Salt Composition Sensor for Liquid Fuel in Molten Salt Reactors

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1. Introduction

In the development of advanced nuclear reactors, particularly molten salt reactors (MSRs), monitoring salt composition is crucial to ensuring safe and efficient operation [1]. Traditional methods, such as electrochemical and spectroscopic techniques, face significant challenges in high-concentration environments, where uncertainties and maintenance issues hinder their effectiveness [2]. Our research has demonstrated that by leveraging the differences between liquidus and solidus temperatures in molten salts, which are influenced by the overall salt composition, these changes can be accurately monitored using a thermocouple and a cooling cup. This method provides a reliable measure of salt composition, laying the groundwork for future applications in uranium concentration monitoring.

This approach not only enhances the accuracy of uranium monitoring but also offers significant potential for integration into remote and automated control systems in MSRs. The ability to continuously and accurately monitor uranium levels is essential for the autonomous operation of these reactors, ensuring that any changes in fuel composition are detected in real-time. This is particularly important for maintaining the balance of nuclear material within the reactor, which is critical for both operational safety and compliance with international safeguards. Our research represents a significant step toward achieving these goals, offering a novel solution that overcomes the challenges posed by current monitoring technologies.

2. Methods and Results

2.1 Experimental setup

All experiments were conducted within an argon (Ar) atmosphere glovebox to maintain a controlled environment and prevent oxidation. The furnace used was a well-type tube furnace with an inner diameter of 159 mm, installed at the bottom of the glovebox. For the experiments, a stainless steel crucible was used as the outer container, within which either an alumina crucible or a quartz crucible was placed depending on the sample size.

To measure 50 g of salt, a 50 mm diameter alumina crucible was utilized, whereas a 20 mm diameter quartz crucible was employed for 10 g salt measurements. Both the alumina and quartz crucibles were positioned at the same distance from the center of the tube furnace to minimize temperature differences between them (Fig 1a).

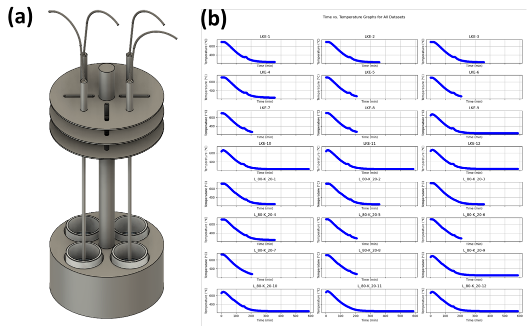

Fig. 1. (a) Experimental setup for monitoring salt temperature with K-type thermocouples in alumina crucibles in the stainless crucible. (b) salt temperature profile while cooling LiCl-KCl eutectic salt and LiCl-KCl(80 mol%-20 mol%) salt.

Temperature monitoring was performed using a K-type thermocouple, which provided a minimum resolution of 1 K. The salt and thermocouple were placed inside the crucibles, and the furnace was heated to 1073 K to melt the salt. Following this, the furnace was cooled at a rate of 2 K/min down to 573 K, during which the temperature of the salt was continuously monitored.

The salts used in the experiments were 99% pure anhydrous salts, purchased from Sigma-Aldrich. Depending on the experimental conditions, the salts were mixed using a high-precision balance located within the glovebox to ensure accurate measurements.

2.2 Salt Composition Monitoring via Temperature Profiles

2.2.1. Eutectic salt

Temperature monitoring was carried out during the cooling process of the LiCl-KCl eutectic salt (Fig. 2), which was repeated three times using four different crucibles. The results indicate that the temperature varies by up to 10 K depending on the position of the thermocouple within the crucible. Additionally, the observed freezing point of the eutectic salt exhibited a variance of up to 1 K across different trials. This minor variation suggests that while the overall temperature profile is consistent, slight positional differences of the thermocouple can lead to measurable differences in temperature readings, particularly at critical points such as the eutectic freezing point.

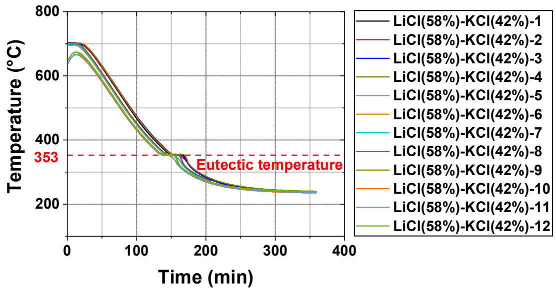

Fig. 2. Temperature profiles during the cooling of LiCl-KCl eutectic salt.

2.2.2. Salt Composition Monitoring

Beyond measuring the freezing point of the eutectic composition, measurements were also performed on LiCl-KCl molten salts with compositions deviating from the eutectic point. By differentiating the temperature with respect to time, the points at which the temperature change of the salt slows down were identified (Fig. 3a). These points correspond to phase transitions within the salt. As observed in Fig. 3b, the cooling rate of the molten salt varies with each phase transition, and the liquidus and solidus temperatures provide critical information for predicting the composition of the salt. This demonstrates that the monitoring technique can effectively track phase changes, which is essential for understanding and controlling the salt composition during reactor operations.

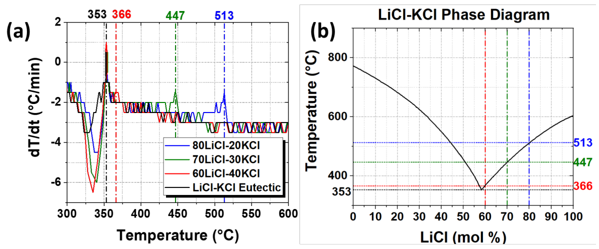

Fig. 3. (a) The time derivative of temperature for various LiCl-KCl compositions, showing points of slowed temperature change corresponding to phase transitions. (b) The phase diagram of LiCl-KCl illustrates the relationship between LiCl mol% and temperature, with liquidus and solidus lines indicating the potential for composition prediction based on cooling behavior.

3. Conclusion

The method demonstrated in this study successfully predicted the composition of a binary salt system, even in environments where up to 1% impurities were present. This approach, utilizing a simple thermocouple setup, offers a reliable and straightforward means of in-situ, real-time monitoring of UCl_3 concentration in the nuclear fuel salt of molten salt reactors. The ability to track and predict salt composition with this technique represents a significant advancement for the safe and efficient operation of molten salt reactors, particularly in maintaining accurate control over the fuel composition during reactor operation.

Acknowledgments

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