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Triple-bore hollow fiber membrane contactor for liquid desiccant based air dehumidification

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ABSTRACT

Dehumidification is responsible for a large part of the energy consumption in cooling systems in high humidity environments worldwide. Improving efficiency is therefore essential. Liquid desiccants offer a promising solution for dehumidification, as desired levels of humidity removal could be easily regulated. The use of membrane contactors in combination with liquid desiccant is attractive for dehumidification because they prevent direct contact between the humid air and the desiccant, removing both the potential for desiccant carryover to the air and the potential for contamination of the liquid desiccant by dust and other airborne materials, as well as minimizing corrosion. However, the expected additional mass transport barrier of the membrane surface can lower the expected desiccation rate per unit of desiccant surface area. In this context, hollow fiber membranes present an attractive option for membrane liquid desiccant contactors because of their high surface area per unit volume. We demonstrate in this work the performance of polyvinylidene fluoride (PVDF) based triple-bore hollow fiber membranes as liquid desiccant contactors, which are permeable to water vapor but impermeable to liquid water, for dehumidification of hot and humid air.

1. Introduction

1.1. Background

Cooling is a major consumer of energy worldwide. In the context of Middle East countries, like Saudi Arabia, energy demand for cooling comprises approximately 52% of the total demand in summer [1]. Dehumidification, the removal of water vapor from the air, is responsible for a significant part of the energy consumption for cooling processes in humid climates worldwide. The energy required for dehumidification leads to both higher costs of electricity and a large carbon footprint in areas where grid energy is supplied via fossil fuels. Estimates are that the energy efficiency of cooling equipment can be improved by up to 33% using innovative dehumidification technologies [2]. Desiccants are one of the good choices of dehumidification technology. They function by direct absorption of water vapor [3] or by indirect absorption using a membrane contactor containing a liquid desiccant [4–9]. Liquid desiccants in particular are becoming increasingly popular because of their operational flexibility [10]. A common type of liquid desiccant is a highly concentrated inorganic salt solution. Typical inorganic salts include lithium bromide, calcium chloride, magnesium chloride and lithium chloride. The driving force for transfer or condensation of water vapor into the desiccant solution is its lower vapor pressure, as compared to pure water. The vapor pressure of the desiccant solution can be reduced even more by decreasing the temperature of the solution or by increasing the concentration of salt in the solution. The condensation of water vapor leads to an increase of the desiccant temperature, since latent heat of water condensation is released. The air is cooled as latent heat is transferred to the desiccant solution. The extent of energy/moisture removal from the air is governed by the concentration of the liquid desiccant and its temperature; a concentrated cool desiccant is a good dehumidifying solution [11,12].

A liquid desiccant air conditioner (LDAC) is adapted specifically for latent cooling (humidity removal), making it one of the best available technologies for cooling in humid climates [10,13,14]. Another advantage of liquid desiccant based air conditioning is

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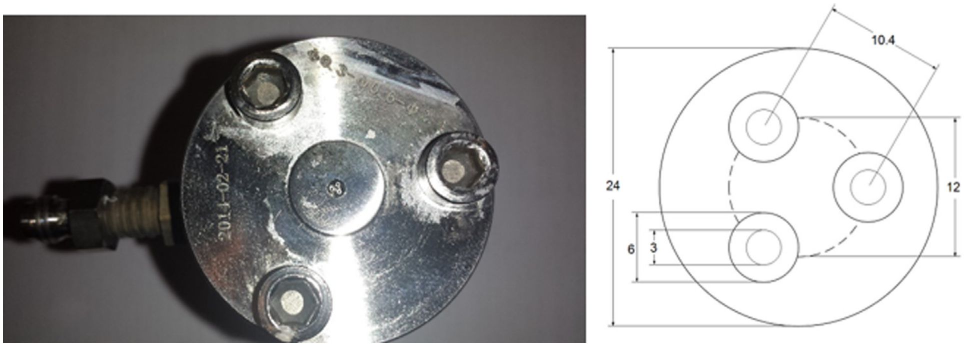

Fig. 1. Image of triple-needle spinneret and its distribution with dimensions.

that it uses heat as its primary operating energy source. Because of this feature, the electrical demand is estimated as low as 25% that of vapor-compression air conditioning [10,15]. In the context of renewable energy sources, liquid desiccants offer an advantage over solid desiccants when using solar energy for regeneration [16–26].

