Reagent-Membrane Separation of Multicomponent Aqueous Solutions

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Relevance of the research. Water hardness is one of the most common and significant water supply issues, affecting both domestic and industrial water use. The presence of dissolved calcium and magnesium salts not only reduces the efficiency of detergents but also leads to scale formation on heating elements and heat transfer surfaces. This results in decreased system performance, increased maintenance costs, and premature equipment wear. The situation is exacerbated by the growing demand for high-quality water due to industrial expansion, stricter sanitary regulations, and improved living conditions . Traditional water softening methods, such as boiling, chemical treatment, and ion exchange, have several limitations: they often require significant energy consumption, the use of chemical reagents, and generate waste by-products. In this context, modern membrane technologies, such as reverse osmosis and nanofiltration, have gained particular relevance, as they effectively remove hardness ions. However, membrane fouling and reduced membrane lifespan pose significant challenges.

Scientific interest in combined methods, such as reagent-membrane technologies, is driven by their high efficiency and ability to overcome the shortcomings of traditional approaches. Implementing such methods will not only improve water treatment quality but also reduce operational costs and environmental impact. Thus, research in this area aligns with current demands for improving water purification systems and developing innovative, sustainable technologies. A significant number of studies have focused on traditional water softening methods, such as thermal, chemical, and ion-exchange techniques. However, the application of membrane technologies, especially in combination with chemical reagents, remains an actively researched topic. Many studies analyze the performance of membrane systems (reverse osmosis, nanofiltration) and their efficiency in removing hardness ions. However, optimizing reagent-membrane interactions, the mechanisms of hardness complex formation and removal, and improving membrane system longevity remain insufficiently explored. This highlights the need for further research in this area, making the present study both relevant and timely.

The aim of work is to study the crystallization kinetics of calcium and magnesium phosphate in aqueous solutions by analyzing the liquid and solid phases and to evaluate the efficiency of the reagent-membrane method for treating multicomponent aqueous solutions.

Research Tasks:

To achieve this objective, the following tasks were undertaken:

1. Investigate the mechanism of chemical reagent interactions with hardness ions (calcium and magnesium).
2. Optimize the parameters of membrane technologies in combination with reagents to prevent membrane fouling.
3. Develop an experimental setup for implementing the reagent-membrane method.
4. Conduct experimental studies on the effect of various reagents on water softening efficiency.
5. Assess membrane durability when applying the developed method.

Scientific novelty of the work:

1. It has been demonstrated that infrared (IR) irradiation during crystallization from solutions stabilizes the charge of crystallization nuclei when the stoichiometric ratio of reagents is reached.
2. It has been shown that distributed reagent dosing through a membrane contactor with capillary elements enhances the extraction of target components (hardness salts).
3. It has been established that increasing particle charge and optimizing hydrodynamic conditions stabilize the permeability of porous membranes when concentrating sol up to 400 g/L in the solid phase.

Theoretical and Practical Significance:

1. The feasibility of reagent-membrane softening of water-alcohol solutions with high hardness levels has been demonstrated for the first time.
2. A high level of softening has been achieved under conditions of stoichiometric reagent addition.
3. Conditions for deep concentration of hardness salts sol on porous membranes have been developed without forming a polarization layer on the membrane surface.
4. The possibility of utilizing dried hardness salt concentrate as a mineral fertilizer has been demonstrated.
5. Based on the research findings, a preliminary design for softening gas production multicomponent aqueous solutions has been developed in the form of an autonomous mobile unit. The proposed technological scheme, along with a material balance calculation, has been submitted for review to Gazprom-Project Engineering LLC.

Thesis to be defended:

1. Optimization of hardness salt precipitation – Effective precipitation and crystallization control require maintaining a stoichiometrically balanced reagent-to-hardness salt ratio. The phase transition is regulated by precipitant concentration, temperature, and mixing intensity.
2. Efficiency of membrane separation in colloidal systems – Ceramic membranes with a pore size of 0.4–0.8 μm are optimal for reagent-membrane separation, effectively isolating colloidal nanoparticles of hardness salts and preventing their aggregation into larger particles.
3. Reduction in reagent consumption and increased environmental safety – The reagent-membrane method requires 2–3 times less precipitant compared to traditional reagent-based softening. The spent hardness salt concentrate is disposed of as a flowable sludge with a solid content of up to 100 g/L, reducing environmental impact.
4. Increased productivity and reduced energy consumption – The reagent-membrane method operates at low working pressures (up to 4 atm), reducing energy consumption and making the process economically viable for industrial applications.
5. Technology application prospects – The developed method is applicable not only for treating water-methanol solutions in gas extraction but also for other multicomponent aqueous systems requiring selective removal of hardness salts and other contaminants.