



Mechanisms for scale formation in simultaneous membrane distillation crystallization: Effect of flow rate



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ABSTRACT

The present study aims to elucidate the crystallization mechanisms in simultaneous membrane distillation crystallization (MDCr), which is an innovative technology to control problems related to scale formation under high recovery conditions. Experiments were performed in a laboratory-scale MDCr system using hydrophobic hollow fiber membranes. The dominant mechanisms of scale formation was experimentally determined. Results showed that the intermediate flow rate results the lowest fouling propensity. Flux decline occurred by both surface and bulk crystallization at low flow rates and by rapid bulk crystallization due to the secondary nucleation at high flow rates.

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Introduction

Membrane distillation (MD) is a thermally driven separation process in which a hydrophobic membrane acts as a barrier against the liquid phase [1,2]. This membrane allows vapor passage through the membrane pores and blocks water penetration, leading to the separation of fresh water from saline water [3]. This process has been studied since the 1960s [4], and development in membrane manufacturing during the 1980s enabled the preparation of commercial membranes with desired properties. Improvements in module design and a better understanding of the transport phenomena through the membrane also contributed to renewed interest in MD [5–7].

MD has many advantages over the conventional thermal distillation processes such as multistage flash (MSF) and multi-effect distillation (MED) [3,8]. MD enables almost 100% rejection of ions, macromolecules, colloids, cells, and other non-volatiles from the process stream [9]. The operation of MD requires relatively a low temperature difference, which allows the utilization of alternative energy sources including waste heat, solar energy, or

geothermal energy as a preferred energy source [10]. Moreover, MD is less dependent on the salt concentration of feed solution, resulting in higher recovery of permeate than reverse osmosis (RO) [3].

Although MD has attracted significant attention as a potential technology for the desalination of seawater and brackish water, it has critical setback associated with membrane fouling due to scaling [11,12]. When MD operates for a long time, or in the presence of inorganic matters such as CaCO₃, CaSO₄, or MgSO₄, the membrane surface will become blocked [13]. Scale formation may lead to pore wetting, which is defined as the penetration of water and other chemicals into the pores of the membrane. This eventually leads to an abrupt decrease in flux and obstruction of passage [11,14,15].

One of approaches to overcome such limitations of MD is simultaneous membrane distillation crystallization (MDCr), which is a hybrid desalination process for concurrent productions of pure water and salt crystal from the saturated brine solutions [16–18]. Since the salts are continuously removed from the system as forms of solid crystals, MDCr can alleviate fouling due to scale formation [19]. In addition, MDCr may be used for the recovery of valuable salts as well as fresh water from wastewater effluent and seawater reverse osmosis (SWRO) brine [20]. The integration of conventional membrane processes with MDCr provides an intriguing method for achieving zero liquid discharge due to the possibility of overcoming the limits of scale formation and fouling [21].

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However, little information is available on the design and operation of MDCr systems. Since simultaneous crystallization and separation occur in MDCr, it is important to optimize operating conditions to minimize fouling by scaling and maximize water production. Accordingly, the present study is focusing on the investigation of crystallization mechanisms in MDCr systems to provide insight into their optimization. A set of laboratory-scale experiments using hollow fiber MD membranes were conducted in a direct contact MDCr configuration. Based on the results, the effect of flow conditions on the mechanisms of scale formation in MDCr were elucidated.

Materials and methods

Feed solution and membrane

To confirm the mechanism of scaling, a synthetic feed water was used for MDCr experiments. The feed water was formulated from deionized water and sea salts of 65 g/L. This concentration was determined based on the salt concentration of the RO brine in conventional SWRO desalination plants. All experiments were conducted after pre-filtering the prepared feed solution with GF/C filters.

Hydrophobic PVDF (polyvinylidene fluoride) membranes (Eco-nity, Korea) were used for all the MDCr experiments. The nominal pore diameter of the membranes was 0.22 μm . The inner diameter of and outer diameter of the fibers were 0.7 mm and 1.3 mm, respectively. A laboratory-scale membrane module with an effective membrane area of 0.0125 m² was prepared for each experiment. The module flow pattern was outside-in, where feed water (hot water) contacts the shell side of the membrane and permeate (cold water) is collected in the lumen.

