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# Isothermal dehumidification or gas drying using vacuum sweep dehumidification

Paul Scovazzo[a,*], Anthony J. Scovazzo[b]

[a] *University of Mississippi, Department of Chemical Engineering, 134 Anderson Hall, University, MS 38677, USA*
[b] *AJS Consulting Engineers, 3131 Mount Vernon Avenue, Alexandria, VA 22305, USA*

## HIGHLIGHTS

► Combined gas expansion with a vacuum to isothermally dehumidify gases.
► Achieved dehumidification efficiencies >200% or product dew pts <0 °C.
► Decoupled latent and sensible heats allowing independent humidity control.
► Matched existing system performances but with zero sensible heat ratios.
► High temperature tests mimicked drying applications for recycle dryers.

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## ABSTRACT

This article discusses a novel isothermal system for removing water vapor from gases using water selective membranes. Previous membrane systems for dehumidifying atmospheric pressure gases suffered from low driving forces across the membrane. The approach presented and tested here used a fraction of the dehumidified gas as “a dehumidifying working fluid” that passes through an expansion valve prior to re-entering the membrane unit. The combination of gas expansion and low absolute pressure sweep gas establishes a driving force strong enough to achieve dehumidification efficiencies >200%. The produced gas humidity is significantly reduced compared to the feed gas. It is even possible to produce gases with dew point’s <0 °C. Experiments confirm these results using sweep gas pressures obtainable by rotary water-sealed or single stage reciprocating vacuum pumps. These evaluations encourages further research especially, but not limited to, those applications where the data indicated the technology is competitive with existing systems; such as, building ventilation dehumidification and dryers.

## 1. Introduction

Dehumidification is the process of removing water vapor from gases. It is an energy intensive and widely needed process in manufacturing and building air conditioning. For example, air conditioning represents 50% of a building’s energy use and is critical for the worker productivity, manufacturing quality, and health. Dehumidification is also a component of energy saving recycle (clothes) dryers [1]. In the context of air conditioning, ventilation standards (ANSI/ASHRAE Standard 62.1-2010) produce large dehumidification requirements since ventilation air is the largest source of moisture in a building [2]. Conventional temperature control air conditioning is ineffective for controlling humidity since in off-peak sensible heat hours the sensible heat load is low but moisture load may remain high. The air conditioner’s refrigeration cycle operates for only a short portion of each hour. For the majority of the hour humid ventilation air flows through an inactive coil, flooding the building with excess humidity [2]. This creates the need to separate the treatment of sensible and latent loads by using a dehumidification technology.

Dehumidification technologies in common use are energy intensive and lack precise control. Water phase change is common to these technologies, which change the temperature of the gas while removing the humidity. This may require the application of a second technology to return the gas temperature to the original or another desired temperature. The following are three currently available air dehumidification technologies:

*Cooling coil*: This technology places a cold coil in the gas stream. The temperature of the coil is below the desired wet-bulb temperature of the product gas. Humidity condenses out of the

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[*] Corresponding author. Tel./fax: +1 662 915 7023.
*E-mail addresses:* scovazzo@olemiss.edu (P. Scovazzo), Tony@AJSGreenMEP.com (A.J. Scovazzo).

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**Table 1**
Polymers used for high pressure gas dehumidification along with the dehumidification membrane used in this article, [emim][$BF_4$]. Permeability given as permeability coefficient (1 barrer = $3.348 \times 10^{-16}$ mol/[m Pa s]) or as permeance (2.988 GPU = $1 \times 10^{-9}$ mol/[$m^2$ Pa s]). The permeance listed for [emim][$BF_4$] is for the combined [emim][$BF_4$]/membrane module used in the experimental section; the measurement of this combined permeance appears elsewhere [14].

| Material/membrane | Water permeability (barrer) or permeance (GPU) | Selectivity vs. $N_2$ (air) | Ref. |
|---|---|---|---|
| Polydimethylsiloxane (PDMS) | 40,000 barrer | 140 | [13] |
| Cellulose acetate (CA) | 60,000 barrer | 24,000 | [13] |
| Sulfonated polyethersulfone (SPES) | 15,000 barrer | 210,000 | [13] |
| Polyethylene oxide (PEO–PBT) | 100,000 barrer | 52,000 | [13] |
| Sulfonated poly(ether ether ketone) | 30,000 barrer & 1500 GPU | 300,000 | [13] |
| Poly(vinylalcohol)–EDTMPA | 998 GPU | | [19] |
| [emim][$BF_4$] | 354,000 barrer & 1050 GPU | 16,300 | [14] |

gas onto the cold surface of the coil. The gas stream leaving the coil is at the desired dew point temperature, and the dry-bulb temperature is only slightly above the dew point temperature. The gas must then be heated to the desired dry-bulb temperature. This reheating represents an additional energy penalty required to dehumidify the gas. A conventional Vapor Compression Refrigeration Cycle (VCC) could produce the cold coils and could also supply the reheat energy with the added cost of the fan to overcome the friction of the reheating heat exchanger. When the process requires both sensible and latent heat removal the sensible cooling provided by the VCC is beneficial. However, many situations occur where the process does not require the sensible cooling.

