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Module scale-up and performance evaluation of thin film composite hollow fiber membranes for pressure retarded osmosis

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ABSTRACT

Pressure retarded osmosis (PRO) demonstrates great potential in energy harvesting when combining with seawater reverse osmosis. However, the lack of suitable membrane modules and the issue caused by the membrane fouling greatly impede the practical application of PRO to a larger scale. In this study, two-inch thin film composite hollow fiber modules were fabricated by using in-house developed PRO membranes. The produced PRO modules have a maximum effective area of 0.5 m^2. By assessing the PRO performances of the modules with different sizes, external concentration polarization (ECP) was found to have significant impact on the flux reduction during module scale-up. Different module designs, including fiber bundles, distribution baffles and distribution tubes, were thus adopted as an attempt to boost the membrane performance. A power density of 8.9 W/m^2 at 15 bar was obtained using tap water as feed and 1 M NaCl solution as draw solution. PRO performance tests were also carried out using the developed two-inch modules on a pilot-scale setup with actual wastewater retentate as feed solution. Low pressure nanofiltration was selected as the pretreatment of the wastewater retentate to mitigate fouling. A power density of larger than 8 W/m^2 was obtained when pretreated wastewater retentate was used as the feed solution, implying high potential of PRO in the pilot scale. Nevertheless, full potential of PRO can only be realized by mitigating ECP, which could be achieved by improving the module design in the further endeavor.

1. Introduction

Over the last century, the soaring world's population and global economy have intensified the ever-increasing demand for freshwater [1,2], promoting fast growth in desalination technologies such as seawater reverse osmosis (SWRO) [3]. However, large energy consumption in the process is a key concern for sustainable deployment of SWRO plants [4]. Pressure retarded osmosis (PRO), a process where energy could be harvested when water permeates though a semipermeable membrane from a low salinity stream to a pressurized high salinity stream, was proposed in 1970s and now is widely recognized as a potential effective energy reduction measure when combined with SWRO process [5].

Many attempts have been made to demonstrate PRO potential for energy reduction in hybrid configurations [6–9]. Altaee et al. reported that up to 31% of energy cost could be saved through SWRO-PRO process based on their simulation results [10]. Four different SWRO-PRO hybrid systems were discussed by Kim et al. with respect to energy/water consumption [7]. In Singapore, PRO has also been proposed to be coupled with SWRO in a hybrid process to not only reduce energy consumption of SWRO but also dilute the RO brine for disposal [11]. Though PRO shows fast advancement recently [6,10,12–17], the lack of suitable membrane modules [18] and the issue caused by the membrane fouling [8,19,20] greatly impede practical application of PRO to a larger scale.

The production of hollow fiber (HF) modules is well developed in industry in terms of fiber packing [21,22], module potting [23,24], and tubesheets supporting [25]. Nevertheless, fabricating suitable HF modules for PRO remains challenging due to the unique requirement raised from its process. Ren et al. tried to fabricate a PRO module based on the commercial HF ultrafiltration (UF) modules from Koch Membrane Systems Inc. [26]. A polyamide layer was synthesised by

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interfacial polymerization in the lumen. A flux of 17.5 $L/m^2 h$ was obtained in the active layer facing draw solution (AL-DS) mode with a salt flux of 5.52 $g/m^2 h$. This work demonstrated the possibility of fabricating an active layer on a UF module with 300 fibers. Wan et al. had also successfully fabricated a PRO module with 300 fibers from in-house made hollow fibers [27]. A typical centrifugal potting was used to prevent the wicking of the fibers during module fabrication. However, it was found that the repair of the defect fibers was needed after the PRO module was produced. Also, the fibers in the outmost and central regions were more vulnerable to bursting during high pressure test. Apart from the difficulties in scaling up the PRO modules, external concentration polarization (ECP) may play a crucial role in the large module where the flow condition is much more dynamic and thus complicated though its effect is generally considered insignificant in the PRO operation as compared to internal concentration polarization (ICP) [28]. The lack of suitable PRO modules greatly hinders the development of the PRO process. This calls for more research efforts in engineering PRO module that can support larger-scale operation of PRO process. A systematic development of PRO module in a large scale is necessary to facilitate the practical applications of PRO process.

In Singapore where water resources are limited, the utilization of wastewater retentate from water reclamation process as feed in PRO was proposed to save river water or surface water that are more precious [29]. However, fouling with the wastewater retentate was found to severely reduce the water flux in PRO [29–31]. Since the wastewater retentate is a pressurized stream (> 5 bar), low-pressure nanofiltration (NF) seems to be a cost-effective strategy to mitigate the fouling in PRO via pre-treating the wastewater retentate. However, this idea has not been tested in a pilot scale yet.

This work aims to develop PRO hollow fiber modules from lab scale to pilot scale with the considerations of the impacts of ECP and the variation of the selective layer properties caused by module scale-up. The developed pilot-scale modules were also tested using actual wastewater retentate as feed together with nanofiltration (NF) pretreatment as fouling mitigation strategy. The study is expected to shed lights on the module development for PRO process to demonstrate the PRO feasibility in pilot scale.

