Hybrid desalination technologies for sustainable water-energy nexus: Innovation in integrated membrane module development

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Abstract

Global water scarcity is an imminent problem caused by the increasing water demand arising from population and economic growth. Against this background, technologies for water resource management and treatment have been developed steadily to meet the water demand targets. However, further advances are necessary for securing environmental and economic sustainability. The management of saline water and wastewater is one of the focus areas to tackle the problems of water scarcity and sustainability in the context of water desalination.

Hybrid desalination is one of the most practical and efficient technologies that can afford environmental and economic sustainability. Hybridization of multiple processes maximizes the advantages of individual technologies and minimizes their drawbacks. The overall research on desalination and research on hybrid desalination, in particular, increased by a compound annual growth rate of 16.6% and 21.8%, respectively, from 2011 to 2020. Meanwhile, in 2020, 10.7% of scientific articles and reviews dealt with hybrid technologies. Moreover, the advances in hybrid technology are not limited to academic research; they have been widely implemented in the desalination industry. Reverse osmosis–multistage flash (RO-MSF) hybrid technology has been adopted for the largest desalination plant in the world, with a total water production of 1,036,000 m^3/day in Ras Al-Khair, Saudi Arabia.

The synergetic impacts of hybridization have various benefits depending on the desalination processes selected. In an RO-MSF system, the hybridization leads to additional water production with higher water recovery compared to a standalone RO system. Improvement in energy efficiency is another advantage of hybrid technologies as observed in the case of membrane distillation–adsorption (MD-AD) hybrid system. However, the challenges of hybrid desalination technologies are the complexity of process design, optimization, and operations. In this paper, the case of a forward osmosis–membrane distillation (FO-MD) hybrid system is presented to identify the challenges and potential solutions for hybrid desalination technologies.

An FO process is driven by the osmotic pressure difference between two streams and produces water across a hydrophilic polymeric membrane. By using a saline solution, known as the draw solution, freshwater may be recovered from a targeted feed solution stream with relatively lower salinity. MD is a thermal membrane process that makes use of the difference in vapor pressure between hot and cold streams to transport water vapor across the membrane to a cold permeate solution. These two membrane processes (FO and MD) are selected to treat the produced water, which is a byproduct in the oil and gas industry; produced water has extremely high salinity and complex organic composition and hence is one of the most challenging wastewater streams for water treatment. Since FO and MD employ two different energy potentials (i.e., osmotic and thermal energies, respectively), hybridization allows maximizing the use of available energy in target streams (i.e., produced water). To solve the challenge of complexity of hybridization, a novel integrated membrane module was developed for an FO-MD hybrid system.

To evaluate the performance of the FO-MD hybrid system for produced water treatment, synthetic produced water streams were prepared according to water quality references from a conventional oil and gas production facility. Separate FO and MD experiments were conducted to study the membrane-fouling phenomena of different produced water qualities. In addition, the FO-MD hybrid system is operated with varied combinations of produced water streams for sustainability evaluation. The experimental results demonstrate the great potential of the FO-MD hybrid system for sustainable produced water treatment. Long-term operation of the hybrid system and experiments with real produced water samples are necessary for scaling up and optimizing the technology.

Investigating the water–energy nexus related to the desalination technologies integrated with renewable energy is one approach to broaden the applications of hybrid desalination

technologies. Such a study will emphasize the advantages of hybridization despite the complex challenges. The benefits of hybrid technologies in terms of greater water production, higher recovery, and cleaner water quality will be synergized with less energy consumption by their integration with renewable energy. Meanwhile, artificial intelligence (AI)-based process design, optimization, and control will be an important tool to address the complexity of hybrid desalination technologies and will provide a comprehensive understanding of the challenges, for which the conventional experimental and theoretical studies are still limited. AI algorithms, such as machine learning and artificial neural network algorithms, are the leading approaches to the advancement of AI-assisted smart desalination.

Keywords

Hybrid desalination; Water-energy nexus; Reverse osmosis–multistage flash; Forward osmosis–membrane distillation