Study of Thickness Effect on Freeze-Valve Scheme for Molten Salt Reactor Safety System

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Abstract. Molten Salt Reactor (MSR) is a liquid fuel reactor type candidate for Generation IV reactors due to its excellent safety system. A freeze valve is one of the safety systems used in MSR to prevent reactor accidents due to uncontrolledfuel temperature increases. The freeze valve is designed to melt when the fuel temperature approaches the melting point of the reactor wall and opens the fuel path to the subcritical tank. Several experiments have been successfully carried out in this research to study the mechanism of action of the freeze-valve. Opening time of the plug is an important aspect in regard to molten salt relocation. Thus, this research was conducted to analyze the effect of different thicknesses on the freeze- valve (paraffin material) with hot fluid at 90 °C. The thickness variations used were 9, 11, and 16 mm with the same diameter of 28 mm. It is found that about 9 mm thick is needed to have an opening within 10 minutes.

Keywords: MSR (Molten Salt Reactor); Freeze-valve; Drain tank; Paraffin; Melting

1 Introduction

Three major accidents in a nuclear power plant have presented valuable lessons learned for its improvement. The incapability of coolant to transfer heat and cooling has been the major factor in accidents. For that reason, researchers have been proposing generation IV reactors to cope with the problem. GEN IV international forum (GIF) focuses on advanced reactors that improve safety and reliability [1,2]. One proposed reactor is the molten salt reactor (MSR), where fuel and coolant are mixed in the liquid phase. MSR is leading on simplicity in terms of geometry and heat transfer route compared to solid fuel reactor type [3]. Since it uses molten salt, the operating temperature range is wider than conventional water reactors. Thus, the pressure parameter can be kept lower.

Molten Salt Reactors (MSRs) have gained significant attention in recent years due to their inherent safety features and potential for efficient power generation. One critical

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aspect of MSR safety systems is the freeze-valve scheme, which utilizes a freeze plug to passively shut down the reactor in case of an emergency [4–7].

The development of freeze-valve technology has been the subject of numerous studies aimed at enhancing the safety systems of Molten Salt Reactors (MSRs). Researchers such as Giraud et al. [8] have made significant contributions to this field by developing a system that utilizes a copper disk cooled with additional steel to efficiently store heat. Tiberga and colleagues [9] have also investigated the freeze-valve system, incorporating an air-cooling mechanism to maintain the solidification of the plug. While these studies have made valuable advancements, further research is warranted to fully explore and optimize the freeze-valve experiment in the context of MSR safety systems. In light of the importance of freeze-valve systems, it is imperative to conduct comprehensive research and experimentation to enhance their effectiveness and reliability. This study aims to contribute to the existing body of knowledge by investigating the effect of thickness on the performance of freeze plugs, specifically in the context of the safety system for MSRs.

The thickness of the paraffin plug is systematically varied to examine its influence on the overall performance and reliability of the freeze-valve scheme. By assessing the thermal response of the paraffin plug to the time required for complete melting at various thicknesses, valuable insights can be gained into the behavior of freeze plugs in MSR safety systems. This research will aid in the design and optimization of freeze-valve mechanisms, thereby improving the safety and operational efficiency of MSRs.

2 Method

In this study, we focused on investigating the influence of paraffin thickness on the melting rate of the plug. To facilitate the melting process, heated water was utilized, as illustrated in Fig. 1. Paraffin exhibits a melting point ranging from 46 to 68°C and possesses a density of approximately 0.9 g/cm3.

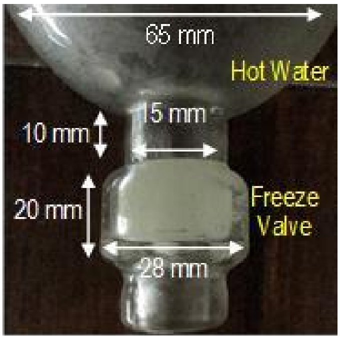

Fig. 1. Freeze-valve design

To begin the experiment, the paraffin was initially solidified in the neck of the bottle, allowing us to achieve target thicknesses of 9, 11, and 16 mm, respectively. Subsequently, 500 ml of water at 90 °C was poured into the bottle, and an immersed heating element was employed to heat the water from the top. The heating process was carried out until the plug completely disappeared from the bottle's neck. However, the recording duration was limited to a maximum of 10 minutes.

