Conceptual Design of Density Lock-based Molten Salt Drain for Replacement of the Freeze Plug

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ABSTRACT

The freeze plug (or freeze valve) is an important component securing the safety of molten salt reactors (MSR) capable of withstanding high temperatures and corrosive environments, in which integrity of the conventional mechanical valve could not be guaranteed. During normal operation of the reactor, the external cooling freezes the salt in the freeze plug tube. Therefore, the isolation between the reactor vessel and drain tank can be achieved. When the certain events/accidents occur, the external cooling stops and the solidified salt melts by the heat generated from the reactor vessel [1]. It is capable of thawing in 5 min with the use of the external heater, and in less than 10 min passively [2]. As a result, shutdown of the reactor occurs by transferring the fuel-loaded molten salt inventory from the reactor vessel to the drain tank [1]. However, the reliability issue of the freeze plug in aspect of the thawing and freezing of the salt in a local position. To improve the reliability of the molten salt drain system, a new component, which facilitates replacing the free valve is proposed in this study. Our suggestion for the salt drain in MSR is based on "density lock", which utilizes the density difference between hot and cold salts due to the temperature difference. The detail design, feasibility, and advantage of the density lock-based salt drain system are drawn.

1. Introduction

To improve the reliability of the molten salt drain system, a new component, which facilitates replacing the free valve using "density lock" is proposed. When the temperature of the hot molten salt rises and causes thermal expansion, the density lock breaks. Cold molten salt then flows into the drain tank, and the inert gas inside the tank moves through a pipe connected to the reactor, and the gas pushes the hot molten salt out. Replacing the freeze valve, it eliminates external control of the cooling/heating of the salt and can address existing freeze valves with design reliability issues (molten salt discharge due to external cooling failure during normal operation and delayed reactor shutdown caused by the slow thawing of the solidified salt). Especially, it requires less time to start releasing molten salt compared to thawing the solidified salt of freeze plug. Accordingly, it will contribute to improve MSR safety system and promote technological development in the field.

2. Concept of design

2.1 Density lock in PIUS

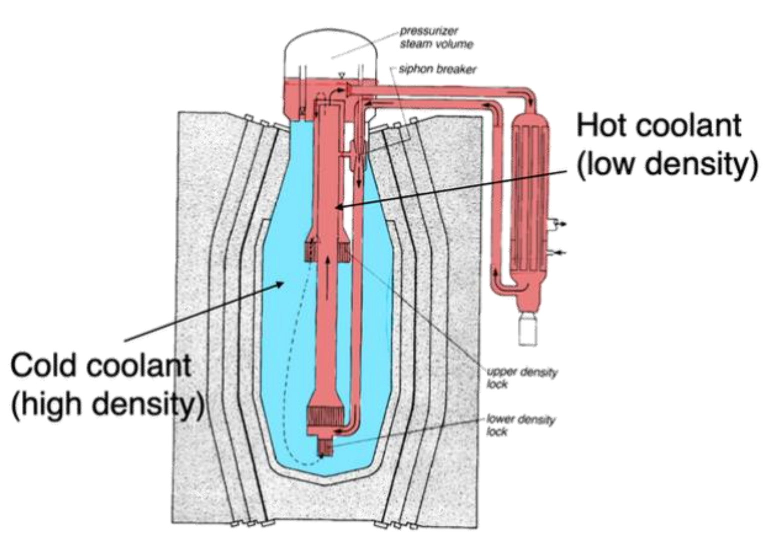

Fig. 1. Design of PIUS plant [3].

- **The density lock utilizes the difference in density resulting from the difference in the temperature and balance between the hydrostatic pressure and forced convection.**
- **The blue area is cold coolant, and the red area is hot coolant. By the density difference, they maintain density equilibrium.**
- **In an emergency in the reactor, the density equilibrium would be broken. Then cool and hot coolant would mix.**
- **By mixing these coolants, the cold coolant enters into reactor, and the boron in cold coolant lowers the reaction in the reactor.**

