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

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1. Introduction

The freeze plug (or freeze valve) is an important device 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 a certain emergency occurs, 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 molten salt inventory from the reactor vessel to the drain tank [1].

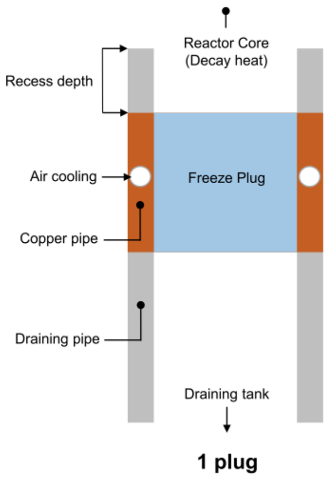

Fig. 1. Vertical cross sections of freeze plug design [2].

However, the freeze plug has potential risks such as a malfunction of the external cooling and reliability issue in the melting time of the solidified salt.
The malfunction or shutdown of the coolant supply system to the pipe causes unintended thawing of the freeze plug, and it leads to the outflow of molten salt that circulates in the nuclear reactor. Furthermore, the thermal balance problem between the freeze valve and the heating system occurs apprehension of the freezed salt maintaining. In the freeze plug, to maintain the temperature of the molten salt in the freeze plug below the melting points is important. However, thermal transients induce unwanted thermal cycling within the valve system. It includes continuous cooling problem in the freeze plug and potentially cause leakage due to localized cooling deficiencies [1]. In addition, continuity issues exist in the freeze valve. To prevent freeze valve, the frozen salt should be melted below 1200°C due to the structure damage, however, the damage can occur below 1200°C [2]. There have been cases where the high thermal load of molten salt induced thermal fatigue in freeze plug components. As a result, it leads to the breakdown of freeze valve and unwanted leakage of molten salt occurred [1].

To resolve the potential issue of the freeze valve design, a novel concept based on the density lock, which isolates the salt in the reactor vessel from the drain tank is suggested in this study. In this paper, its working principle, conceptual (preliminary) design, and the future works to demonstrate and optimize the suggested system is discussed.

2. Conceptual design of Density lock-based isolation/drain system

2.1. Density lock in PIUS

The density lock concept is originally suggested in PIUS (Process Inherent Ultimate Safety) reactor by utilizing the difference of density resulting from the temperature difference. Similar to the thermal stratification, the hot and cold fluids locate the upper and lower part of the reactor coolant system in a narrow boundary. Therefore, the mixing between the fluid can be mitigated. The contact area can be identified in Figure 2, the area is the upper density lock and the lower density lock. The blue area is cold coolant, and the red area is hot coolant. At the area, two liquids maintain density equilibrium.

Although the density lock due to the density difference is expected during the normal condition, the density equilibrium would be broken in an emergency. In an emergency, the hot coolant that circulates in the reactor coolant system will be emitted to space, which exists cold coolant. Then, the mixing between the hot and cold fluids occurs. The empty space is filled with cold coolant. The cold coolant includes high-rate boron, which reduces the reaction of the nuclear and temperature. Therefore, the replacement device for freeze plug utilizes density lock's density equilibrium and safety mechanism after density equilibrium is broken [3].

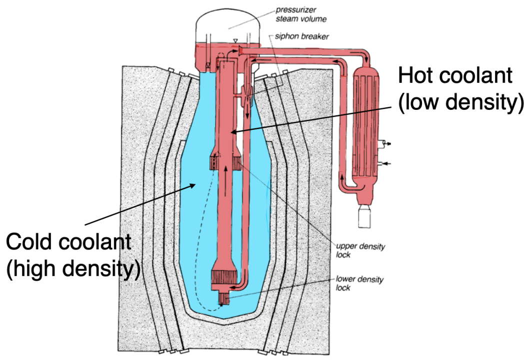

Fig. 2. Design of PIUS plant [3].