Experimental set-up

A schematic diagram for a laboratory-scale MDCr system is illustrated in Fig. 1. This system is composed of several parts: a

Table 1
Operating conditions for MDCr.

Operation parameter	Condition
Feed solution	65,000 mg/L sea salt solution
Effective area	0.0125 m ²
Flow rate	200, 450, 1000, 1250 mL/min
Feed temperature	60 °C/20 °C

feedtank (crystallizer), a permeate tank, a conductivity and temperature monitor, an outside-in membrane module, two gear pumps, a heat exchanger, a stirrer and heater, and a water bath for cooling. All the experiments were performed in batch mode. During the experiments, flux, conductivity, and turbidity was measured sequentially to examine the performance of MDCr and elucidate the mechanism of crystallization. The temperature of the feed water was adjusted to 60 °C using a heater. The temperature of the permeate was kept constant at 20 °C using the water bath and the heat exchanger. Due to the difference in vapor pressure between the feed and permeate sides, the water vapor was transported across the membrane to the permeate side and condensed inside the membrane lumen. The electric conductivities of feed water and permeate were continuously measured using the conductivity monitor immersed into the feed tank and permeate tank. An electronic balance connected to a personal computer through a RS-232C cable was used to continuously measure the mass of permeate to calculate water flux through the membrane. The operation conditions are summarized in Table 1.

The permeate flux was expressed in terms of time and concentration factor (VCF), which is defined as a ratio of the initial feed volume (V_f) to concentrate volume (V_c). The concentration in the feed solution was expressed in terms of relative concentration, which is defined as the ratio of the salt concentration in the concentrate (C_c) to that in the initial feed solution (C_f).

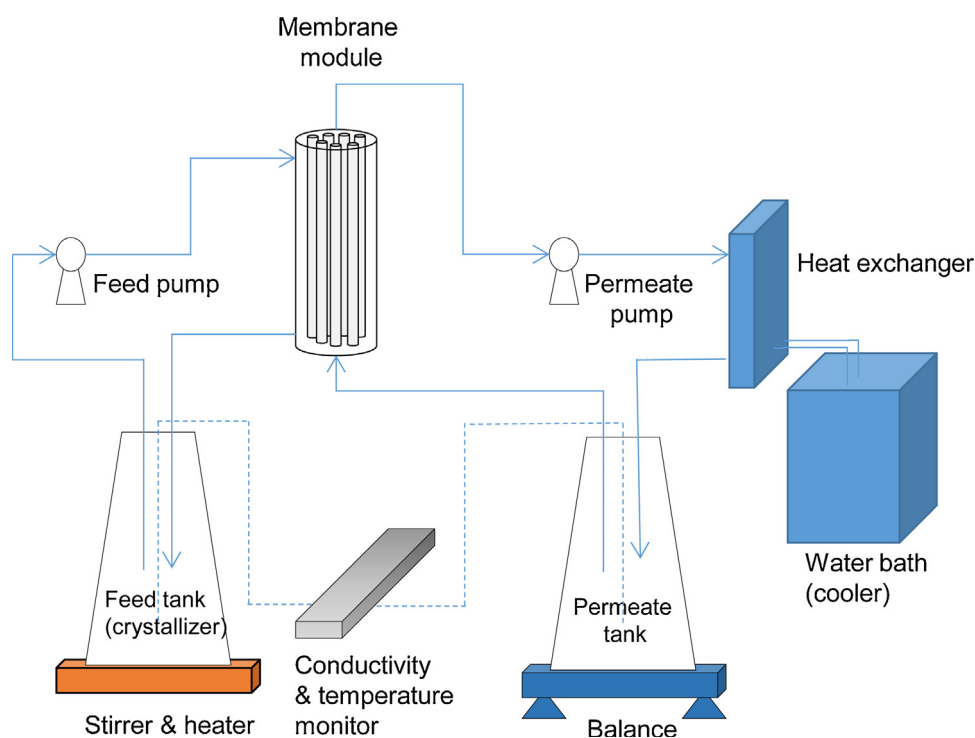


Fig. 1. Schematic diagram for MDCr experimental set-up.

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