactor maintains the density lock between hot and cold molten salt without temperature rise and thermal expansion. In such a situation, between two molten salts, bead-shaped barriers exist, which have a middle density between the two molten salts. It has the role of promoting the hot molten salt circulation and preventing the invasion of hot molten salt into cold molten salt tank.

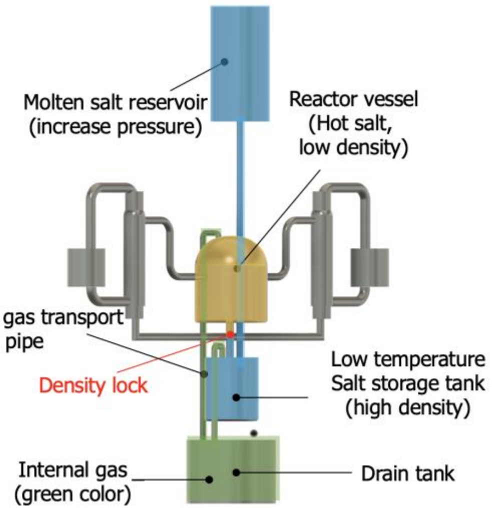

Fig. 2. The system layout of density lock application for the MSR.

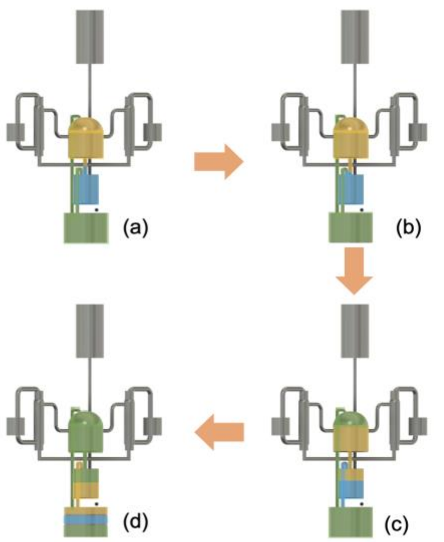

Fig. 3. Drain system mechanism of the density lock-based salt during an emergency

(b) Step B is the temperature-increasing step of circulating (hot) molten salt in the reactor. As molten salt temperature rises, the molten salt volume also increases by thermal expansion and expands into cold molten salt tank. Consequently, the height of density lock is formed lower level than before. At this point, the barrier also moves to density boundary.

(c) When the reactor system is shut down, a large volume of circulating molten salt flows downward into the density lock and cold molten salt storage. As a result, the descending hot molten salt causes the break of the specific density boundary. After the collapse of the density lock, the hot molten salt flows into the low-temperature molten salt storage by gravity force and thermal expansion, and occupied cold salt in the low-temperature storage is driven into the drain tank by the hot molten salt. The gas in the drain tank also flows into the reactor vessel through the connecting pipeline, driven by the cold molten salt. In the pipeline, a check valve is installed. Therefore, the internal gas can move in one direction.

(d) The gas driven into the reactor vessel occupies inside the reactor and they promote releasing the remaining molten salt into the drain tank. When the cold molten salt reaches the drain tank and the pipe is filled with it, the residential molten salt continues to flow into the drain tank by gravity and the siphon principle.

3. CFD simulation set up

3.1. Objective of simulation

In this step, a molten salt reactor (MSR) with an applied density lock is analyzed using CFD to evaluate density lock stability during pump operation, examine the molten salt conditions in the core and tank, and identify the factors affecting the density lock forming position. Furthermore, since this simulation is based on normal reactor operation, it does not operate the molten salt release cycle during an emergency. Therefore, the drain tank and pipes which connected to the core are not included in the simulation experiment design.

3.2. CFD modeling

The experimental Conceptual design density lock with utilizing MSR modeling is designed with utilizing MSBR (Molten Salt Breeder Reactor) [4] component dimensions. In addition, the fuel properties in the design also referenced to MSBR fuel material properties [4].