2.2 Mechanism

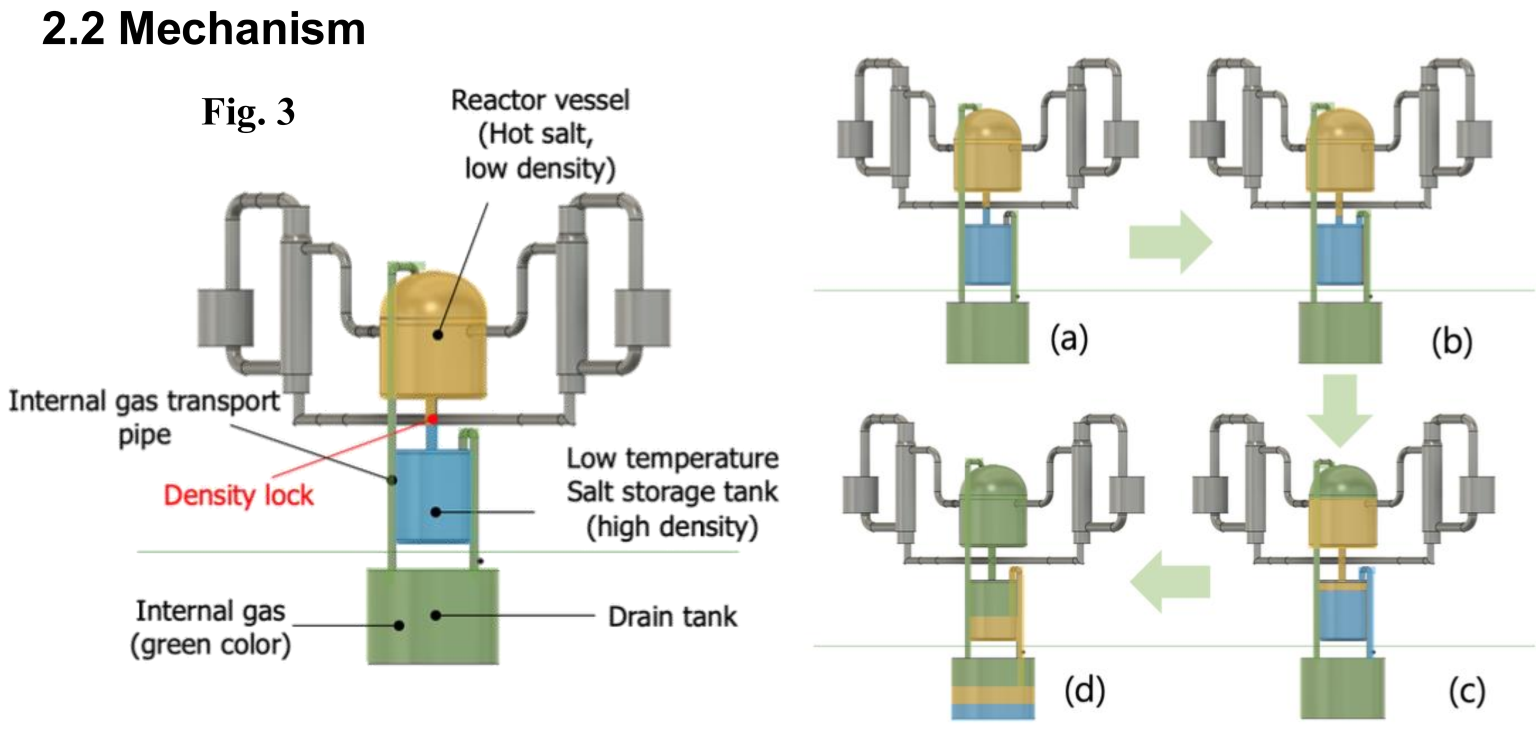

Fig. 2. System layout of the density lock-based salt isolation and working principle of the density lock-based salt isolation during the accident conditions

(a) The normal operating condition in which the density lock maintain stable.

(b) The temperature of the hot salt in the reactor increases due to power excursion, loss of flow, loss of cooling. Thermal expansion of the hot salt causes the penetration to cold salt in the density lock.

(c) The descending hot salt breaks the density lock. Hot salt slides down to the low-temperature salt storage tank and cold salt is then transferred to the drain tank. The gas occupied the drain tank moves into the reactor vessel through the connecting pipeline between the reactor vessel and drain tank and they drive out remaining molten salt in reactor vessel.

(d) The siphon effect causes the molten salt to continue flowing into the drain tank. The transfer of the hot salt to the drain tank will be continued until the reactor vessel is empty.

