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Ultrasonic assisted direct contact membrane distillation hybrid process for membrane scaling mitigation

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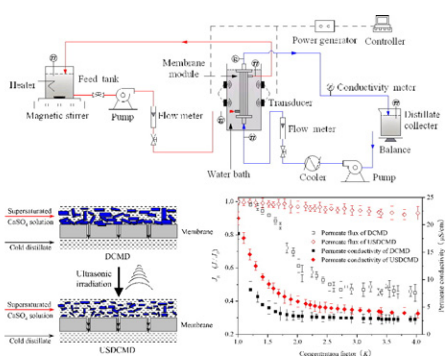
HIGHLIGHTS

- Ultrasonic assisted membrane distillation hybrid process was designed.
- The effect of ultrasonic irradiation on membrane scaling was investigated.
- Ultrasonic irradiation can effectively mitigate $CaSO_4$ membrane scaling.
- $CaCO_3$ had little effect on permeability with or without ultrasonic irradiation.
- Ultrasonic irradiation can restrain silica colloid deposit and maintain flux.

GRAPHICAL ABSTRACT



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ABSTRACT

A novel ultrasonic assisted direct contact membrane distillation hybrid process was designed and the effect of ultrasonic irradiation on membrane scaling mitigation during membrane distillation process was investigated. Under ultrasonic irradiation, ultrasonic wave refreshed the liquid-membrane interface continuously and reduced concentration polarization in the boundary layer adjacent to membrane surface simultaneously. Therefore, ultrasonic irradiation could mitigate membrane scaling caused by $CaSO_4$ and prevented the permeate flux decline. Although the ultrasonic irradiation could restrain the crystal size of $CaCO_3$ deposits and clean membrane surface, the experimental results demonstrated that it was not necessary to introduce ultrasonic irradiation into membrane distillation process for $CaCO_3$ membrane scaling mitigation. Due to fast precipitation rate, the concentration of $CaCO_3$ solution would not cause notable permeate flux decline in the absence of ultrasonic irradiation. There would be a gradual permeate flux decline during the concentration process of silica solution because of the formation and deposition of colloidal polysilicic acid on membrane surface. The ultrasonic irradiation caused the zeta potential of silica colloids to approach neutral and enhanced the tendency of colloid deposit, but the membrane surface could be effectively kept clean and the permeate flux was hardly affected by concentration factor increasing.

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1. Introduction

Membrane distillation (MD) is a thermally driven membrane separation technology and usually applied in which water is the major component present in the feed solution to be treated [1]. The MD process may be used as a substitute for conventional separation processes such as multistage vacuum evaporation, reverse osmosis, and distillation [2]. Compared to those processes, the advantages of MD include: (1) lower operating temperature and vapor space required than conventional distillation, (2) lower operating pressure than RO, (3) 100% (theoretical) rejection of non-volatile solute, (4) unlimited by high osmotic pressure, and (5) lower energy consumption than multistage vacuum evaporation [3–5].

Although there have been extensive studies on the application of MD for water purification, significant advancements are still needed for MD to reach the theoretical cost competitiveness and develop market share growth [6]. Membrane scaling in MD process is of particular importance, as scaling can alter membrane surface properties, change membrane pore structure, potentially lead to wetting of membrane pores and ultimately decrease membrane process efficiency [7–9]. Membrane scaling occurs when inorganic salts precipitate and accumulate on membrane surface, thus blocking the pores for vapor to diffuse across the membrane and subsequently lowering water flux. Scaling of sparingly soluble salts such as $CaCO_3$, $CaSO_4$, and silicates has been identified as a cause of flux decline when recovering water from natural streams, including brines from desalination processes [10–14].

Recently, many efforts have been made on membrane scaling mitigation during MD process by physical or chemical methods. The pH control of feed is a common method to reduce or eliminate MD scaling. In almost all cases, acidification of the feed can cause alkaline salts, the main component of scale, to become drastically more soluble [15]. Antiscalants can be used to prevent inorganic scaling, and are potent for carbonate scales, as well as phosphate, sulfate, disperse colloids and metal oxides. He et al. [16] reported that polyacrylic acid antiscalant was particularly effective in reducing calcium sulfate scale during MD process. However, it should be noted that some organic antiscalants may reduce the surface tension of the feed, which can promote membrane wetting. Chen et al. [17] incorporated gas bubbling into direct contact membrane distillation (DCMD), and found that gas bubbling delayed the occurrence of permeate flux decline due to membrane scaling deposition. Gryta [18] performed a study with a magnetic water treatment device on hollow fiber MD, the magnetic field caused significant changes in the morphology of crystal deposits on membrane surface and the $CaCO_3$ deposit layer thickness became smaller, the flux decline was mitigated. The method heating or boiling feed water is called thermal softening, and can also help reduce scale by causing $CaCO_3$ and other salts to precipitate out in heating step [19]. Microfiltration (MF) and nanofiltration (NF) are sometimes used before MD process to remove scaling and large molecules in the feed, Kesieme et al. [20] used a cartridge filter to capture calcium scale and obtained high recovery of groundwater RO concentrate with MD, Karakulski and Gryta [21] introduced NF process to soften the tap water preliminary and improved MD module efficiency.

