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Advanced thin zeolite/metal flat sheet membrane for energy efficient air dehumidification and conditioning

Rong Xing, Yuxiang Rao, Ward TeGrotenhuis, Nathan Canfield, Feng Zheng,
David W. Winiarski, Wei Liu *

Energy and Environment Directorate, Pacific Northwest National Laboratory, 902 Battelle Blvd., Richland, WA 99354, USA

HIGHLIGHTS

- Air conditioning consumes a large amount of electricity globally in warm humid climates.
- Efficient membrane dehumidification requires both high permeance and selectivity.
- Thin zeolite/metal sheet membranes are demonstrated for this application first time.
- H_2O permeance of 6.8×10^{-6} mol/(m^2 Pa s) and H_2O/air separation factor of 300 are obtained.
- 50% Energy efficiency enhancement is possible with the membrane separation.

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ABSTRACT

Air conditioning consumes a very large amount of electricity globally. Energy efficiency of the conventional vapor compression cooling is low in warm and humid climates due to water condensation. Membrane separation is viewed as one efficient process for air dehumidification. In this paper, we report the development of a novel thin flat sheet zeolite membrane for the air dehumidification application. The membrane is prepared by deposition of an ultra-thin H_2O-selective zeolite membrane film ($\sim$3 μm) on a thin ($\sim$50 μm) porous metal sheet support. Under separation temperature of 32 °C and feed air relative humidity (RH) of 90%, a quality membrane shows water permeance as high as 6.8×10^{-6} mol m^{-2} Pa^{-1} s^{-1}, which is about 1 to 3 orders of magnitude higher than the previously reported in the literature, and a water vapor/air separation factor over 300. In addition, this zeolite/metal thin-sheet membrane exhibits excellent stability as no apparent decline of separation performances is observed during 8-day continuous testing with humid in-house air. To simulate various climate conditions, the membrane is tested over a range of separation conditions which include temperature, feed air RH, and permeate pressure. It is estimated that 50% or higher energy efficiency gain over the conventional vapor compression system can be obtained when the membrane separation factor is above 200. The results suggest the possibility to develop an on-line, compact membrane dehumidifier for significant enhancement of air conditioning energy efficiency.

1. Introduction

Increasing energy demand in the building sector worldwide and growing concerns of indoor air quality have driven the development of new energy-efficient cooling processes and air conditioners. According to a recent U.S. Department of Energy (DOE) report, buildings consume 40% of the primary energy in the United States. Space air cooling accounts for approximately 12.7% energy consumption and 13% of CO_2 emissions from buildings (US DOE Report DE-FOA-0000289, 2010). Currently, more than 90% of space cooling is provided by the vapor compression system originally optimized for high efficiency in removing building sensible heat loads. In warm and humid climates and with increasing building ventilation, such a system has a high energy cost per unit of sensible heat removed because of water condensation from fresh humid air. Therefore, it is highly desired to develop a novel air conditioning system that can efficiently control building temperature and humidity in warm and humid climates.

There have been several gas/air dehumidification technologies either reported in the literature or being used in various industries, including electro-osmotic dehumidification, sub-cooling below dew point, solid adsorbents (Kanoğlu et al., 2004) (e.g., silica gel, polymers, zeolite), and liquid desiccants (Kessling et al., 1998; Lazzarin et al., 1999; Yin et al., 2007) (e.g., LiCl, $CaCl_2$, ethylene glycol). However, the capital cost and/or energy consumption of these technologies are considered too high, and they have not been widely adopted for

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* Corresponding author. Tel.: +1 509 375 2524; fax: +1 509 372 5997.
E-mail address: Wei.Liu@pnnl.gov (W. Liu).

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buildings yet. For instance, the latent coefficient of performance (COP) in the desiccant cooling system ranges from 0.5 to 1.0 (US DOE Report DE-FOA-0000289, 2010), which is far below the thermodynamic efficiency (Mina et al., 2005). Although further studies on the desiccant materials and designs have been reported to improve cooling efficiency (Kanoğlu et al., 2004; Yin et al., 2007; Xiong et al., 2010), the reported COP is still below a target set by the DOE, i.e., COP ~1.14. This is because the conventional desiccant systems require constant adsorption/regeneration cycling at two different operation temperatures.

Recently, concept of membrane dehumidification for air conditioning/drying has been reported by several research groups (El-Dessouky et al., 2000; Auvil et al., 1993; Liu et al., 2001; Bonne et al., 1990; Wang et al., 1992; Isetti et al., 1997). In this approach, a semi-permeable membrane material is used to selectively remove water vapor from a humid air stream. The water vapor/air separation is driven by a pressure gradient of water vapor between two sides of the membrane under a constant temperature. During the membrane dehumidification, there is no heat source needed, no regeneration involved, and no environmental emission (solid, liquid, or gas) generated. Thus, the membrane dehumidification is a completely green process. Membrane separation is a thermodynamically efficient process, and almost all dehydration (or water management) processes in a living system are conducted via a membrane. It was reported that an indirect/direct evaporative cooling system incorporating membrane dehumidification could gain 86% energy efficiency over the stand-alone mechanical vapor compression (El-Dessouky et al., 2000). These performance attributes are very attractive for the development of simple, efficient and low cost dehumidification devices to reduce energy consumption for cooling of warm and humid air (Pia et al., 2004; Piao et al., 2003; Matsubara, 2010).

