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Dehumidification and humidification of air by surface-soaked liquid membrane module with triethylene glycol

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ABSTRACT

A novel liquid membrane system, a surface-soaked liquid membrane, with triethylene glycol (TEG) on the hydrophilic-treated surface of the hydrophobic microporous membrane was developed and used for the dehumidification and humidification of air. The selectivity of the TEG liquid membrane for water vapor with respect to air was over 2000, which was derived from the selective absorption of the TEG liquid. A flat-type liquid membrane module with a dual membrane surface was designed, of which the TEG liquid membrane thickness was 18 μm and the permeation area was 0.13 m^2. The liquid membrane humidifier and dehumidifier consisted of the membrane module and a vacuum pump. As a dehumidifier, the membrane system recovered water vapor at 4.1 g/h from 70%RH room air at 298 K. For use as a humidifier, the air flow was effectively humidified by the permeated water vapor through the membrane module. The effects of the air humidity and sweep air flow rate were studied and discussed. Simple model calculations based on the permeability of the water vapor well predicted the experimental results.

1. Introduction

The dehumidification and humidification of air are basic separation and mixing processes between water vapor and air for industrial and home uses. For the dehumidification of air, mechanical/refrigerative dehumidifiers are the most common types, which condense water vapor in the air by decreasing the air temperature. Unlike this, dry room air is usually humidified by the direct atomization of water. Since the dehumidification and humidification of air are the different processes to separate water vapor from the air, a membrane separation for water vapor with a high-flux will be applicable to both processes. For example, room air can be humidified using a membrane module placed outdoors, which absorbs moisture from the outdoor air and feeds it to the room air.

Membranes for water vapor separation have been developed on a hydrophilic polymer base [1–4]. A polyimide hollow fiber membrane [5] and a fluorinated ion-exchange polymer membrane [6] have been commercially used for membrane air dryers in industrial areas. These polymer membrane modules have not become alternative processes to the conventional dehumidification or humidification methods because of their low flux.

Besides the hydrophilic polymer membranes, a liquid membrane that is non-volatile and hygroscopic could offer a high selectivity and flux for water vapor. In our previous report [7], the permeabilities of the water vapor and air through a triethylene glycol (TEG) or polyethylene glycol liquid membrane of 50–70 μm thickness were measured using a small membrane cell with a 23 cm^3 permeation area. This report has proved that the TEG liquid membrane would be applicable for a membrane dehumidification process.

Following our previous basic research, a membrane module was designed and the performance of dehumidification/humidification was tested using the TEG liquid membrane in this study. A novel liquid membrane system, the surface-soaked liquid membrane, consisting of the TEG liquid was designed. The membrane module with the TEG liquid membrane was used for dehumidification, i.e., water recovery from air, as well as air humidification. The performance of the membrane systems was compared to the model calculations based on the permeability.

2. Experimental

2.1. Liquid for material-TEG

The material for the liquid membrane in this study is triethylene glycol (TEG) that is hygroscopic with a low volatility property. Fig. 1 shows the absorption amount of TEG for water vapor, which was measured in different ambient humidities by a magnetic suspension balance (FMS-S, RUBOTHERM, Germany).

The absorbed amount of water vapor at 60%RH was 0.30 kg-water/kg-TEG. On the other hand, the absorbed amount of air to TEG was estimated to be 0.00008 kg-air/kg-TEG by a process simulator

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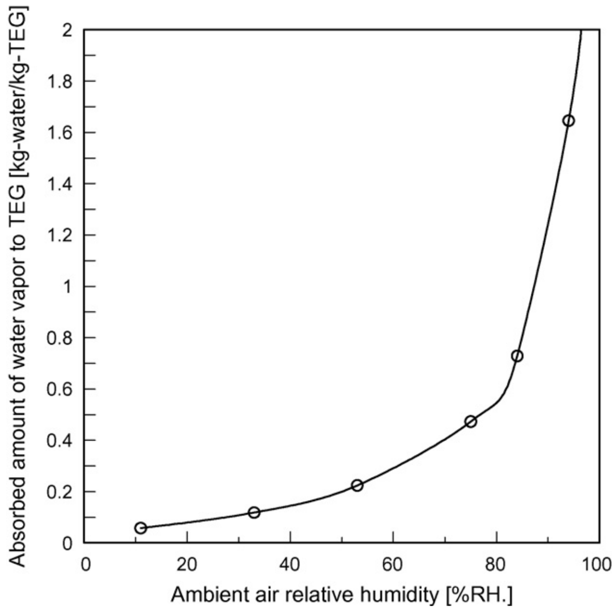

Fig. 1. Absorbed amount of water vapor to triethylene glycol (TEG) in different ambient air relative humidity (temperature: 298 K; pressure: 1 atm).