To capture the experimental setup and monitor the thermal behavior, a thermal camera was employed, as depicted in Fig. 2. The apparatus consisted of a heating system, temperature control mechanism, and a designated test section. A schematic diagram illustrating the temperature distribution throughout the experimental setup is presented in Fig. 3. Furthermore, Fig. 4 exhibits a typical thermal camera image depicting four observed positions.

The combination of the experimental setup, paraffin plug, heated water, and thermal camera allowed us to investigate the effect of paraffin thickness on the melting rate comprehensively. The recorded data from the observed positions will be analyzed and evaluated to provide valuable insights into the behavior and performance of the freeze-valve system. This analysis will aid in understanding the relationship between paraffin thickness and the melting process, contributing to the optimization and design of freeze-valve schemes for Molten Salt Reactor safety systems.

Fig. 2. (a) apparatus setting of freeze-valve study with (b) thermal camera

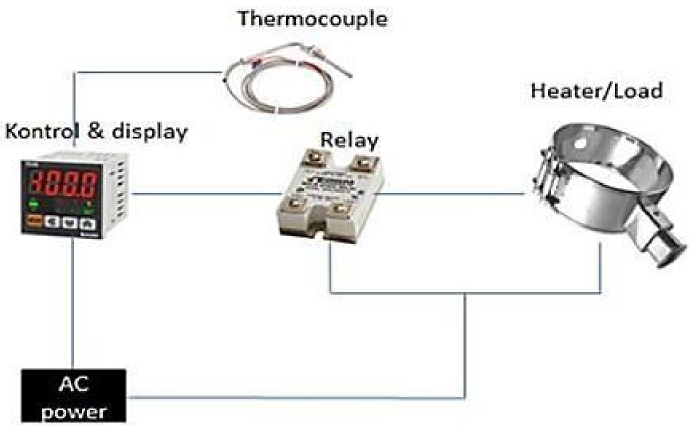

Fig. 3. Instrumentation schematic of temperature control

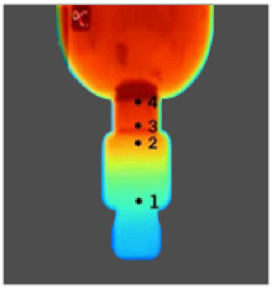

Fig. 4. Typical temperature profile with four observation points

3 Result and Discussion

The results of the experiment provide valuable insights into the heat transfer processes and behavior of the system. Firstly, Fig. 5 illustrates that the water temperature increased due to conduction from the heating plate. The heat energy was then transferred to the water above the plug through convection. Since no insulator was used, a portion of the heat energy dissipated into the surrounding environment through radiation. Initially, the plug temperature appeared lower, indicated by the green color in the thermal image. As the experiment progressed, the color changed to orange, indicating the transfer of heat energy through conduction. Concurrently, the images captured a visible decrease in the thickness of the plug over time. Approximately at the 9-minute mark, the remaining plug began moving downward and eventually exited the bottle, leading to a complete outflow of water within a mere 5 seconds.

Fig. 6 showcases the temperature readings at the four observed points. To determine the temperature values, procreate software was employed, and the color scale was synchronized accordingly. Points 2, 3, and 4 were immersed in the heated water, reflecting temperatures near the target temperature. On the other hand, point 1 represented the bottom part of the plug, which experienced a lower temperature compared to the water region.

These findings highlight the dynamic nature of heat transfer within the system and provide insights into the behavior of the plug as it undergoes melting. The recorded temperatures at different points offer a comprehensive understanding of the thermal distribution and variations within the experimental setup. Such insights contribute to the optimization and design of freeze-valve schemes for Molten Salt Reactor safety systems, with the potential to enhance their reliability and efficiency.

Fig. 7 provides further insights into the experiment by presenting the temperature profile and digital camera images of the 11 mm thickness case. The temperature profile exhibits similar trends to the previous case, indicating consistent behavior. Notably, at the 1-minute mark, the melting process appeared to progress faster in the middle region of the plug compared to the outer diameter. This discrepancy may be attributed to potential imperfections that occurred during the plug fabrication process. It is possible that bubbles formed during solidification, becoming trapped within the plug and influencing the melting dynamics. Subsequently, the melting process accelerated, leading to complete melting of the plug at approximately 9 minutes.