2.2. Application of density lock for the MSR

Figure 3 is the system layout of the density lock-base slat isolation. The blue color is cold molten salt, and the yellow color is hot molten salt. The green color denotes inert gas that occupies the drain tank. When the density lock is collapsed, the gas pass through the transport pipe. The hot molten salt circulates throughout the reactor. On the other hand, cold molten salt is stored and stays in the containment vessel. To stay in a liquid state, the heat is supplied from the secondary system's residential heat. So, its temperature is lower than the hot molten salt. By the difference of temperature, two molten salts have different densities. So, the density lock form in the vessel.

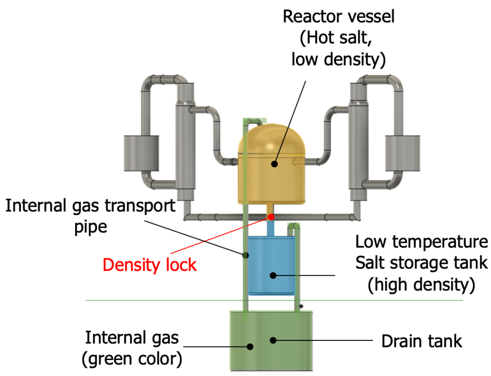

Fig. 3. System layout of the density lock-based salt isolation

Figure 4 is the mechanism of the replacement device's safety reaction. Between two molten salts, the bead-shaped barriers exist. Its density is between that of the hot molten salt and the cold molten salt. The barrier has roles to promote the hot molten salts circulate in the reactor. Because molten salt is circulated by a pump, without a separate blocking device, the cold and hot molten salts may mix. Then maintaining the density lock is a hard problem. However, adopting a barrier can prevent hot molten salt from invading the cold molten salt's space. The invading block helps prevent the mixing of two liquids and facilitates the circulation of hot molten salt.

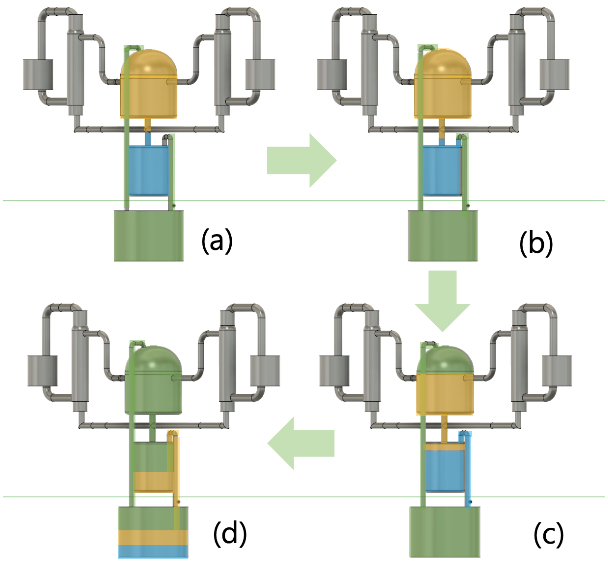

Fig. 4. Working principle of the density lock-based salt isolation during the accident conditions

(a). Step A is the normal operating condition in which the density lock maintain stable. This means that a density equilibrium is maintained between the hot and cold molten salt and the reactor operates without any issues.

(b). Step B is the stage where the temperature of the molten salt circulating in the reactor increases. When the increasing temperature situation, the molten salt thermally expands. Since the barrier has the density between the two molten salts, it follows the expanding space of the hot molten salt. So, the floating height decreases. Continuous thermal expansion causes the hot molten salt to penetrate the space of the cold molten salt in the density lock. At that time, the hot molten salt is surrounded by the cold molten salt. Some cold molten salt absorbs the heat, others rise through the pipe connected to the drain tank.

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surrounded by the cold molten salt. Some cold molten salt absorbs the heat, others rise through the pipe connected to the drain tank.

(c). If the reactor shut down, a large amount of circulating molten salt flows down into the density lock. The descending hot salt results in the break of the density lock. Once the density lock is collapsed, hot salt slides down to the low-temperature salt storage tank by gravity force and volume expansion. The 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. By installing the check valves in the connecting pipeline, the undesired invasion of the hot salt from the reactor vessel to the drain will be prevented.

