Abstract

The increasing emission of mercury, particularly from the energy sector, poses a significant threat to both the environment and public health. This necessitates the development of effective removal strategies, including those targeting wastewater generated during wet flue gas desulfurization (WFGD) processes. Simultaneously, a steady rise in waste materials from both conventional (e.g., fly ash) and unconventional (e.g., spent photovoltaic panels) energy sources highlights the urgent need for innovative approaches to waste valorization. One promising direction involves utilizing these materials as a source of silica for the synthesis of zeolites, which can serve as adsorbents for mercury ions through adsorption processes. However, there exists a notable research gap concerning the comprehensive evaluation of zeolitic adsorbents under both static and dynamic conditions. A comparative analysis of these two approaches is crucial, as studies limited to static systems fail to fully elucidate the sorption mechanisms that may occur under realistic process conditions.

Contemporary research increasingly incorporates numerical methods, such as statistical experimental design, to reduce the number of necessary trials while enabling the identification of significant and often non-obvious relationships between process variables. This is important not only for improving research efficiency but also for minimizing environmental impact—fewer experiments translate to reduced consumption of reagents and energy, as well as lower waste generation.

The study began with the selection and characterization of suitable raw materials for zeolite synthesis. Fly ash from bituminous coal combustion was used for the synthesis of zeolite X, while a silicon-rich thermally treated fraction of a spent photovoltaic panel was employed for zeolite A production. A complete two-level statistical experimental design (PS/DK24) was developed to guide the synthesis experiments. Based on this design, a series of hydrothermal synthesis reactions were conducted. The quality of the synthesized materials was assessed using X-ray diffraction (XRD), enabling the identification of crystal structure types and degrees of crystallinity, as well as the correlation of these features with synthesis parameters.

The zeolites exhibiting the highest crystallinity – types X and A – were selected as mercury ion adsorbents from aqueous solutions. The first stage of sorption experiments was carried out under static conditions using model mono-cationic solutions. The effects of key process parameters - such as pH, adsorbate concentration, contact time, and adsorbent dosage – on sorption efficiency were analyzed. The results were interpreted using classical adsorption isotherm models, including both two-parameter models (Langmuir, Freundlich, Dubinin–Radushkevich) and more complex three-parameter models (Sips, Toth, Redlich–Peterson).

Building on the results from static systems, dynamic sorption experiments were conducted using both synthetic mono-cationic solutions and real wastewater from WFGD installations. The data obtained were compared with column flow and sorption kinetics models, including those by Wolborska, Bohart–Adams, and Yoon–Nelson, constituting the final phase of the research.

The conducted experiments demonstrated that energy sector-derived waste materials can serve as valuable precursors for the synthesis of zeolites with effective sorption properties for the treatment of wastewater from wet flue gas desulfurization processes. Both zeolite X and A effectively removed mercury ions from model aqueous solutions, with performance dependent on process conditions and the sorption system employed. The integration of static and dynamic experimental approaches enabled a more comprehensive assessment of sorptive behavior, while the application of advanced isotherm and flow models facilitated quantitative process description.

These findings support the feasibility of utilizing waste-derived materials as feedstock for the synthesis of functional adsorbents and underscore the importance of conducting experiments under conditions closely resembling real-world applications. Moreover, the use of statistical and numerical methods in experimental design contributed to enhanced research efficiency and reduced environmental impact.