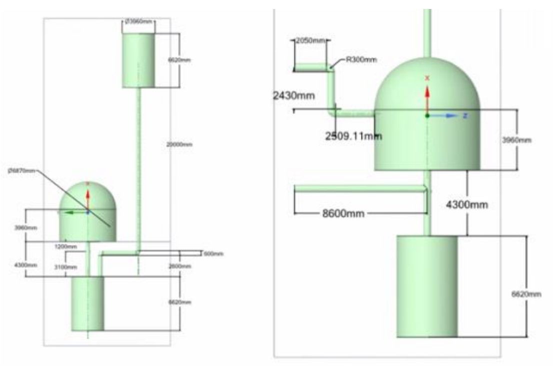

Fig. 4. Simulation experiment modeling

Table I: The dimension of MSBR components simulated in the CFD.

Component	Diameter (mm)	Height (mm)
Reactor vessel	6870 mm	3960mm
Cold salt storage tank	3960mm	6620mm
Molten salt reservoir	3960mm	6620mm
Pipe	500mm	X
Salt inlet pipe from heat exchanger	500mm	1200mm
Pipe (cold salt storage tank - Molten salt reservoir)	500mm	2000mm

This simulation experiment model is designed to be 1:1 in size with utilizing MSBR design data, and to maintain density lock, adding a molten salt reservoir.

Table II: The fuel properties data [4].

Properties	Data
Density [kg/m^3]	Piecewise-linear Point 1: 803.15[K] - 3397.96 [kg/m^3] Point 2: 1023.15 [K] – 3251 [kg/m^3]
Cp(specific heat) [J/kg-K]	1357 [J/kg-K]
Thermal conductivity [W/m-k]	1.19 [W/m-K)]
Viscosity [kg/m-s]	0.109e-3 [kg/ m-s]* exp(4090 [K]/ Static Temperature) Range (800K – 1025 K)

Table I and II summarize the detailed dimensions of the components in MSBR and the main fuel properties in the simulation, based on the MSBR fuel properties data, respectively.

3.3. Mesh quality and cell sensitivity

In the mesh step, a mesh is generated through the auto mesh method, and then performed comparison of cell sensitivity test that sizes are 1 m, 0.5 m, 0.1 m, and 0.075m.

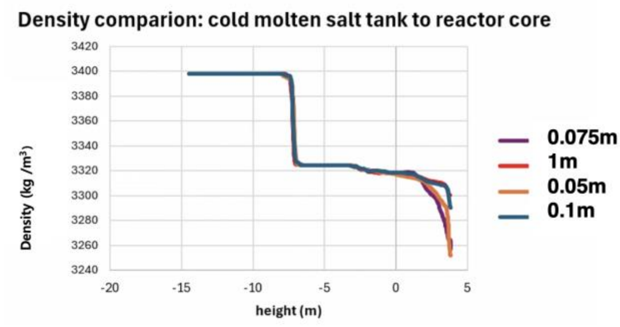

Fig. 5. Cell sensitivity density data comparison: salt tank to Reactor vessel

Table III. The cell information in mesh generation

Size (m)	Number of meshes	faces	Nodes
1m	318492	744249	122388
0.5m	330010	771245	126850
0.1m	1436705	3253185	483291
0.075	2482998	5582090	809032

In the mesh sensitivity analysis, the height that forms density lock shows equal for all cell sizes. However, the differences are shown in the -5m~5m, the height boundary is core. By increasing cells, the data density also increases. Therefore, the simulations were performed on 0.075 m-sized cells.

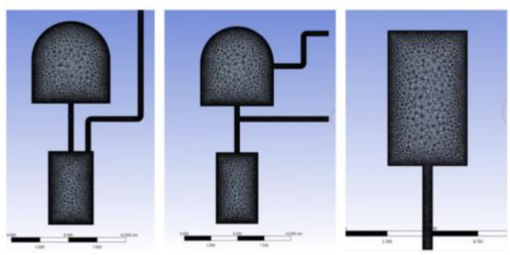

Fig. 6. 0.075m cell mesh generation section plane.