(ProII, Glycol package, Invensys). The mole-base ratio or selectivity of absorption for water vapor to air is 6000 in air with a 60%RH at 1 atm. On the other hand, diffusivities of water and air through TEG are estimated at 4.9×10^{-10} and 3.3×10^{-10} m^2/s. The selectivity for water to air in the diffusion process is only 1.5.

The permeabilities of water vapor and air, Q_W and Q_{Air}, through the TEG liquid membrane have been reported in our previous study [7] as $2.69–4.03 \times 10^{-12}$ kmol m/(s m^2 kPa) and 1.60×10^{-15} kmol m/(s m^2 kPa), respectively. The ideal separation factor of water vapor with respect to dry air is 1700–2500. This separation factor is in comparable order to the selectivity during absorption. From the view point of a solution–diffusion mechanism for membrane permeation, the solution step controls the permeation or separation of the water vapor from air by the TEG liquid membrane.

2.2. Surface-soaked liquid membrane

To be used for water vapor separation, a thin TEG liquid layer should be supported under a transmembrane pressure condition. In our pervious report, a double-layer type TEG liquid membrane was proposed and tested for the dehumidification of air [7]. A liquid membrane consisting of TEG soaked in a PTFE microporous membrane, 35 μm thick, was supported on a hydrophobic microporous membrane. This double-layer construction of the liquid membrane, however, made it difficult to form a membrane module. As a simple alternative construction of the liquid membrane, a surface-soaked liquid membrane was adapted in this study.

A hydrophobic microporous membrane, a Durapel membrane (Millipore), consisting of 0.1 μm micropores and 95 μm thick was the base material. The wetting tension [8] of the original Durapel membrane is 21 mN/m, which is lower than the surface tension of the TEG liquid (45 mN/m). The hydrophobic surface of the membrane will not be wetted by the hydrophilic TEG liquid [9].

In order to change the membrane surface to hydrophilic, the corona discharge treatment was applied to the top surface of the microporous membrane. With the surface treatment by a wire-type corona discharge machine (AGI-020S, Kasuga Denki, Japan), the wetting tension of the membrane surface increased to 54 mN/m (5 treatments) or 70 mN/m (8 treatments). After this surface treatment, the membrane surface property changed to hydrophilic, while the bottom surface of the same membrane had the original wetting tension of 21 mN/m.

The contact angle of TEG and water on the surface of the surface-treated Durapel membrane is shown in Fig. 2 versus the liquid–vapor surface tension. The contact angle on the PTFE sheet [10] is also shown as the line in the figure. The contact angle of TEG liquid on the hydrophilic-treated surface changed from 118° to 55° or 34°.

When the permeate side is in vacuum by a pump, the TEG liquid spreads on this top hydrophilic surface of the Durapel membrane. The TEG liquid will wet and then soak into the pores of the Durapel membrane, and the stable liquid layer will be formed quickly. The hydrophobic bottom layer will support the top TEG liquid layer due to the hydrophilic–hydrophobic interaction within the microporous membrane. The TEG liquid layer on the surface of the surface-treated Durapel membrane will be durable under a transmembrane pressure up to 2–3 atm. This simple structure of the liquid membrane is called the surface-soaked liquid membrane.

2.3. Membrane module

A flat membrane module for water vapor permeation from the air had the dimensions of 32 cm × 32 cm × 3 mm as shown in Fig. 3.

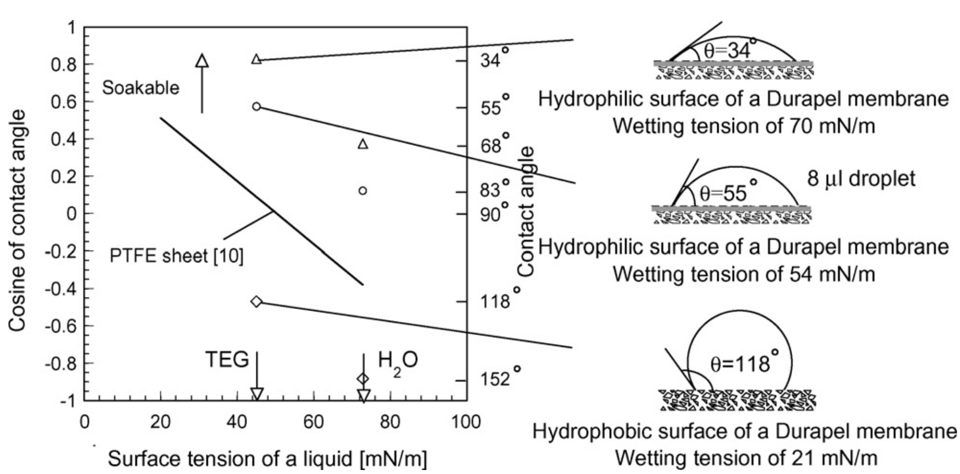

Fig. 2. The wettability of liquids with different surface tension on some solid surfaces (temperature: 293 K).