In this paper, we report a novel and highly efficient membrane for air dehumidification applications. Fig. 1(a) illustrates the process flow diagram of combined membrane dehumidifier with vapor compression cooling. The paths of air temperature and relative humidity for the three conditions (A), (B) and (C) are tracked on a psychometric chart in Fig. 1b. In this process, an incoming warm and humid air stream (A) is first filtered to remove particulates, and then passes through a membrane dehumidifier where water vapor is continuously removed as the air flows over the membrane. The permeated water vapor and air are compressed by a vacuum pump to above water dew point and discharged as condensed water and saturated air, respectively. In this way, the latent heat is rejected into the environment. The dehumidified air (B) is sent to a mechanical vapor compression

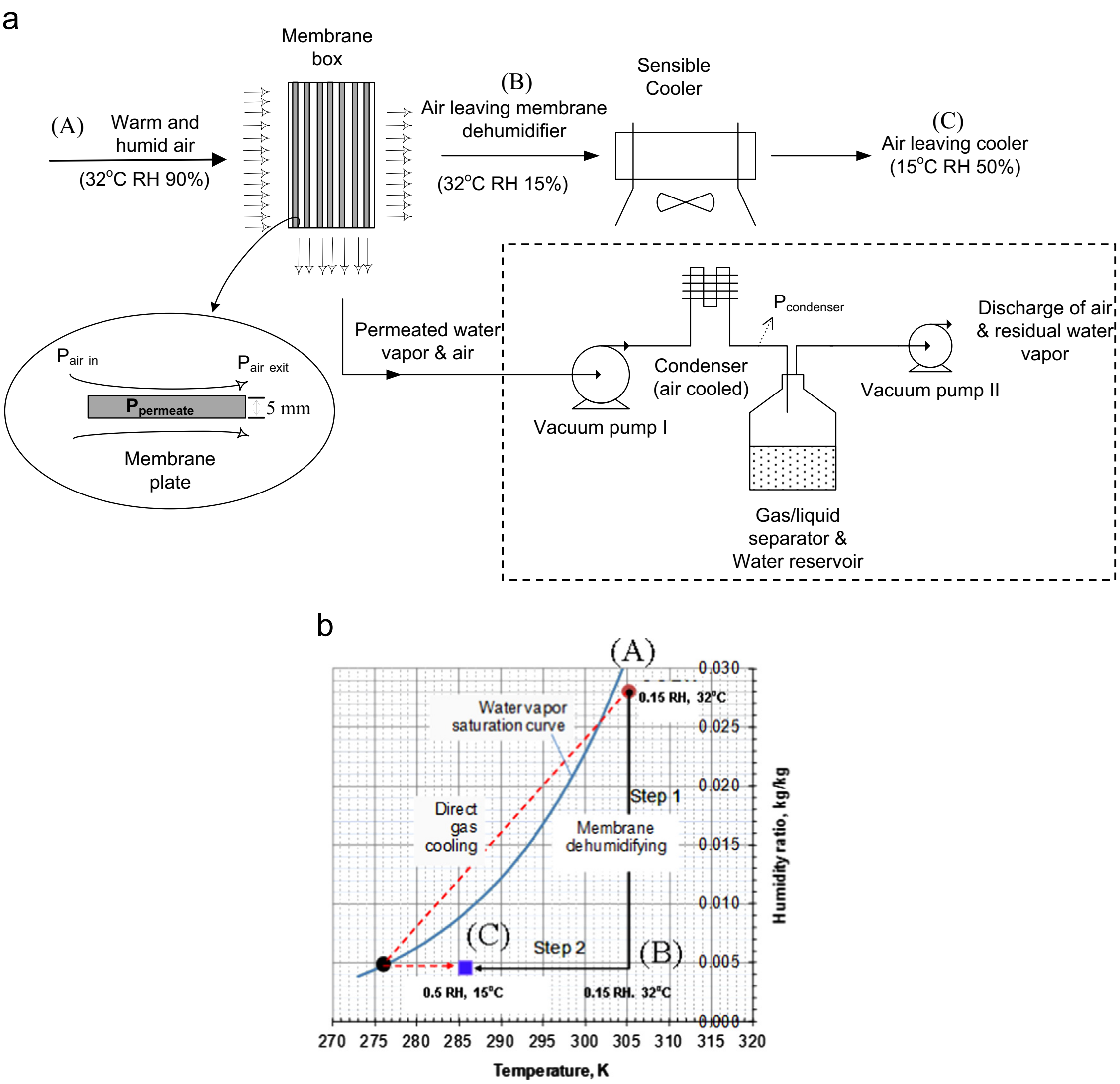

Fig. 1. Schematic and operation conditions of combined membrane dehumidifcation and vapor compression cooling. (a) Process flow diagram, (b) corresponding three conditions of (A), (B) and (C) on the psychometric chart. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)