3. Design of the experimental apparatus

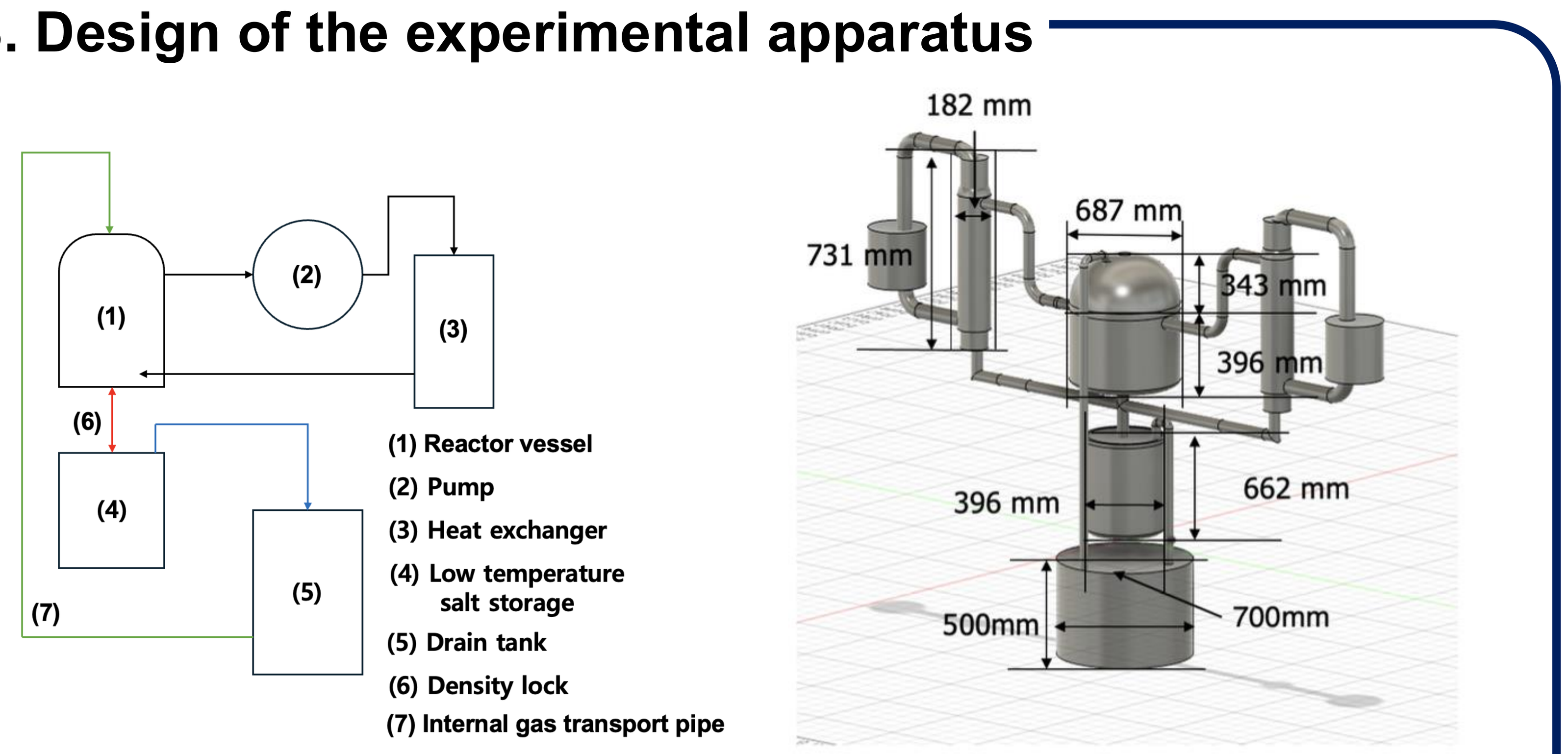

Fig. 4.Two-dimensional and three-dimensional drawing of the designed experimental apparatus

Component	Diameter (ft, in)	Height (ft, in)
Reactor vessel	22ft 6.5in	13ft
Drain tank	13ft in	21ft 9in
Control nods	3.5in	12 ft 6 in
Heat exchanger	6ft	24ft

Table I: MSBR system component dimension summary [4].

Component	Diameter (mm)	Height (mm)
Reactor vessel	687 mm	396mm
Salt storage tank	396mm	662mm
Heat exchanger	182mm	731mm
Drain tank	700mm	500mm

Table II: The component dimensions of designed experimental apparatus

4. Results and Discussion

Fuel proportion: LiF 71.7%, BeF2 16%, ThF4 12%, UF4 0.3%
Density: 3.752-6.68 * 10^(-4) * (Temperature °C)

Melting point	Temperature (High density)	Temperature (low density)	High-density (kg /m^3)	Low-density (kg /m^3)	Density difference (kg /m^3)
498.85°C	750°C	530°C	3397.96	3251	146.96

Table III. The fuel properties of MSBR [4].