Ultrasonic wave is referred to the acoustic wave with the frequency between 20 kHz and 10 MHz. Several concomitant effects, such as heat generation, mechanics and cavitation effect, present themselves during the propagation of ultrasonic wave in various media, and these effects have been recognized to be beneficial to many physical and chemical processes [22]. For membrane separation processes, the ultrasonic technique is used mainly in membrane fouling monitoring, membrane cleaning, and membrane flux enhancement [23–29]. Li and Mairal et al. [30–32] applied ultrasonic technique as a non-destructive, real-time, in situ measuring technique for direct monitoring of membrane fouling and cleaning during ultrafiltration (UF) and RO, and found that the ultrasonic technique is a useful technique for the non-destructive investigation of fouling and cleaning in membrane applications. Kobayashi et al. [33–37] introduced ultrasonic technique to create novel anti-fouling membrane processes for membrane water treatments, it was reported that ultrasonic irradiation during membrane filtration was very effective in removing foulants from membranes. Massive evidences exist that the ultrasonic effect is useful for water cleaning of fouled membrane, the ultrasonic cleaning presents advantages and is an effective method compared with other typical cleaning methods using physical and chemical methods [38–40].

Although the ultrasonic irradiation has been successfully applied to enhance the performance of membrane separation process such as microfiltration (MF), UF, and RO, relatively few studies have been carried out with the use of ultrasonic to eliminate or prevent the membrane fouling in MD process. Consequently, in the present study, an ultrasonic assisted direct contact membrane distillation (USDCMD) hybrid process was developed to mitigate membrane scaling and enhance the performance of MD process.

2. Experimental

2.1. Materials and membrane module

The polytetrafluoroethylene (PTFE) hydrophobic hollow fiber membrane with a mean pore diameter of 0.26 μm, supplied by DD Water Group Co., Ltd. (China), was chosen to fabricate membrane modules. Forty pieces of hollow fibers were assembled into a polyester tube (diameter $d_{in}/d_{out} = 15/20$ mm/mm) with two UPVC T-tubes and two ends of the bundle of fibers were sealed with solidified epoxy resin to compose a membrane module. The effective membrane length was 100 mm for each membrane module. The characteristics of the membrane and membrane modules are presented in Table 1.

2.2. USDCMD setup

The USDCMD experimental setup is schematically shown in Fig. 1. The hot feed, which was stirred continually by a magnetic stirrer, flowed through the shell side of the fibers, and the cold distillate flowed through the lumen side. The initial volumes of the feed and the distillate were 4.0 L and 0.25 L, respectively. Both solutions were circulated in the membrane module with the help of two magnetic pumps (MP-15RN, Shanghai Seisun Pumps, China). The feed and the distillate flowed co-currently through the module, and the circulation feed rate (V_f) was 0.25 m/s, while the cold side (V_p) being 1.0 m/s. The feed temperature ($T_{f\text{-}inlet}$) was fixed at 53 °C by a Pt-100 sensor and a heater connected to an external thermostat (XMTD-2202, Yongshang Instruments, China). The distillate temperature ($T_{p\text{-}inlet}$) kept at 20 °C by a spiral glass heat exchanger immersed in the constant temperature trough of the cooler (SDC-6, Nanjing Xinchen Biotechnology, China). The temperature of both fluids was monitored at the inlet and outlet of the membrane module using four Pt-100 thermoresistances connected to a digital meter (Digit RTD, model XMT-808, Yuyao Changjiang Temperature Meter Instruments, China) with an accuracy of ±0.1 °C. An electric conductivity monitor (CM-230A, Shijiazhuang Create Instrumentation Technologies, China) was used to monitor the distillate water quality.

Table 1
The characteristics of the membrane material and the membrane module.

Membrane and module	Properties
Membrane material	PTFE
Mean pore diameter (μm)	0.26
Porosity (%)	45.07
Inner diameter of hollow fiber (mm)	0.80
Membrane thickness (mm)	0.39
Number of hollow fibers	40
Effective membrane length (mm)	100
Effective membrane area (cm^2)	198.4