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Experimental investigation of gas dehumidification by tri-ethylene glycol in hollow fiber membrane contactors

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ABSTRACT

In this study, hollow fiber membrane contactors have been applied for gas dehumidification using tri-ethylene glycol as absorbent. The effects of gas and liquid flow rates, inlet concentration of tri-ethylene glycol and flow direction on dehumidification efficiency have been investigated. The results reveal that membrane contactors can remove water vapor very effectively using tri-ethylene glycol, and very low water dew point as low as −50 °C can be achieved. It also shows that liquid phase is not the limiting resistance in this system, as a result of very high solubility of water in tri-ethylene glycol.

Introduction

Gas dehumidification is a challenging issue in many engineering applications, such as natural gas purification, air conditioning, pneumatic systems and other industrial processes. Raw natural gas contains impurities such as H_2O, CO_2 and H_2S that may result gas hydrate formation, corrosion problems and cause environmental hazards during transport [1]. To prevent the formation of gas hydrate and corrosion problems, it is necessary to remove water vapor from the gas by dehydration methods before transmitting and processing [2].

Dehumidifying processes remove moisture from gas by means of cooling cycles, vapor absorption or adsorption with desiccants and membrane technology [3]. Among these methods of gas dehumidification, absorption by hygroscopic liquids received significant attention recently because of its high efficiency, no water vapor condensation and relatively low energy consumption [4,5].

Liquid desiccants that commonly have been employed for air dehumidification are divided into two categories: (1) aqueous solution of salts like, lithium chloride (LiCl), calcium chloride ($CaCl_2$) and lithium bromide (LiBr) that usually used for residential and commercial building applications, (2) glycols like tri-ethylene glycol (TEG) that frequently used for industrial applications. The disadvantages of aqueous solution of salts versus glycols are corrosion and salt crystallization problems [6,7].

The conventional devices that were applied for this separation process are Packed columns. The performance of air dehumidification with liquid desiccants in packed columns have been investigated by several investigators [6,8–12]. Separation through this conventional process sometimes leads to difficulties such as foaming, channeling, flooding and liquid hold up. Furthermore, liquid desiccant droplets may be carried over by process gas since the process gas is in a direct contact with the liquid desiccant.

Recently, hollow fiber membrane contactors have been used in order to overcome these drawbacks. Also science the packing density of fibers can be very high, the dehumidification effectiveness is very encouraging.

Due to the advantages of membrane-based liquid desiccant, gas dehumidification by this method is now gaining increasing attention and provide promising alternative [3,13–18]. The gas–liquid membrane contactor in the form of hollow fiber is like a shell-and-tube heat exchanger. The bundle of fibers that placed in the shell formed tube side, while the space between the shell and the fibers form the shell side [15]. Gas and liquid phases are separated from each other by a permeable membrane. The membrane function in this separation process is to provide narrow barrier and specified contact area between gas and liquid phases and usually has no effect on the selectivity in separation process [19]. For gas dehumidification, a hygroscopic liquid usually flows on the lumen side of hollow fibers while gas flows on the shell side. The gas–liquid interface is formed at the pores near by the gas or

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Nomenclature

d_o	fiber outer diameter (mm)
d_i	fiber inner diameter (mm)
n	number of fiber
Q_{in}	inlet gas flow rate ($m^3\ s^{-1}$)
Q_{out}	outlet gas flow rate ($m^3\ s^{-1}$)
C_{in}	inlet water vapor concentration ($m^3\ s^{-1}$)
C_{out}	outlet water vapor concentration ($mol\ m^{-3}$)
A_m	mass transfer area of the membrane contactor (m^2)
J	water vapor absorption flux ($mol\ m^{-2}\ s^{-1}$)
η	removal efficiency (%)

liquid depends on the membrane property. In a hollow fiber membrane contactor (HFMC), water molecules diffuse from the gas side through pores of membrane and reaches the gas–liquid interface and then absorbed in the liquid absorbent [14].

Additional mass transfer resistance, plugging of membrane pores and membranes short life time are the main disadvantages of these contactors.

If membrane pores are filled with an absorbent liquid (membrane wetting), membrane resistance increases significantly because of lower diffusivity of diffusing component in liquid [8,20]. Membrane fouling is one of the main operating difficulty in membrane microfiltration applications and membrane contactors. No convective flow passes through the membrane pores as a result of this problem. However, in industrial applications, due to narrow fibers, plugging may be a major problem in cases that feed gas has a large size suspended particles [21]. The durability problem is the most important disadvantage for membrane contactors in industrial processes, however, in recent years, studies on membrane materials have been considered by investigators and the durability problem has been resolved.