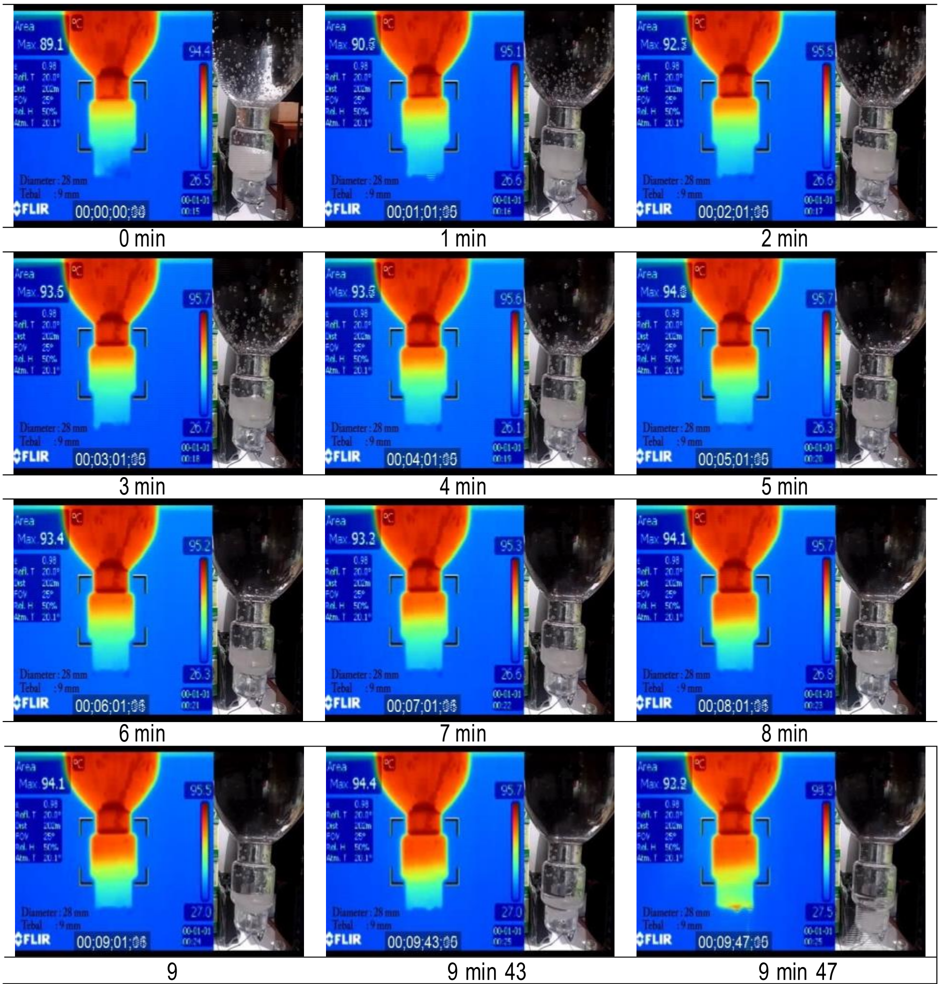

Fig. 5. Temperature profile and picture of 9 mm plug thickness at 90 °C

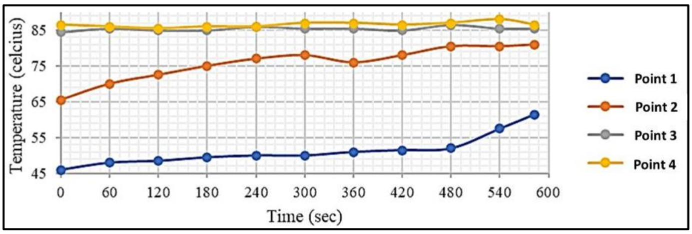

Fig. 6. Graph of temperature vs. time for 9 mm thickness

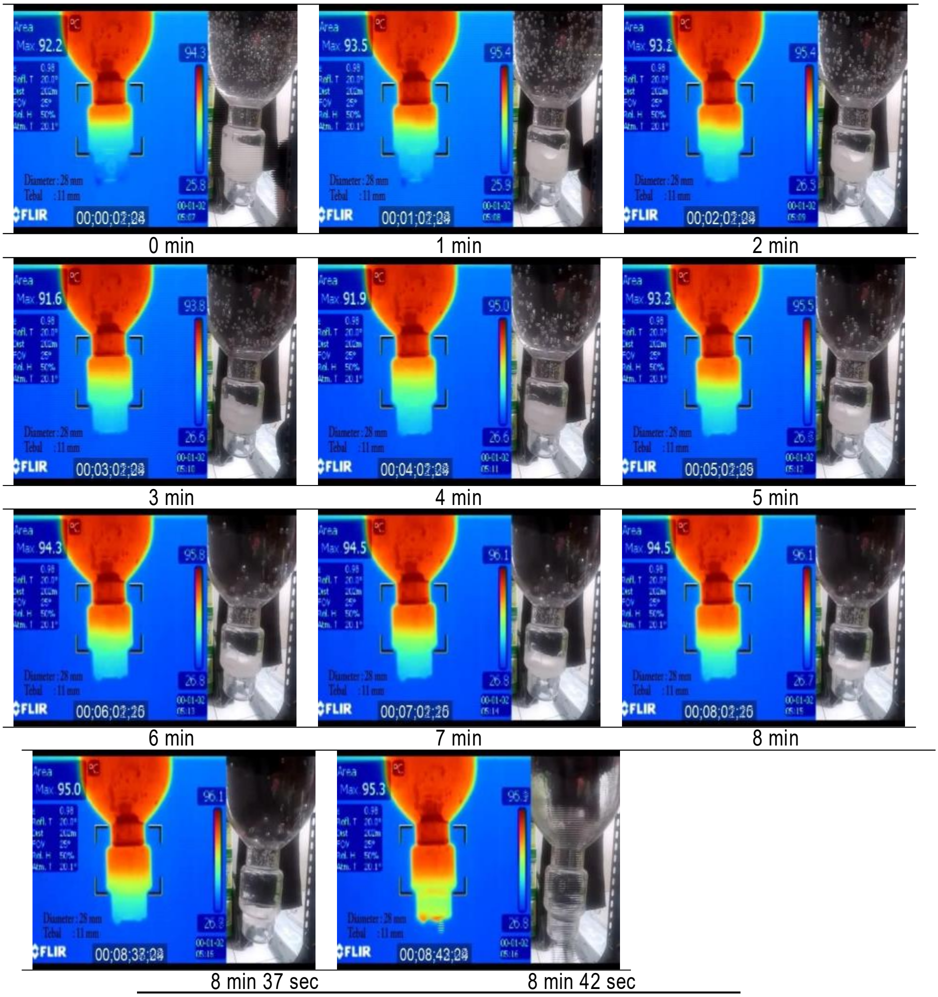

Fig. 7. Temperature profile and picture of 11 mm plug thickness at 90 °C

To facilitate a comprehensive understanding of the observations, Fig. 8 presents a comparison of the temperature readings at the four observed points. At point 1, the temperature increased gradually over time. This gradual increase could be attributed to the slower heat transfer in the lower region of the plug. In contrast, point 2 exhibited a more consistent and continuous temperature progression, indicating a relatively uniform heat transfer process in that region. Points 3 and 4 maintained a relatively constant temperature of around 90 °C throughout the experiment, as they were immersed in the heated water and reached near the target temperature.

These findings provide valuable insights into the temperature dynamics and variations within the experimental setup. The observed differences at various points emphasize the importance of considering spatial variations and potential factors such as imperfections or bubble formations when analyzing the behavior of freeze plugs. The results contribute to our understanding of the melting process and temperature characteristics, thereby aiding in the optimization and design of freeze-valve schemes for Molten Salt Reactor safety systems.

