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Theoretical analysis of a seawater desalination process integrating forward osmosis, crystallization, and reverse osmosis

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ABSTRACT

A hybrid forward osmosis (FO)/crystallization/reverse osmosis (RO) process for seawater desalination was proposed, and the theoretical analysis of the process was conducted. When the FO unit is considered as the main desalination unit, the crystallization and RO units can be regarded as a draw solute recovery process. First, in the FO process, fresh water is extracted from seawater and permeates into draw solution. This diluted draw solution is cooled down in the crystallization process and the draw solute is precipitated up to the saturation at low temperature. As a result, the feed stream of the RO process has lower concentration, and consequently, total energy consumption is expected to be reduced. In order to apply the proposed process in practice, the selection of suitable draw solute should be carefully determined. In the present work, five substances were suggested as draw solutes in the proposed system: ammonium oxalate, ammonium aluminum sulfate, sodium periodate, sodium phosphate and sodium sulfate. Based on properties of the substances, total energy consumption was analyzed for each draw solute. The total energy was calculated by the sum of cooling energy in crystallization process and pumping energy in RO process. Through the hybridization of these three unit processes, the energy requirement for fresh water production can be reduced to 2.15 kW h/m^3. Thus, it is concluded that the proposed process can be highly competitive.

1. Introduction

In recent years, seawater desalination technology has shifted from thermal processes towards membrane-based processes due to the latter's low energy consumption [1–4]. Reverse osmosis (RO) process which is one of the membrane-based desalination processes is a standard industrial practice that has been refined in recent decades [6–9]. However, several issues remain, including energy consumption higher than the theoretical minimum (approximately two times higher at 50% recovery) [5], the need to use a high-pressure pump, the tendency of frequent membrane fouling, and the difficulty in cleaning the membrane [6–9]. As a substitute for the RO process, forward osmosis (FO) has attracted considerable attention [10]. The FO process is expected to reduce energy consumption because it utilizes the natural osmotic gradient between two solutions. In the desalination process, one of the solutions is seawater, and the other is a draw solution with a higher osmotic pressure than the seawater. Further benefits of the FO process are a low tendency for fouling and ease of cleaning compared to the RO process. At present, problems in the FO processes that must be immediately addressed include the development of suitable draw solutes and the implementation of a draw solute recovery process.

Considering the recovery of the draw solute, there have been several attempts to use methods using distillation columns, nanofiltration (NF), membrane distillation (MD) and magnetic nanoparticle [11–20,42,43]. McGinnis and Elimelech [11] researched the recovery process with a distillation column combined with ammonia-carbon dioxide as a draw solute. They simulated the energy requirement for the recovery of the draw solute and reported that the specific energy required was less than around 1 kW h/m^3 for equivalent work. Although this seems highly competitive compared with the existing desalination process, further researches are necessary for solving draw solute leakage problem as well as cost analysis considering additional heat input used for fully removing NH_3. Several publications have suggested the use of hydrophilic magnetic nanoparticles for draw solute [42,43]. The suggested draw solutes in the publications result in considerably high flux and regeneration performance. In order to utilize the substance in practice, further researches are also needed to solve agglomeration problem, to evaluate cost and energy and to optimize the process. Zhao et al. [12] carried out a study of brackish water desalination using the hybrid FO/NF process. They found that this process had several advantages

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