Low-cost Plasma Spectroscopy for Monitoring Gaseous Fission Products from Small Modular Reactors

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1. Introduction

Small Modular Reactors (SMRs), including Very High-Temperature Reactors (VHTRs), Molten Salt Reactors (MSRs), and Liquid Metal Fast Reactors (LMFRs), are emerging as a solution for carbon-neutral energy production due to their enhanced safety, scalability, and integration potential with renewable energy systems. However, their economic viability is challenged by high capital costs and the complexity of in-situ monitoring systems [1]. Efficient and cost-effective monitoring of fission gases, particularly xenon (Xe) and krypton (Kr), is essential for maintaining fuel integrity and optimizing reactor performance [2]. Conventional methods for monitoring these gases are often complex and costly, limiting their practical use for SMRs. Recent studies have showed that optical spectroscopy, including laser-induced breakdown spectroscopy (LIBS), is a viable approach for real-time monitoring of noble gases and aerosols at off-gas line in molten salt reactors due to its robustness and ability to deliver accurate measurements remotely [3]. Inspired by these findings, this study proposes a low-cost plasma spectroscopy-based method for in-situ monitoring of gaseous fission products from SMRs, aiming to improve economic feasibility without compromising safety standards.

2. Methods

2.1. Glow-discharge fission gas monitoring system

An atmospheric plasma spectroscopy system was developed to monitor fission gases, specifically xenon (Xe), in a helium (He) matrix. As illustrated in Fig. 1, high-purity (99.999%) He and a mix gas (He and [Xe] 500 ppm) were used, with the gas flow rates precisely controlled by mass flow controllers (MFCs, max flow rate 1000 sccm) to ensure stable and reproducible conditions. A DC power supply was used to generate a stable glow discharge between two titanium electrodes, applying a maximum voltage of 6 kV and a current of 6 mA in constant current mode. The resulting discharge produced a characteristic emission spectra from the gas mixture, which was analyzed using a UV-Vis spectrometer (Avantes, ULS2048CL-EVO). The spectrometer, directly connected to the discharge cell through an optical window, measured emission lines corresponding to Xe and He, enabling real-time monitoring of fission gas concentrations.

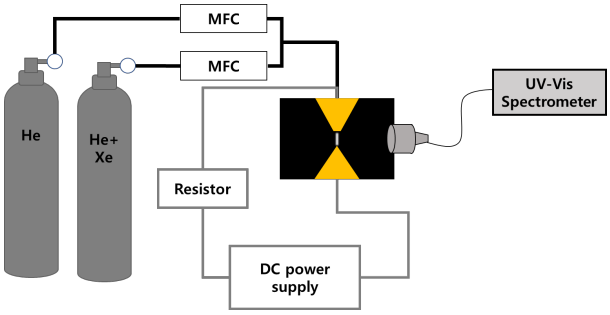

Fig. 1. Experimental setup

2.2 Discharge condition

To check discharge conditions, the current was varied from 2 mA to 6 mA in constant current mode while monitoring changes in the spectrum. Two thousand measurements were performed for each current setting to assess he stability of discharge, based on the statistical analysis of the most prominent spectral peak. At a fixed current of 6 mA, the gas flow rate was maintained at 100 sccm, and the Xe concentration was systematically varied to observe the corresponding changes in average discharge voltage. This approach enabled the identification of discharge stability for accurate and consistent fission gas monitoring.

2.3 Xe concentration calibration and in-situ monitoring

The spectra were measured by varying the flow rates of pure He and He+Xe mixtures with Xe concentrations

ranging from 0 to 500 ppm under a constant current mode (2–6 mA) to calibrate Xe concentration. A total of 2000 measurements were performed for each concentration setting, and the Interquartile Range (IQR) method was used to identify and exclude outliers to enhance data reliability.

For in-situ monitoring, continuous measurements were conducted by varying Xe concentration to assess the corresponding changes in spectral signals. A constant current of 6 mA was applied during the glow discharge, and the Xe concentration was sequentially adjusted through the following levels: 0, 200, 300, 100, 400, 50, 250, 500, 150, and back to 0 ppm. The plasma discharge was turned off and on during each concentration change to minimize transient effects. Spectral data was measured at 0.1 s intervals to check feasibility of real-time monitoring.

3. Results and Discussion

3.1 Discharge condition

To evaluate the stability of the plasma discharge, emission spectra were measured 2000 times under identical conditions while varying both the Xe concentration and applied current. The most intense spectral peaks were extracted from these measurements, and their relative standard deviation (RSD) values were calculated to assess the stability of discharge. Initially, none of the conditions tested yielded RSD values below 5% across the entire range of Xe concentrations, indicating insufficient stabilization (Fig. 2a). To further investigate, the spectra were divided into two halves due to significant noise in the first 1000 measurements, and the RSD was recalculated using only the latter 1000 measurements (Fig. 2b). This analysis showed that at current levels of 4, 5, and 6 mA, the RSD values fell below 5%, confirming stable plasma generation under these conditions. Additionally, when the Xe concentration was varied at a fixed current of 6 mA, the discharge voltage measurements showed RSD values of less than 2.5%, further demonstrating the reliability and stability of the discharge system for fission gas monitoring.