1.2. Membrane dehumidification

In spite of energy-related advantages, liquid desiccants have some drawbacks. Corrosion of metals resulting from the contact with salt-based liquid desiccants is one of them [10]. Therefore, the potential for droplet carryover from traditional packed-bed or falling film liquid desiccant systems has prevented widespread adoption in all but a few carefully maintained applications.

The use of membrane contactors in liquid desiccant based dehumidification systems has been evaluated by a number of authors [5,27–32]. Membrane contactor based dehumidification is attractive because it separates the desiccant and air streams by use of a porous membrane surface, effectively eliminating any chance for droplet carryover of desiccant solution into the airstream. Moreover, the membrane interface allows for independent operation of liquid and gas phases, so that no liquid condensate is generated as the desiccant absorbs the moisture [30,33,34]. The membrane also protects the desiccant solution from contamination by some airborne particulates, which could degrade the purity of the solution over time and lead to system clogging. Potential drawbacks to application of membranes in liquid desiccant cycles are the added mass transport resistance of the membrane and the cost.

1.3. Hollow fiber membrane dehumidification

The use of hollow fibers with liquid desiccants for dehumidification applications is attractive because of the high surface area provided per unit volume [35]. In addition, the porosity of hollow fibers can offer faster, more efficient moisture transport if leakage can be prevented. Hollow fibers have been used successfully in liquid desiccant applications using a lithium chloride solution pumped through polyetherimide membranes [30].

In the present work we propose and test a new device for dehumidification based on a liquid desiccant solution pumped through polyvinylidene fluoride (PVDF) triple-bore hollow fibers under typical ambient summer air conditions in Jeddah, Saudi Arabia. We selected calcium chloride as the salt of choice in our experiments because it is a common salt in liquid desiccant applications and it is a lower-cost alternative compared to lithium chloride [10]. One of the short-term motivations is to integrate the dehumidification and cooling system in closed green houses, which could work with controlled humidity levels and low energy consumption in desert areas. We describe a new hollow fiber triple bore configurations, which has the advantages of high desiccant volume to surface ratios, high mechanical stability, and easy handling. Here we extensively demonstrate their performance in modular set-ups, which could be easily scaled up for dehumidification application.

2. Materials and methods

2.1. Polyvinylidene fluoride (PVDF) triple bore hollow fiber

2.1.1. Spinning solution

Polymer/dope solution with various concentrations ranging from 12 to 15 wt% of PVDF (purchased from Kynar®/Arkema Inc., Dubai; Grade – HSV 900) were prepared by dissolving in N-methyl-2-pyrrolidinone (NMP, ≥ 99.5%, Merck). Powdered PVDF was dried in oven overnight before using to prepare dope solution. Dried PVDF powder was added in small portions to NMP in order to avoid lump formation and stirred using overhead mechanical stirrer at 600 RPM for 24 h at 70 °C. The prepared dope solution was charged into the feed reservoir of hollow fiber fabrication machine and degassed for 24 h to remove air entrapped within the dope solution.

2.1.2. PVDF hollow fiber fabrication

PVDF hollow fibers were fabricated by a non-solvent-induced phase-inversion process with a dry-wet spinning line (SepraTec Inc. Korea). The effect of dope concentration, flow rates of dope solution and bore liquid, air gap, and take-up speed were extensively studied. All hollow fibers for this study were prepared using water as bore liquid at 10 ml/min. Dope solution of 14 wt% at 12.5 ml/min (or 20 RPM) was pumped using a gear pump through a specially designed triple-bore spinneret (Fig. 1) (needle OD 0.6 mm and orifice ID 2.4 mm) kept at 10 cm air gap before coagulating in the water bath. The formed hollow fibers were washed in hot water (50 °C) for at least 10 h and stored in RO water for three days (exchanging the water everyday) to remove any residual solvent.

2.2. Hollow fiber characterization

2.2.1. Scanning electron microscopy (SEM) analysis

SEM images to check the morphology of dry PVDF hollow fiber membranes were obtained using field emission scanning electron microscopes (FEI Quanta 200 or 600) at accelerating voltage of 5 kV. Fibers dried overnight were used for SEM analysis after being carefully fractured in liquid nitrogen. Hollow fiber membranes were sputter coated with platinum (~3 nm-thick, Quorum Q150T ES) to make the polymer surface conductive for surface analysis.