Performance Evaluation of Ion-Exchange Resins in i-SMR Coolant Chemistry Management Systems Under High-Pressure and Low-Temperature Conditions

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1. Introduction

Small Modular Reactors (SMRs) offer enhanced safety and economic efficiency, emerging as a next-generation nuclear power solution with low cost and high efficiency. In particular, South Korea is developing the Innovative Small Modular Reactor (i-SMR), integrating boron-free operation and passive safety systems to ensure long-term operational stability under high-temperature and high-pressure conditions.

For the stable operation of an i-SMR, the Modular Makeup and Purification System (MMPS) is essential for removing impurities from the reactor coolant system, with Ion-Exchange Resins (IXRs) serving as the core technology. However, most IXRs have only been validated under large PWR conditions (40~50bar), requiring further performance evaluation under the high-pressure (150 bar) and low-temperature (50°C, 70°C) conditions specific to i-SMR.

This study evaluates the adsorption performance and durability of IXRs under high-pressure and low-temperature conditions, assessing their feasibility for i-SMR MMPS applications and contributing to long-term operational stability [1][2].

2. Methods

This study evaluated the target ion removal efficiency and durability of IXRs under high-pressure (150 bar) and low-temperature (50°C, 70°C) conditions. For comparison, a baseline experiment was conducted at 1 bar and room temperature (RT). The resins selected included strong acid cation-exchange resins with sulfonic acid functional groups (NRW150, NRW160, NRW160LS) and strong base anion-exchange resins with quaternary amine functional groups (NRW505, NRW600). All resins used in this study were commercially available nuclear-grade ion-exchange resins.

The target ions included metal cations (Co^{2+}, Ni^{2+}, Cr^{3+}, Mn^{2+}, Zn^{2+}, Zr^{4+}, K^{+}) related to reactor corrosion and anions (Cl^{-}, F^{-}, I^{-}, SO_4^{2-}) affecting coolant chemistry stability.

For the purpose of dynamic flow testing, a customized system utilizing HPLC was employed to regulate solution flow under high-pressure conditions (150 bar), while a peristaltic pump-based system was separately set up for baseline experiments at ambient conditions (1 bar, RT). The solution was injected at a constant flow rate using a pump, passed through the IX column, and the effluent was fractionally collected for breakthrough curve analysis and comparison. Solution analysis using Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES) and ion chromatography (IC) was performed to assess adsorption performance. Breakthrough curve fitting was conducted to derive key performance indicators such as breakthrough capacity (B_{CAP}), half-saturation time ($t_{1/2}$), and adsorption capacities at specific saturation points (q_{BV50}, q_{BV100}). By comparing these performance metrics, the adsorption efficiency and ion-exchange performances of different IXRs were evaluated [3][4].

The experiment consisted of the following three stages.

(1) **Single-ion adsorption experiment:** Solutions of each selected cation and anion with concentrations 1000 ppm were individually contacted with cation- and anion-exchange resins, respectively, to evaluate adsorption capacity and removal efficiency under high-pressure and low-temperature conditions. Additionally, optical microscopy (OM) was used after the experiment to observe physical deformation, such as cracks or structural changes in the resins.

(2) **Multi-ion adsorption experiment:** Mixed cation solutions of the selected and cations and anions with concentrations 1000 ppm were contacted with cation- and anion-exchange resins, respectively, to analyze competitive adsorption characteristics and adsorption performance.

(3) **Mixed-ion adsorption experiment:** All selected cations and anions were combined together and contacted with 1:1 mixed-bed column(cation resin : anion resin) to evaluate adsorption performance and analyze ion interactions.

3. Results and Discussion

3.1. Resin Structural Integrity

The experiment was conducted using a 1000 ppm $CoCl_2$ solution under flow conditions at 10 bar and

150 bar, maintaining a 10-hour flow condition, and the results were compared with fresh resin. No physical deformation was observed, indicating that the resin maintained its structural integrity even under high-pressure conditions. No cracks or structural deformations were detected, suggesting that the resin remains structurally stable in high-pressure environments. The presented figure compares the fresh resin, 10 bar, and 150 bar conditions using an optical microscope at 50× magnification (Fig. 1).

