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An ultrasonic assisted direct contact membrane distillation hybrid process for desalination

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ABSTRACT

A novel ultrasonic assisted direct contact membrane distillation (USDCMD) hybrid process was designed and the effects of feed temperature, feed concentration, feed velocity, ultrasonic power and frequency on mass transfer were investigated. Under ultrasonic irradiation, changes and damages in membrane structure were found on PVDF membrane, while the pore size and the stretching strain of PP fibers were also enlarged and declined, respectively. The PTFE hollow fiber was selected to carry out USDCMD. The results showed that ultrasonic irradiation could effectively enhance mass transfer. Under the ultrasonic irradiation of 20 kHz and 260 W, the maximum permeate flux enhancement of 60% was obtained under conditions of feed temperature of 53 °C, feed velocity of 0.25 m/s and feed salt concentration of 140 g/L. The increment was enlarged with the decrease of feed temperature, feed velocity and ultrasonic frequency as well as the increase of feed concentration and ultrasonic power. Ultrasonic irradiation had no significant influence on the mechanical strength, pore size and hydrophobicity of the PTFE membrane in a 240 h continuous USDCMD experiment, and the novel membrane distillation process exhibited satisfying performance stability, which indicated that ultrasonic irradiation can be applied to membrane distillation for mass transfer enhancement.

1. Introduction

Membrane distillation (MD) is a thermally driven process suitable for applications in which water is the major component present in the feed solution to be treated [1]. There is a thermally driven vapor transport through non-wetted porous hydrophobic membranes where the driving force is the partial vapor pressure difference across the two sides of membrane pores [2]. In recent years, MD displays a very good application prospect in desalination [3–5]. Compared with conventional desalination processes such as nanofiltration (NF), reverse osmosis (RO) and thermal evaporation, MD can utilize waste heat of low quality, treat wastewater containing higher salt concentration [6–8], and even remove some organics that used to be difficult to remove [9–11]. According to the adopted condensation methods, the MD systems can be classified into four different categories: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD) and vacuum membrane distillation (VMD) [12]. Among these four MD configurations, the DCMD is the most studied and it is also considered to be the simplest in design and application [13]. This is due to the fact that condensation steps carried out inside the membrane module lead to a simple operation mode without the need of external condensers like those in SGMD and VMD.

Although there have been extensive studies on the applicability of MD for water purification applications, the industrial implementation of MD is not yet feasible because of the following four major factors: (1) low permeate flux and mechanical intensity of the hydrophobic membrane, (2) membrane fouling and membrane pore wetting, (3) long term performance instability, and (4) inefficient current MD process systems. Among these considerations, the improvement of membrane permeate flux is believed to be foremost for further commercialization of MD [14]. It is well known that the permeate flux is influenced by the membrane properties, temperature polarization, concentration polarization and channeling effect [15]. Except optimization of membrane materials, development of novel MD devices and effective MD processes is another solution to enhance the permeate flux. Teoh et al. designed different hollow fiber membrane modules with baffles and spacers, it was observed that the permeate flux can be enhanced about 30% [16]. Phattaranawik et al. [17] also found that the DCMD in spacer-filled channels achieved a higher flux than without spacers and the temperature polarization could be effectively inhibited. Chen et al. [18] incorporated gas bubbling into the DCMD system

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and the gas bubbling not only enhanced the permeate flux but also delayed the occurrence of major flux decline. Li and Sirkar [19] fabricated a rectangular cross-flow membrane module with face box and the cross flow helped to achieve a high permeate flux by reducing the temperature polarization in the feed. To improve hydrodynamics and MD module performance, Yang et al. [20] designed some novel hollow fiber modules with curly fibers, central-tubing for feeding, spacer-wrapped and spacer-knitted fibers.