Temperature (High density)	Temperature (low density)	High-density (kg/m^3)	Low-density (kg/m^3)	Density difference (kg /m^3)
15°C	260°C	1003.2	789.08	214.12

Table IV. The coolant properties of PIUS

	dQ (MW)	C (J/g*K)	Mass (kg)	dT (K)
25%	562.5	1.375	98830.4	4.139322608
10%	225	1.375	98830.4	1.655729043
5%	112.5	1.375	98830.4	0.827864522
1%	22.5	1.375	98830.4	0.165572904

Table V. Calculation of temperature change according to dQ

Temperature (°C)	Density (kg/ m^3)	Volume (m^3)	Mass (kg)
750°C	3251	30.4	98830.4

Table IV. Initial condition of fuel in the Reactor vessel

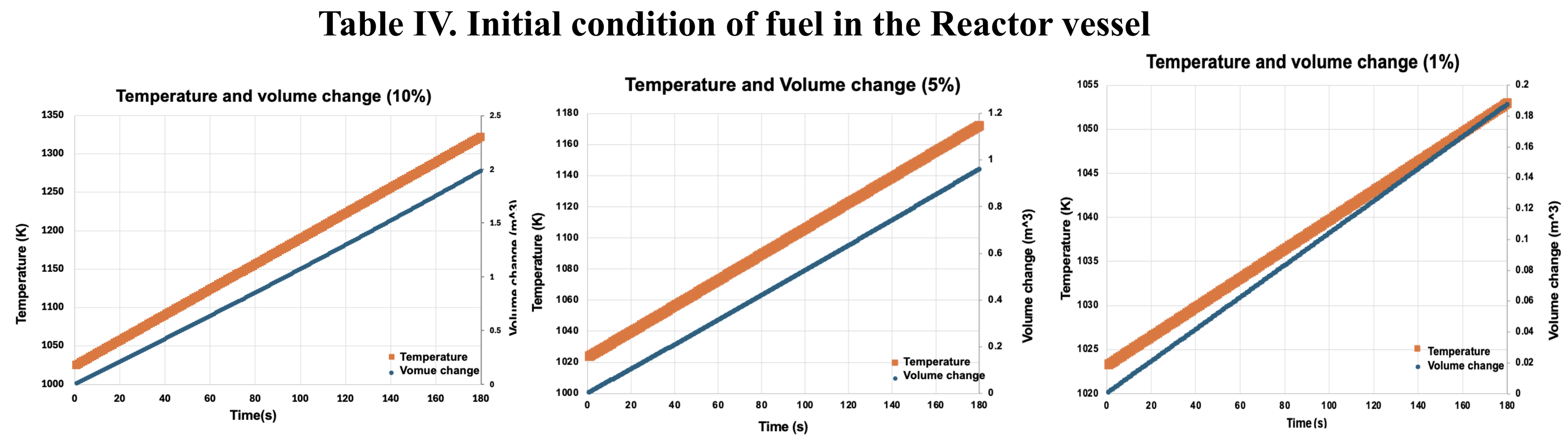

Fig.5. Time-dependent Changes in Volume and Temperature of Molten Salt for Each Output