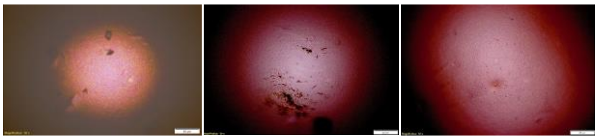

Fig. 1. Optical Microscopy of NRW160 (New / 10bar / 150bar)

3.2. Single Ion-Exchange Performance

The performance evaluation of the IXRs was conducted under high-pressure (150 bar) and low-temperature (50°C, 70°C) conditions for cation- and anion-exchange resins (NRW150, 160, 160LS, 505, 600). The evaluation was based on breakthrough capacity (B_{CAP}), half-saturation time ($t_{1/2}$), and adsorption capacity at 50% / 100% saturation points. (q_{BV50}, q_{BV100}). The results showed significant differences in adsorption performance depending on resin type and temperature conditions.

For cation-exchange resins, most ions, including Co^{2+}, Ni^{2+}, and Cr^{3+} exhibited the highest adsorption performance in the 160 resin, following the trend NRW160 > NRW160LS > NRW150 in terms of breakthrough capacity (B_{CAP}). However, Zn^{2+} and Zr^{4+} showed the highest adsorption capacity in the 160LS resin, indicating a different trend compared to other cations.

For anion-exchange resins, most ions exhibited the highest breakthrough capacity (B_{CAP}) in the NRW505 resin under both 70°C and 50°C conditions, except for a few specific cases. The NRW600 resin followed in terms of adsorption capacity.

Fig. 1. Breakthrough Capacity of Cation IXR

Resin		150		160		160LS	
Temperature		50°C	70°C	50°C	70°C	50°C	70°C
B_{CAP} (mg/g)	Co^{2+}	64.2	58.9	77.6	77.8	56.6	94.0
	Ni^{2+}	61.2	54.6	72.9	72.2	67.1	73.7
	Cr^{3+}	39.2	36.3	43.5	45.1	40.0	36.6

Fig. 2. Adsorption Rate of Ni for Each Cation IXR

Resin		150		160		160LS	
Temperature		50°C	70°C	50°C	70°C	50°C	70°C
Adsorption Efficiency (%)	BTP	98.8	88.1	92	91.4	84.9	93.3
	50%	112	109	111	110	108	108
	100%	141	138	132	131	132	129

Most cations, including Ni, exhibited adsorption efficiencies below 100% at the breakthrough point (BTP). However, at 100% saturation, their adsorption rates approached the theoretical value (100%). This indicates that during the initial breakthrough stage, some ions may not be fully retained by the resin and pass through. Over time, as the adsorption sites of the resin become saturated, the removal efficiency of the target ions gradually increases. However, Zr and Cr reached only 78%–90% of the theoretical value at 100% saturation. This suggests that the delayed initial adsorption of multivalent ions and their slower diffusion within the resin matrix influenced the results.

For anion-exchange resins, most ions exhibited adsorption efficiencies of 67%–69% at BTP, with their adsorption rates approaching 100% as they reached full saturation. However, I^- showed a notably higher adsorption efficiency of 83% at BTP.

3.3. Multi Ion-Exchange Performance

The multi-ion experiment enabled the derivation and fitting of breakthrough curves for specific IXRs, allowing for the calculation of key performance indicators [3] [4]. By comparing q_{BTP}, q_{BV50}, and q_{BV100}, the adsorption behavior from breakthrough (BTP) to 100% saturation could be quantitatively evaluated. The multi-cation test was conducted using a solution containing all seven cations (Co^{2+}, Ni^{2+}, Cr^{3+}, Mn^{2+}, Zn^{2+}, Zr^{4+}, K^+), while the multi-anion test was performed with a solution containing all four anions (Cl^-, F^-, I^-, SO_4^{2-}) under flow test conditions.

4. Conclusion

The findings of this study provide essential data for optimizing IXR selection and operational conditions in the MMPS of i-SMR. The structural stability of IXRs under high-pressure conditions was confirmed, and adsorption trends of various ions suggest that tailored resin selection is necessary based on the target ion composition.

The single-ion experiment results showed that, except for certain ions such as Zr and I, most cations and anions exhibited adsorption efficiencies close to the theoretical value (100%) at 100% saturation. This indicates the potential of IXRs to effectively remove target ions even under high-pressure and low-temperature conditions.

In future research, adsorption performance experiments will be conducted under multi-ion and mixed-ion conditions. This will allow for a better understanding of ion interactions and removal efficiency under more realistic operating conditions. Through this study, the purification performance of the i-SMR MMPS can be enhanced, leading to system optimization. Furthermore, it is expected to contribute to improving the long-term stability of next-generation nuclear reactor water treatment systems.

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