(d) When the cold salt reaches the drain tank and the pipe is filled with molten salt, the gravitational force exerted by hot salt, the siphon principle causes the molten salt to continue flowing into the drain tank. In other words, the collapse of the density lock induces the movement of the cold molten salt and triggers the siphon effect. The transfer of the hot salt to the drain tank will be continued until the reactor vessel is empty.

Therefore, to verify this mechanism can be practically applied well, 3D modeling and CFD analysis will be utilized

3. Design of the experimental apparatus

To demonstrate the suggested density lock-based isolation system, an experimental work is scheduled. Based on the design specifications of the MSBR (Molten salt breeder reactor) [4] as summarized in Table I, the dimensions of experimental test apparatus are determined. The scaling ratio between the MSBR and the test apparatus is 1/10.

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

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

The units in the Table I are feet(ft) and inches (in). Therefore, the dimensions were converted into meters (m) and the experimental apparatus was modeled at 1/10 scale. Additionally, the size of the drain tank and the low temperature salt storage tank were designed for experimental apparatus operation. The 3D modeling dimensions of experimental apparatus component are summarized in Table II.

Table II: The component dimensions of designed experimental apparatus

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

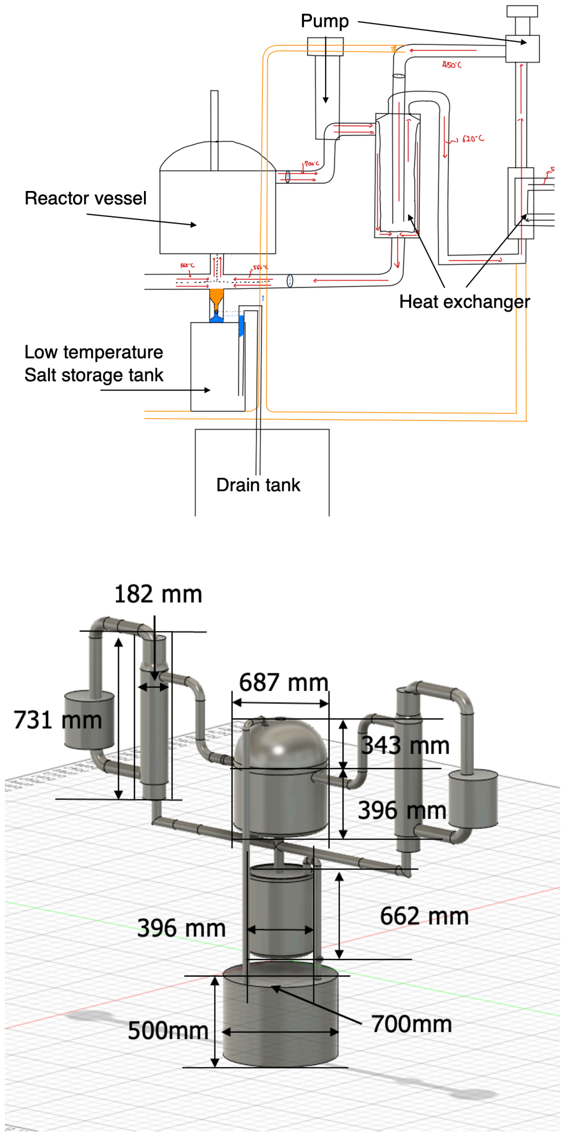

Fig. 5. Two-dimensional and three-dimensional drawing of the designed experimental apparatus

Figure 5 shows the preliminary design of the experimental apparatus to conduct a series of test demonstrating the proposed isolation concept.

The detailed design of the experimental facility will be carried out based on the scaling law to demonstrate the thermal-hydraulic behavior in the prototypical reactor in our experimental facility.

By establishing the experimental apparatus, the system optimization will be conducted with a quantitative evaluation of the effects of the main parameters, i.e., temperature difference between hot salt and cold salt, size of pipeline isolating the hot and cold salts, thermodynamic design, etc.

4. Summary and Future works

Recently, developing Molten Salt Reactors (MSRs) 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 paper 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. 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. Accordingly, it will contribute to improve MSR safety system and promote technological development in the field.

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