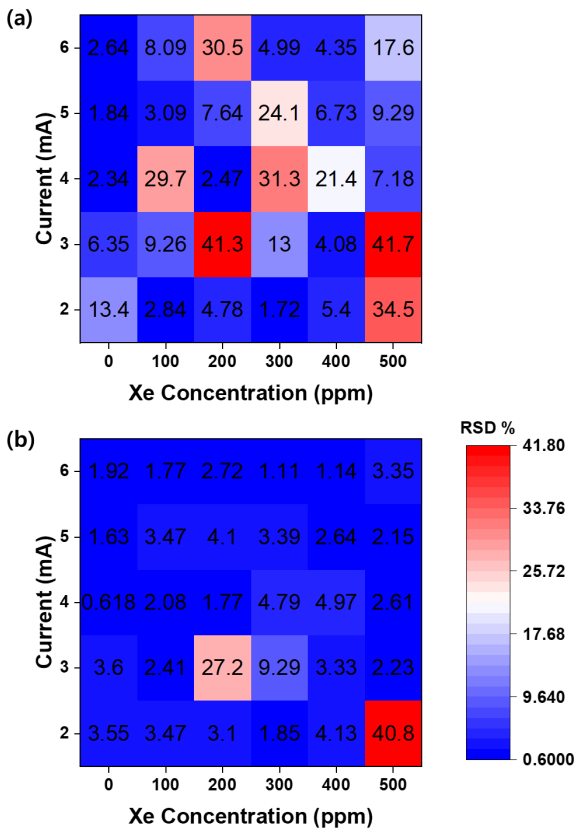

Fig. 2. Relative standard deviation (RSD) of maximum intensity of (a) 2000 spectra and (b) stabilized 1000 spectra.

3.2 Xe concentration calibration and in-situ monitoring

Xe concentration was calibrated by measuring the emission spectra across a range of Xe concentrations (0–500 ppm) under constant current (6 mA) conditions. For an accurate comparison of experimental conditions depending on Xe concentration, the Xe emission line (823.1 nm) intensity was normalized by the intensity of the most dominant He emission line (587.5 nm). As shown in Fig. 3a, a linear relationship was observed between the Xe concentration and the corresponding intensity, indicating that the glow-discharge system provides reliable and quantifiable detection of Xe. The calibration curve demonstrated high linearity with an $R^2 > 0.999$. For in-situ monitoring, the Xe concentration was dynamically adjusted as depicted in Fig. 3b, where the real-time response of the spectral signal corresponded accurately to the sequential changes in Xe levels. These results show that the proposed glow-discharge plasma spectroscopy system is capable of real-time monitoring of Xe concentrations for SMR applications.

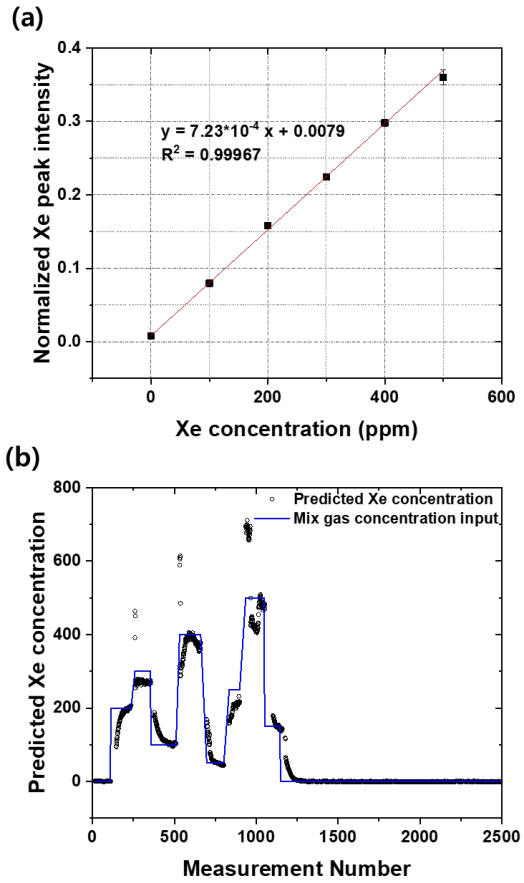

Fig. 3. (a) Calibration curve showing the linear relationship between Xe concentration (0–500 ppm) and normalized Xe peak intensity. (b) Real-time monitoring of Xe concentration.

4. Conclusion

This study demonstrated the feasibility of using a low-cost atmospheric pressure discharge plasma spectroscopy system for real-time off-gas xenon monitoring in SMR applications. The results showed that the proposed method could achieve accurate and stable measurements of Xe concentration with a relative standard deviation of less than 2.5%, confirming its potential as a reliable monitoring technique. However, to further validate the applicability of this approach, future studies should focus on assessing its performance in more complex environments, including mixtures of fission gases and aerosols. Expanding the system's capabilities under these conditions will be crucial for developing a cost-effective off-gas monitoring system for advanced nuclear reactors.

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