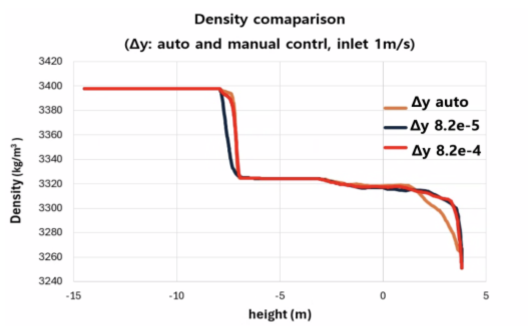

Fig. 7. The cell sensitivity of the Δy auto setup and manual control at cell size 0.075m and inlet 1m/s

Figure 7 compares the density difference between the Δy auto and the manual setup. The black line case, density lock forms at a lower height than the other cases. However, in the black line (Δy=8.2e-5 case), its y+ data is shown near zero, which means this result is beyond the valid range. In the other manual control case (Δy=8.2e-4 case), its y+ data is calculated at a 0.2~0.5, is located within a valid range, and its density lock formed a similar height compared to the auto-generated one. In the auto-generated case, its y+ is calculated in about 0.8, which is in the valid interval and forms a density lock in the same location compared to the other one (Δy=8.2e-4 case). For this reason, this simulation generates an auto-setup and performs the SST K-omega model.

3.4. Boundary conditions and settings in Fluent.

This simulation was performed with a 3D pressure-based SST and K-omega model. The temperature boundary conditions are set to 1023.15 K in the reactor core and 803.15 K at the cold salt tank and molten salt reservoir. At the inlet, molten salt is 913.15K is injected at velocities 1m/s, 2.5m/s, and 5.15m/s.

4. Results and Discussion

4.1 Effect of height of reservoir

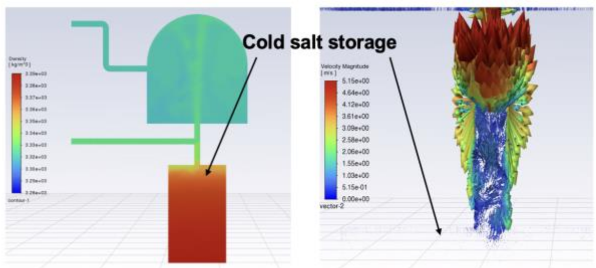

Fig. 8. Between the core and cold salt storage pipe length:2.8m, inlet:5.15 m/s

Figure 8 shows that when the pipe length between the core and the tank is reduced from 4.1m to 2.8m, the vortices generated by the pump reach the storage. Because the gap H between the core and salt tank decreases, the driving force formed by the density lock is significantly reduced than the driving force by the pump. As a result, the mixing occurs in the tank by the stronger driving force of the pump.

Figures 9 and 10 show that as the inlet velocity increases, the density boundary height forming decreases, and a clear boundary appears at around –7 m, using the reactor core center (0 m) reference.

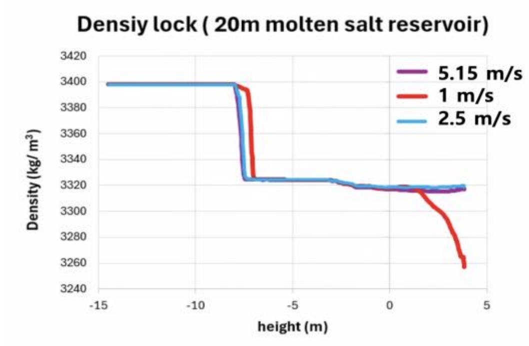

Fig. 9. Density lock forming position: salt tank to Reactor vessel with include molten salt reservoir

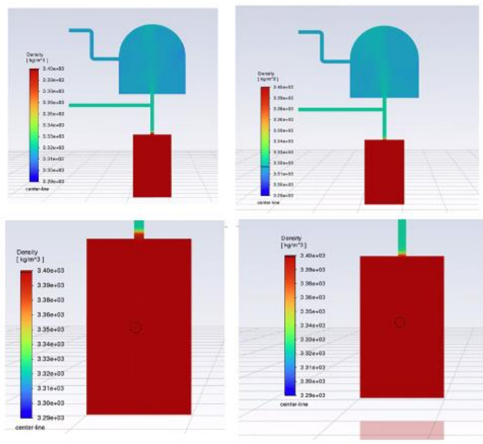

Fig. 10. CFD density lock forming result: density contour levels include molten salt reservoir situation (left: Inlet 2.5m/s, right: inlet 5.15)

4.2 Demonstration of Density-lock

In addition, the density boundary is formed at a lower position in the exclusion of a molten salt reservoir , compared to the inclusion of molten salt reservoirs in figures 11, 12, and 13.

