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Serially connected forward osmosis membrane elements of pressure-assisted forward osmosis-reverse osmosis hybrid system: Process performance and economic analysis

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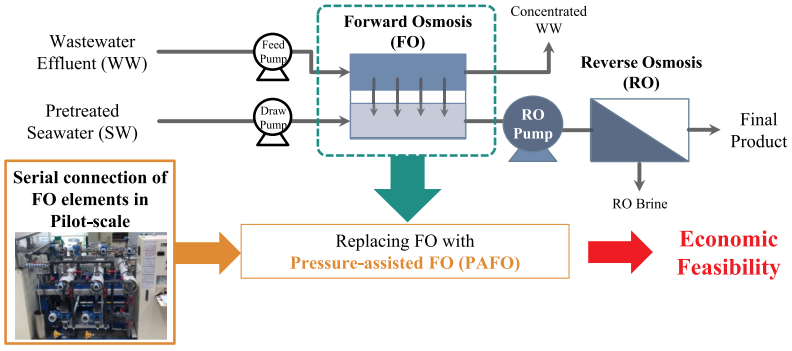
GRAPHICAL ABSTRACT



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ABSTRACT

Due to the improved dilution of draw streams, employing pressure-assisted forward osmosis (PAFO) to the hybrid system of forward osmosis (FO) followed by reverse osmosis (RO) for seawater desalination has been expected to reduce the overall economics. However, replacing FO with PAFO causes an additional energy cost in the seawater dilution step which inevitably leads to a question that PAFO-RO hybrid is truly an economically beneficial option. More importantly, though serial connection of FO elements improves the dilution of initial draw water, this economic benefit is also compensated with the additional membrane. To rationalize its overall performance and economic benefit, thorough performance and economic evaluations were conducted based on actual pilot-scale PAFO operations for serial connection of up to three 8040 FO elements. The results showed the FO-RO hybrid is not an economically feasible option unless a significant unit FO element cost cut-down is guaranteed. Meanwhile, PAFO-RO showed benefits with regards to target RO recovery and unit FO element cost, particularly when two FO elements are serially connected (SE2). It was found that PAFO-RO, indeed, has higher economic potential than FO-RO. A graphical overlapping method suggested in this work can help determine optimal serial configuration and operating conditions of PAFO-RO.

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1. Introduction

Forward osmosis (FO) process was introduced [1] and has been widely acknowledged in and out of academia as one of the promising desalination technologies that can potentially replace seawater reverse osmosis (SWRO) process in the last decade. Utilizing osmotic pressure as the major driving force for water transport, this direct osmosis process requires significantly low amount of electricity as a unit process compared to conventional SWRO processes [2]. In the early stage of FO studies in the last decade, seawater as feed water source has been widely adopted as means of replacing RO [3–5]. These efforts, however, came to an end when a fundamental thermodynamic drawback became problematic for the FO process as a means of stand-alone FO seawater desalination which requires higher energy in the following water retrieving process than the conventional RO [2]. To eliminate this flaw in a practical application, FO has been suggested as a pretreatment measure for RO (i.e. serving as a unit process for seawater dilution by utilizing impaired water sources as feed and seawater as draw), namely FO-RO hybrid process [6]. For electricity cost is the major component of operating expenditure (OPEX) of RO [7], employing diluted seawater guided to the following RO naturally leads to the energy cost saving as opposed to the conventional RO, thereby potentially leading to overall plant cost reduction. A recent study conducted an economic assessment on the FO-RO hybrid based on single element-based pilot-scale testing using an 8040 FO element to simulate serial connection of FO elements and suggested that a significant specific energy cost reduction can be possible [8]. Nevertheless, the economic feasibility of the hybrid process has not been clearly validated since additional capital expenditure (CAPEX) of FO can be significant enough to make the economics of the hybrid scheme not feasible. Thus, a thorough quantitative economic assessment is needed on the basis of pilot-scale testing of actual serial configuration of FO elements.

Pressure-assisted forward osmosis (PAFO) has been studied in recent years to enhance the draw stream dilution by applying moderate hydraulic pressure to the feed side [9–12]. This potentially leads to further energy cost reduction of the PAFO-RO hybrid system. This approach, however, embraces both benefits and disadvantages. Enhanced dilution by PAFO surely reduces the energy cost of RO and FO membrane cost. However, the additional energy cost for pressurizing the feed stream in the FO unit process can be a critical component of the operating expenditure. In this context, such a controversial hybrid process necessitates a thorough economic assessment considering the pros and cons based on actual pilot-scale testing.