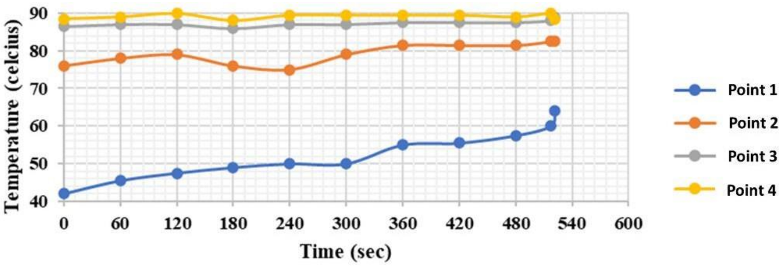

Fig. 8. Graph of temperature vs. time for 11 mm thickness

Fig. 9 provides further evidence supporting the observations made in the previous studies. The temperature mapping and digital camera image displayed in Figure 9 exhibit a similar pattern, confirming that the melting process primarily occurs from the middle-upper surface of the plug. This phenomenon aligns with the observations of potential imperfections during plug solidification. Similar to the 11 mm case, the melting progresses towards the middle part of the plug, forming a hole that facilitates water relocation. After approximately 12 minutes, the hole reaches the bottom part of the plug, allowing for the complete outflow of hot water within a brief 5-second duration.

Fig. 10 illustrates the temperature profiles recorded at the four observed points. Point 1 demonstrates a slow increase in temperature, reaching around 50 °C. Point 2 exhibits temperature fluctuations around 70 °C, potentially indicating variations in heat transfer dynamics in that particular region. However, points 3 and 4 remain below 90 °C. It should be noted that these values may require further accuracy, as the temperature controller was set to maintain a temperature of 90 °C. The temperature controller, equipped with a thermocouple immersed in the water near the heater, may provide more precise readings for these points.

These findings further contribute to our understanding of the temperature distribution and behavior of the plug during the melting process. The observations regarding the hole formation and water relocation emphasize the complex dynamics involved in the melting of the plug. Moreover, the temperature profiles highlight the variations at different points, indicating the importance of considering spatial variations and potential discrepancies in temperature measurements. This knowledge enhances our ability to optimize freeze-valve schemes for Molten Salt Reactor safety systems, leading to improved reliability and performance.

The experimental results demonstrate the importance of different heat transfer mechanisms involved in the melting process. Conduction played a significant role in transferring heat from the heating plate to the water, while convection facilitated the spreading of heat within the water above the plug [10–13]. Additionally, radiation contributed to heat dissipation into the surrounding environment. Understanding these heat transfer mechanisms is crucial for optimizing the freeze-valve scheme, as it can help identify potential areas for improvement in terms of efficiency and heat distribution.