*Desiccant cycle*: This is a three step process. In the first step, the desiccant, exposed to the humid gas, adsorbs the humidity from the gas. This is an exothermal step, so the gas heats up as the water vapor absorbs. In the second step, high grade heat regenerates the desiccant. The third step is to cool the desiccant so that it can be used to process more humid gas. Energy is used in this cycle in both cooling the air after the desiccant step and in the regeneration steps.

*Humidity exchangers*: This is usually a wheel coated with a desiccant, but a few plate type humidity exchangers [3] and several liquid desiccant systems are available to exchange humidity between the process air and a waste air stream. Unlike the desiccant cycle, humidity exchangers do not serve as humidity control because they will not remove all of the required water vapor. It is a pretreatment to humidity control and is effective in reducing the energy cost of humidity control in some climates but not all regions of the world. For example a humidity exchanger can be combined with a VCC to achieve an overall system efficiency greater than the VCC system alone [3]. This system has a fan energy penalty and is also limited to facilities with a clean waste air stream.

## 2. Membrane-based dehumidification background

There are membrane systems for the dehumidification of natural gas [4,5], ethanol, and compressed gas [6]. However, in the context of membrane systems with humid feed gases at standard atmospheric pressures (≈1 bar), the literature and research is limited. Bend Research [7] and Kneifel et al. [8] have designed membrane modules for dehumidifying ambient pressure air that have the proper mass transfer capabilities and minimum treated gas pressure drops. The Bend Research unit was a membrane condenser using cooling water; while, the Kneifel et al. [8] system used an aqueous salt flowing on the permeate side of the membrane to dehumidify via absorption. El-Dessouky et al. [9] did a paper study and simulation of the energy saving of adding a membrane-based dehumidifier prior to sensible heat removal via evaporative cooling in an integration air conditioning system. El-Dessouky et al.'s conclusion was that it could lead to an 86% energy savings compared to using only a conventional VCC cooling coil system.

A number of membrane systems in the literature are variations on the existing technologies discussed in Section 1; namely, cooling coil and absorption. Membrane manifestations of the cooling coil, or "membrane condensers," were used for humidity control in microgravity environments [10] and were proposed for improving the efficiency of condensing dryers [1]. While novel membrane applications, these "membrane condensers" still dehumidify the air by cooling it and give no thermodynamic advantage for dehumidification over standard cooling coil technology. Membrane manifestation of absorption could use aqueous salt solutions; such as LiCl [8]. These membrane systems are variations on the existing desiccant cycle discussed in Section 1. The membrane serves only as a method of contacting the humid air with the desiccant.

Dehumidification is a separation process. The designer of a separation process first asks, "What properties of the mixture's components can be exploited to cause the components to separate?" In using condensation to remove the humidity, conventional designs exploit the difference in phase change temperatures (water vs. air). Adsorption (desiccants) and absorption (aqueous salts) also exploit a phase change from vapor to a solid or liquid matrix. In this context the cooling coil and desiccant cycles use phase change to separate the water vapor from air. Alternatively other properties such as membrane permeability could be exploited in membrane-based separations. The ideal energy cost of separation by phase change (condensation, adsorption, or absorption) is approximately the water's heat-of-vaporization or the "Latent Heat," while the energy cost of a permeability-based separation is only the cost of maintaining a partial pressure difference across the membrane. The US Department of Energy has recognized the low energy cost of membrane separations by including them in road maps for separation research [11].

Using membrane technology it is possible to dehumidify gases by creating a vapor pressure difference across the membrane. This removes water vapor from the gas without changing the temperature of the gas. Unfortunately previous membrane systems for dehumidifying atmospheric pressure gases suffered from low driving forces across the membrane. The approach reported in this article is to use a fraction of the dehumidified gas as "*a dehumidifying working fluid*" that passes through an expansion valve prior to re-entering the membrane unit (patent pending). In this approach, the driving force measured as the effective dew point temperature of the "working fluid" can be below the freezing point of water. For conventional cooling coils to reach dew points below 0 °C, energy intensive defrost cycles are required.

High pressure membrane systems exist for dehumidifying industrial gases [6]. Similar to the process described in our work, some of these units recycle a portion of the produced gas to aid in establishing the driving force for the dehumidification. These industrial systems operate with cross membrane pressure differences >6.5 bar compared to the <1 bar reported below.

Membrane-based gas dehumidification can have technical, energy, and economical advantages over other dehumidification