Especially, in the case of excluding the reservoir and the inlet velocities of 5.15m/s, which resulted in inflow of the hot molten salt and the mixing cold molten tank. As a result of mixing, the internal molten salt rose, and a distinct density boundary was not formed. The mixing flow can be observed in Figure 14.

In Fig. 14, the left case shows that molten salt enters the cold salt storage through the pump and shows the flow in the cold salt tank as a velocity vector. It means the mixing occurs in the tank. In contrast, the right case blocks the inflow of molten salt into the storage by additional pressurization, and velocity vectors are not observed at the cold salt storage inlet.

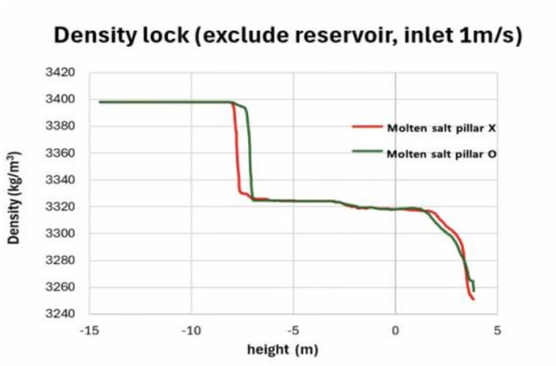

Fig. 11. Comparison of density data between excluding and including molten salt reservoir (inlet 1 m/s)

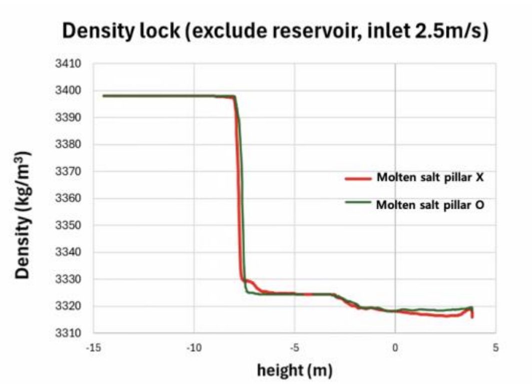

Fig. 12. Comparison of density data between excluding and including molten salt reservoir (inlet 2.5 m/s)

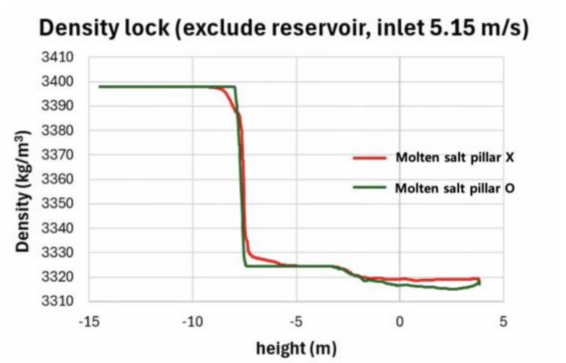

Fig.13. Comparison of density data between excluding a nd including molten salt reservoir (inlet: 5.15m/s)

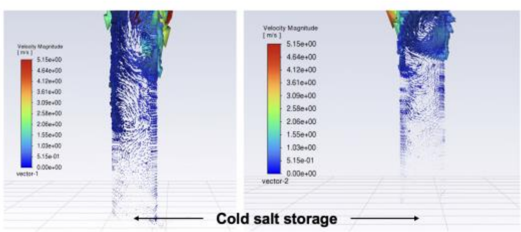

Fig 14. Velocity profiles in the density-lock pipeline: (inlet:5.15m/s, left: exclude reservoir, right: include reservoir)

5. Summary and Further works

Through CFD simulations, the effects of each factor on maintaining the density lock were identified. As shown in Figs. 8 and 14, it is observed that the density boundary formation height decreased as the inlet velocity increased. This is because the higher molten salt flow rate increased the pressure to the density lock, resulting in more molten salt inflow to the cold molten salt tank. Therefore, in the case of including a molten salt reservoir that offsets the pump pressure, a density boundary is maintained in the pipe compared to excluding cases. It shows the higher density lock formation and a clear boundary in figures 11, 12, and 13.

Therefore, the CFD results showed that the effect of pipe length between the core and storage lock and the molten salt reservoir on forming density lock without mixing cold salt storage, and it will continue to calculate and apply each factor effect appropriately to implement the drain system in the future.

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