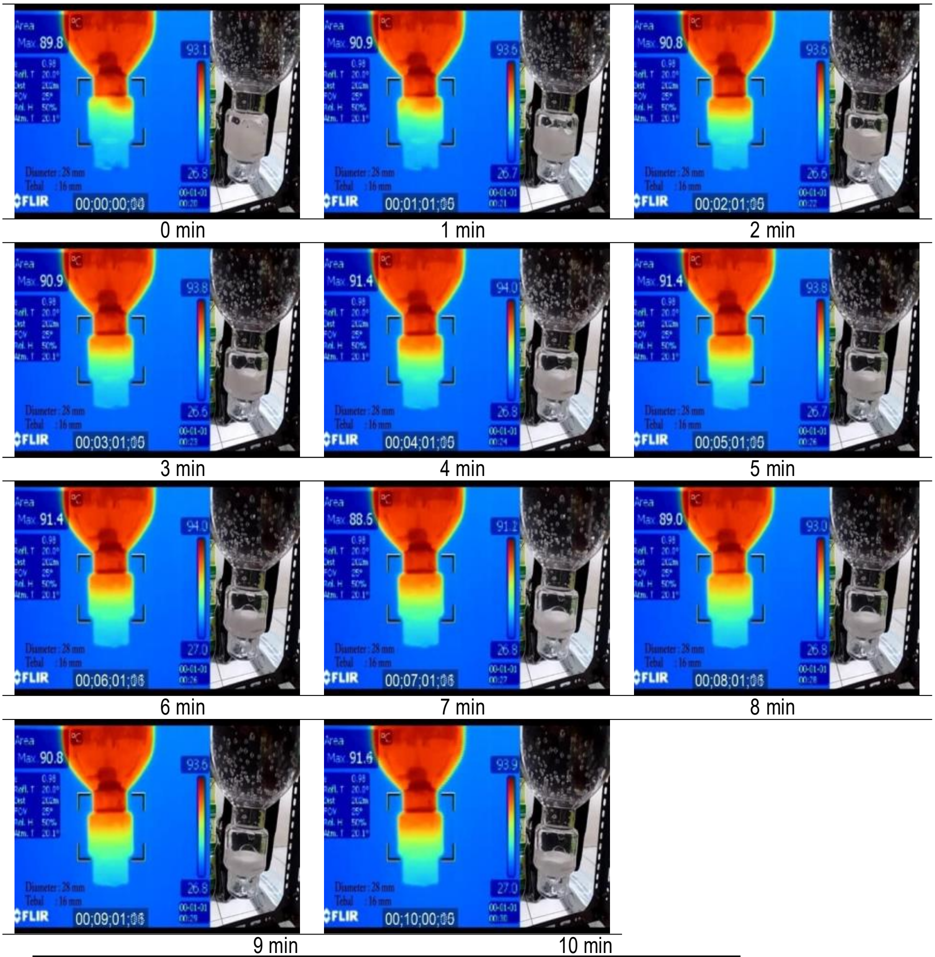

Fig. 9. Temperature profile and picture of 16 mm plug thickness at 90 °C

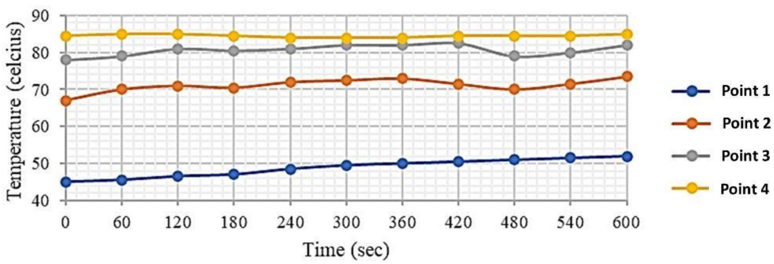

Fig. 10. Graph of temperature vs. time for 16 mm thickness

The observations of faster melting in the middle region compared to the outer diameter in Fig. 7 and 9 suggest that imperfections during plug solidification could impact the melting process. It is important to consider the effects of imperfections, such as bubble formation and entrapment, as they can create variations in heat transfer and lead to uneven melting. Further research could focus on minimizing these imperfections to enhance the overall performance of the freeze-valve system.

The temperature profiles at different observed points in Fig. 6, 8, and 10 highlight spatial variations within the system. These variations can be influenced by factors such as the distance from the heat source and the presence of the plug. Understanding these spatial temperature variations is crucial for designing efficient freeze-valve schemes [5,14].

The formation of holes in the middle part of the plug, as observed in Fig. 9 and 10, indicates a pathway for water relocation and efficient outflow. This phenomenon suggests that the melting process can create a self-driven mechanism for water drainage. Further studies could focus on understanding the dynamics of hole formation and its impact on the overall safety and efficiency of the freeze-valve system.

These research discussions provide insights into the experimental findings and open avenues for further investigations. They highlight key areas of interest to enhance the understanding and optimization of freeze-valve schemes in Molten Salt Reactor safety systems.

4 Conclusion

In conclusion, this study investigated the melting behavior of paraffin plugs with varying thicknesses in hot water, simulating a freeze-valve scheme for Molten Salt Reactor safety systems. The findings highlighted the following key aspects:

1. The experimental results showed that the melting time of the paraffin plug varied depending on its thickness. Thicker plugs exhibited longer melting times, while thinner plugs melted relatively faster.
2. The study emphasized the significant impact of plug imperfections, such as bubble formation during solidification, on the melting rate. These imperfections introduced localized variations in heat transfer, leading to deviations in the melting behavior.
3. The analysis of temperature profiles using a thermal camera provided valuable insights into the melting process. However, the incorporation of inserted thermocouples could improve the accuracy and reliabilityof temperature measurements in future experiments.

Overall, this research underscores the importance of optimizing plug fabrication techniques and understanding the underlying mechanisms involved in the melting process. The findings contribute to the ongoing development of freeze-valve schemes for Molten Salt Reactor safety systems, with implications for enhancing reactor safety and performance.

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