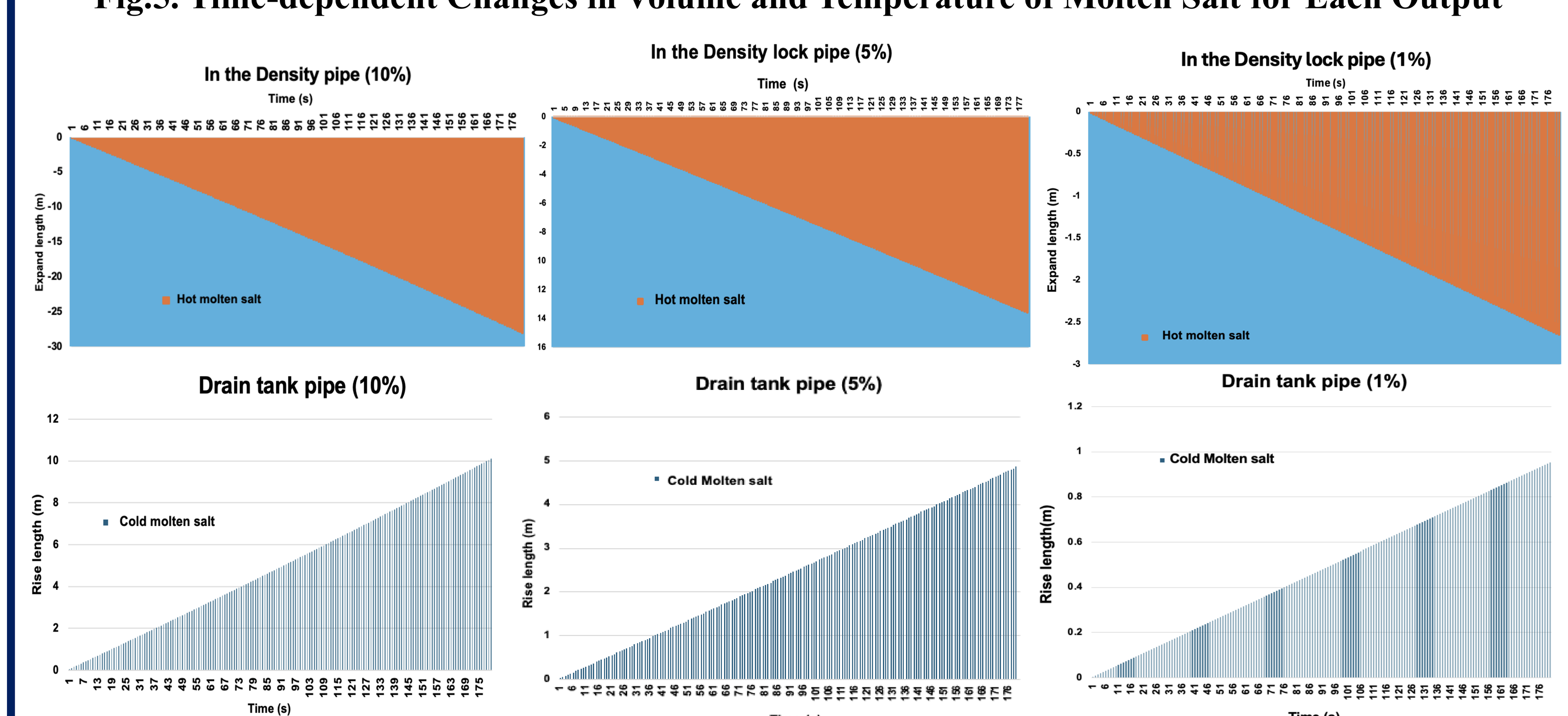

Fig .6. Time-dependent changes in the expansion length of hot molten salt In the density lock pipe and the rise length of cold molten salt in the drain tank pipe as output increases

Diameter of density lock pipe	Diameter of Drain tank pipe
0.15m	0.5m

Table VI. The diameter of pipe [4].

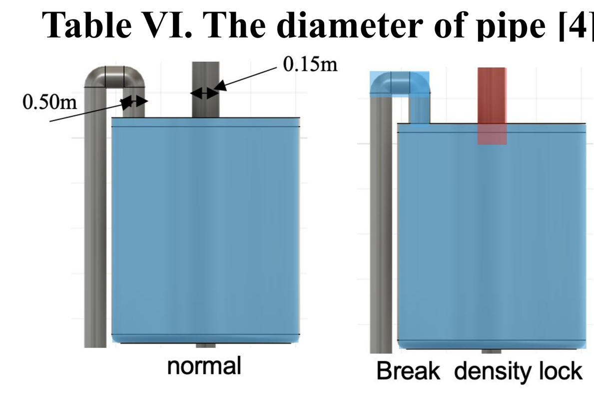

Fig. 7. The situation of normal and breaking density lock

- **These data are obtained by utilizing**

$$\dot{Q} = mc_p\frac{dT}{dt}$$

- **The cold molten salt rapidly rises in the pipe connected drain tank during 180s.**
- **Compared to the freeze plug, the passive melting time of salt in the freeze plug takes about 10 minutes [1]. Therefore, the density lock device can release molten salt faster than the freeze plug.**

5. Conclusion

Most of molten Salt Reactor (MSR) designs adopt freeze valves, which can shut down the reactor by releasing molten salt into a drain tank in an accident. However, there are existing freeze valves with design reliability issues (molten salt discharge due to external cooling failure during normal operation and delayed reactor shutdown caused by the slow thawing of the solidified salt). To address these deficiencies, this study proposes a molten salt isolation and release system based on the density lock, and the scaled-down experimental apparatus of the MSBR is being designed to verify its feasibility and enhance its applicability. In addition, based on the calculation of the molten salt expansion over time, this alternative device can release molten salt in a shorter time compared to the freeze plug. Through this study, the development of an isolation system based on the density lock concept is expected to reduce dependence on the freeze valve and expand the range of safety system options for MSRs.

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