Polymer membranes can be categorized to hydrophilic and hydrophobic types. By perusing the chemical structure of the polymer repeated units, it can be found that polymer is inherently hydrophilic or hydrophobic. Hydrophilic membrane contactors cause membrane pores filled by hygroscopic solution. This phenomenon named membrane wetting, and as it said before membrane mass transfer resistance increases significantly if membrane pores are filled by tri-ethylene glycol. So hydrophobic membrane material such as Polypropylene (PP) is a better choice for air dehumidification in hollow fiber membrane contactor.

Esato and Eiseman [22] were the first investigators that used membrane contactors as a blood oxygenator in 1975. After that, membrane contactors have been applied in many applications such as acid gases capture, water treatment, organic vapor removal, air humidity control, etc. [8,16,23–25].

Isetti et al. [26] were the pioneers that used hollow fiber membrane contactor as new approach in order to air dehumidification by two different aqueous solutions LiCl (42% mass) and $Ca(NO_3)_2$ (56% mass) as absorbents. They used a hydrophobic synthetic membrane as a porous media among the absorbent liquid and humid air. Because of using a hydrophobic membrane, only water vapor permeates through membrane, not liquid.

In 2000, Chiari have been also used this non-traditional approach for air humidification process. Experimental and theoretical investigations have been performed and the results indicate high humidification efficiency. Effect of various parameters on humidification performance have been considered by Chiari [27]. Another experimental and theoretical analysis was carried out by Bergero and Chiari using water and LiCl saturated solution as absorbent in membrane contactors [3]. They used hydrophobic capillary contactors for air humidification/dehumidification processes. Their experimental results show high mass transfer efficiency. Kneifel et al. [19] investigated the properties of transversal flow modules, with respect to the air side pressure drop and water vapor transport. Prominent aim of their work was the study of water vapor permeance of PDMS-coated polyetherimide hollow fiber membranes under typical air dehumidification conditions. They found that a very thin coating layer could reduce the permeance about 20%. The most comprehensive study on air humidity control using hollow fiber membrane contactor have been performed by Zhang et al. recently [15,16,25,28–30]. In order to dehumidify the air using LiCl liquid desiccant, simultaneous heat and mass transfer was investigated in a hollow fiber membrane contactor in both cross-flow and counter-current flow direction. Also, Huang et al. [13,17,18,31] have continued studies on air humidity control processing by using hollow fiber membrane contactor with LiCl liquid desiccant.

In dehumidification processes, usually liquid desiccant such as LiCl is applied for indoor air dehumidification because the vapor pressure of these materials is much lower than TEG [6]. Suitable environmental conditions in both living and working spaces often require air relative humidity control in range of 30–60%. In the field of HVAC, use of aqueous solution of salts as desiccant is sufficient and there is no need to use a strong absorbent like TEG. However, very low water dew point is required in some cases, such as pneumatic systems, gas transmission and LNG plants, where water dew point should be decreased to $-40\ ^{\circ}C$ to $-60\ ^{\circ}C$. It should be noted that the liquid evaporation is usually lower in membrane contactors compared to traditional tray and packed towers because of indirect contact of gas and liquid phases [32].

While tri-ethylene glycol has been used as an absorbent of water vapor in packed beds and tray towers, however it has not been applied as liquid absorbent in hollow fiber membrane contactor for air and gas dehumidification. Therefore in this research, an experimental analysis for air dehumidification has been performed using tri-ethylene glycol as absorbent in hollow fiber membrane contactors. Two membrane contactors with different specifications are utilized in this experimental work. The effects of important variables such as gas and liquid flow rates, TEG concentration and flow direction on the performance of air dehumidification have been studied.

Material and methods

Material and membrane contactors

In this work, tri-ethylene glycol (TEG) was prepared from Jam Petrochemical Co., Iran. The nominal purity was more than 99.5 wt.%. The ambient air was used as a gas sample in this work. Two cylindrical microporous hollow fiber modules were used as membrane contactors for air dehumidification by TEG hygroscopic solution. The membrane contactors (parallel flow) were manufactured by Parsian Pooya Polymer Co., Iran. The properties of the membrane contactors are summarized in Table 1.

Experimental setup

A schematic diagram of the experimental setup for air dehumidification is shown in Fig. 1. The main parts of apparatus are compressor, air humidifier, membrane contactor, peristaltic pump and humidity analyzer. According to the process flow of Fig. 1, an ambient air was entered to the air humidifier by means of air compressor. In air humidifier, the ambient air and water are in direct contact with each other. Humid air that exit from air humidifier was introduced to the shell side of membrane contactor after passing thought air flow meter (LZB-3WB/LZB-4WB, Yutao