As the number of FO elements serially connected increases, further dilution can be expected, though with uncertainties of the serial connection in the overall economics. There have been other attempts to evaluate the economic feasibility of the FO-RO hybrid, yet, with a limitation that the data sets were drawn from lab-scale tests employing small membrane coupons [10,13]. Unlike previously reported FO performance in lab-scale tests, it has been reported that the actual FO element performances in pilot-scale tests are strongly dependent on hydraulic pressure [14–17]. They found that, if the membranes are serially connected, a significant pressure build-up at the inlet (particularly in the draw inlet) arises [14]. This is a direct indication that the economics of PAFO-RO hybrid process is in close relation with the hydraulic pressure dependence of FO elements in series. A recent economic evaluation was employed with single element-based pilot-scale test using an 8-inch FO membrane element. They observed that the economics can be affected by hydraulic pressure dependence [8]. However, such a simulated hydraulic pressure dependence derived from single element-based results may underestimate the electricity cost of PAFO since serially connected FO elements require higher inlet pressure to accommodate equivalent initial flowrate to that of the single element case as discussed above. In addition, contraction of a draw channel dependent on operating factors such as flowrate and pressure [18] can be a crucial determining factor for accurate projection of data sets to the economics.

Therefore, economic analysis by actual serial connection of FO elements improves the validity and reliability of the economic feasibility of PAFO-RO hybrid. Accordingly, the objective of this study is to evaluate the economics of PAFO-RO hybrid by focusing on the hydraulic pressure dependence of the FO element performance. For the economic assessment, a scenario was assumed that the PAFO process was used as pretreatment to an existing full-scale conventional 2-stage RO plant to highlight the economics of the hybrid process in terms of RO energy cost reduction (i.e. $OPEX_{RO}$ saving) and additional CAPEX and OPEX for PAFO.

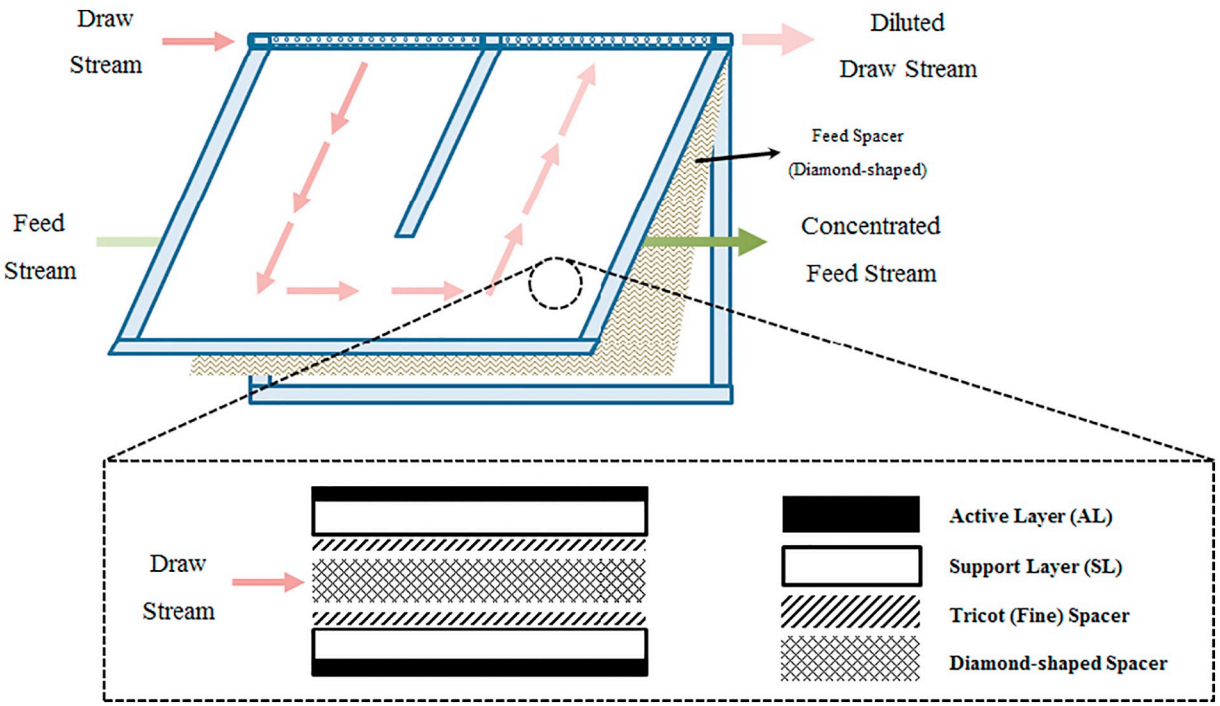

Fig. 1. Structural characteristics of a spiral-wound FO element and the spacer configurations of the membrane leaves of CSM FO-8040.