2. Materials and methods

2.1. Fabrication of PRO membranes and modules

Polyetherimide (PEI, Ultem 1000, Sabic, Saudi Arabia) and N-Methyl-2-pyrrolidone (NMP, CAS#872-50-4, Merck Chemicals, Singapore) were used as the polymer and solvent to prepare polymer dope. The polymer dope solution was pre-filtered before spinning to remove contaminants. Detailed fabrication procedure of the hollow fiber substrates in current work could be found in our previous study [32]. The produced substrates were dried in 50 wt% glycerol (Merck Chemicals, Singapore)/water solution.

A lab-scale PRO module was fabricated by potting 15 fibers into a tube with an effective length of 22 cm directly with both end sealed by fast-cured epoxy. However, a two-step potting was adopted when a large number of fibers was involved in the potting process as wicking of potting material was likely to compromise the effective length of membrane and seal integrity [33,34]. The bundle of the fibers was firstly aligned uniformly and cut smoothly at the end and then sealed with fast-cured epoxy. For the module with 150 fibers, static potting was then carried out, where the module was put vertically with slow-cured epoxy filled in its end, as shown in Fig. 1(a). Centrifugal potting was utilized when preparing modules with 500 fibers and above. The steps were similar to that of modules with 150 fibers except that a centrifugal force was introduced to dispense slow-cured epoxy evenly into the end of the module. Moreover, wicking of potting material was also less expected with this method.

After potting of module, interfacial polymerization (IP) was carried out in the lumen of the substrates to produce a polyamide selective layer. The produced module was soaked in an *m*-phenylenediamine (MPD, CAS# 108-45-2, Sigma-Aldrich) solution and then purged with cyclohexane (CAS# 110-82-7, Merck Chemicals, Singapore) to remove excessive MPD solution on the surface of the membrane. 1,3,5-Benzenetricarbonyl trichloride (TMC, CAS# 4422-95-1, Sigma-Aldrich) solution was then pumped through the lumen to form a thin polyamide layer on the membrane surface. The parameters in the fabrication process, such as flow rate of TMC solution, were proportional to the numbers of the fibers per module. The produced module was stored in de-ionized (DI) water for later usage.

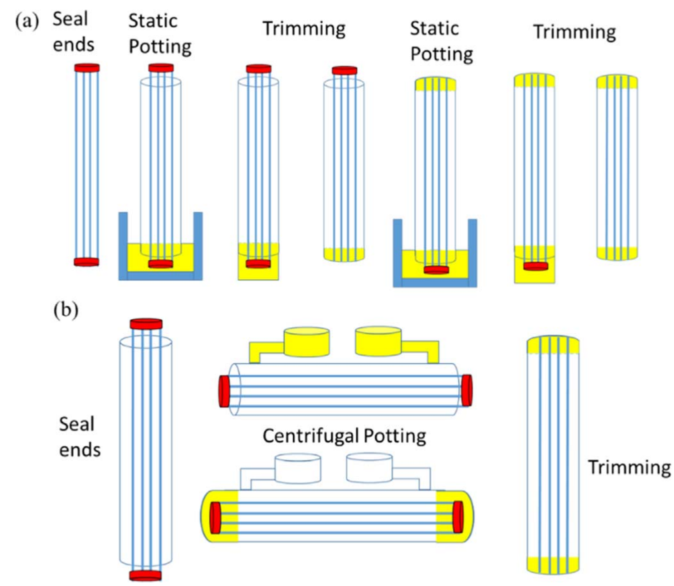

Fig. 1. Schematic drawing of fabrication procedure of modules with (a) 150 fibers and (b) 500 fibers and above.

2.2. PRO module performance

A typical RO filtration setup similar to that in the study of Wang et al. [35] was used to determine the water permeability and salt rejection of the PRO modules. DI water was circulated in the lumen of the fibers at 2 bar for pure water permeability (PWP) measurement. Rejection of these modules was tested using a 500 ppm NaCl solution at 2 bar. The nominal packing density was defined by the ratio of cross sectional area occupied by the fibers to that of the inner chamber of the module. Four different types of module design were also developed to improve the module performance, i.e., one-bundle design, four-bundle design, distribution baffle and distribution tube.

2.3. Defect identification and repair

Leakage due to the presence of membrane/selective layer defects is a common problem in the large-scale hollow fiber module fabrication process and it has been widely reported in the industrial field [34,36,37]. A commonly used industrial practice shown in Fig. 2 was used in the current study. The module to be examined was soaked in a water bath and the shell side of the fibers was slightly pressurized with nitrogen gas. Bubbles could be observed at the end of fiber lumen if a fiber leaked. A wire with glue was then filled in the fiber to seal the identified leaking fiber.

2.4. Pretreatment of PRO feed solution

In this study, one of the feed solutions used for PRO testing is the wastewater retentate from a local wastewater treatment plant that