Ultrasonic wave is referred to the acoustic wave with the frequency between 20 kHz and 10 MHz. Several concomitant effects, such as the mechanics, thermotics and cavatition 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 [21]. For membrane separation processes, the ultrasonic technique is used mainly in membrane fouling monitoring and control, membrane cleaning and membrane flux enhancement [22–28]. Li et al. and Mairal et al. [29–31] applied the ultrasonic technique as a non-destructive, real-time, in situ measuring technique for the non-invasive 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. [32–36] introduced the 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 [37–39]. In addition, ultrasonic intensity and frequency also increased the permeate flux of membranes [40–42]. Although the ultrasonic irradiation has been successfully applied to some membrane separation systems such as microfiltration (MF), UF and RO, this method has not yet been incorporated into the processes of DCMD.

The subject of this research, the ultrasonic assisted direct contact membrane distillation (USDCMD) hybrid process has not been reported so far. Hence, it is our interest to experimentally investigate the effect of ultrasonic irradiation on DCMD. In this study, online ultrasonic irradiation equipment was incorporated into a DCMD system and batch USDCMD experiments were carried out for desalination with sodium chloride solution as the feed. The influences of feed concentration, flow rate and temperature, ultrasonic irradiation power and frequency on USDCMD performance were investigated comprehensively and systematically. In addition, the effects of ultrasonic irradiation on the hydrophobic hollow fibers were also analyzed via scanning electron microscopy (SEM), capillary flow porometer (CFP) and mechanical strength measurement.

2. Experimental

2.1. Materials and membrane module

Three different hydrophobic hollow fiber membranes, polytetrafluoroethylene (PTFE), polypropylene (PP) and polyvinylidene fluoride (PVDF) were chosen to fabricate membrane modules. The PTFE and PP hollow fibers were supplied by DD Water Group Co., Ltd. (China) and the Institute of Seawater Desalination and Multipurpose Utilization, SOA (Tianjin, China), respectively. The PVDF hollow fiber membranes were self-prepared by the dry/wet phase inversion process. Hollow fibers in the number of 40 pieces were assembled into a polyester tube (diameter (mm) $d_{in}/d_{out}=15/20$) 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 membranes and corresponding modules are presented in Table 1.

2.2. USDCMD setup

The USDCMD experimental setup is schematically shown in Fig. 1. The hot salt solution as feed flowed through the shell side of the fibers, while the cold distillate flowed through the lumen side. The initial volumes of the feed and the distillate were 2.0 L and 0.25 L, respectively. To keep the feed concentration constant, the obtained distillate was reflowed to the feed tank every one hour. 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 in the range of 0.07–0.25 m/s, while the

Table 1
The characteristics of the membranes and the membrane modules.

Membrane material	Mean pore diameter (μm)	Porosity (%)	Outer diameter (mm)	Inner diameter (mm)	*LEPw* (Bar)	Contact angle (°)	Effective membrane area (cm^2)
PP	0.28	50.76	0.40	0.20	1.32	94.8	50.2
PVDF	0.14	83.82	1.20	0.90	2.97	99.5	150.7
PTFE	0.26	45.07	1.58	0.80	1.67	129.3	198.4

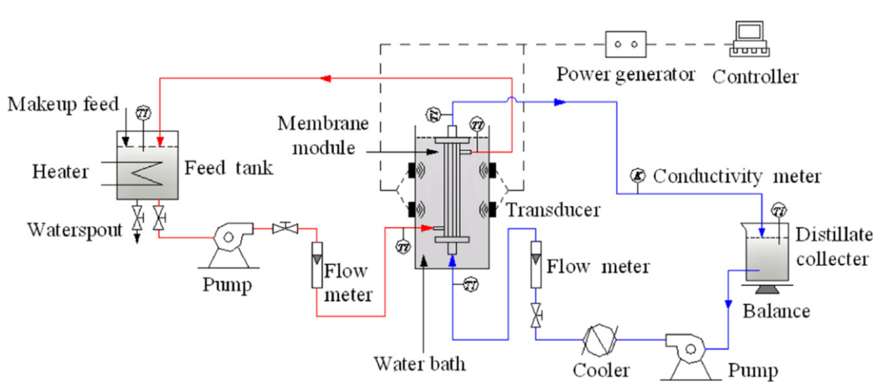

Fig. 1. Schematic diagram of the USDCMD system.