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On the theoretical and experimental energy efficiency analyses of a vacuum-based dehumidification membrane

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ABSTRACT

Vacuum-based membrane dehumidification (VMD) has attracted much research interest due to its potential in increasing energy efficiency for air conditioning systems. However, there is a lack of reports on practical VMD systems and their performance efficiency. In this work, VMD was systematically studied via both theoretical and experimental analyses. Thermodynamics analysis was carried out to evaluate the energy efficiency of a VMD with varying feed air temperature, humidity, and membrane selectivity. It is shown that coefficient of performance (*COP*) of 2–3 is achievable in a VMD system under the least efficient operation of isentropic compression. A compact VMD prototype with an effective membrane area of 2.45 m^2 was developed based on a thin film composite membrane. Apparent membrane permeance and selectivity as high as 11,900 GPU and 1780, were respectively attained. The thermodynamic analysis is validated with experimental results. Energy efficiency of the membrane's dehumidification process increases with higher temperature and humidity. Vacuum pump's efficiency markedly affects the overall VMD system. A survey of commercial vacuum pumps was subsequently conducted and the practical limit of the current vacuum pump technology was observed. A *COP* value close to the thermodynamic limit is obtainable with a few selected vacuum pumps which possess pumping speeds that are higher than 2000 m^3/h.

1. Introduction

Heating, Ventilation and Air Conditioning (HVAC) has been widely employed to control both supply air temperature and humidity in order to provide indoor thermal comfort as well as sustain a hospitable environment for storing goods and equipment in residential, industrial and commercial buildings. In tropical countries, the total energy consumed by the HVAC system is mainly due to the direct cooling process carried out by vapor compression chillers. Outdoor air is passed over the cooling coils of the Air Handling Unit (AHU) to remove both sensible and latent heats. The cooled and dehumidified air is then reheated or mixed with the return air to raise its temperature to the human thermal comfort level. Because of the air's high humidity, chillers need to work to ensure heat exchangers operate below the air's dew point temperature in order to condense the moisture. Excessive energy consumption during these deep cooling steps makes the present coupled cooling and dehumidification process an inefficient one [1].

It is apparent that decoupling the latent duty from the chiller's duty would significantly improve chiller efficiency where chillers are applied only for the sole purpose of sensible cooling which accounts for only 10–20% of the total cooling load. Thus far, attempts have been conducted to handle the latent load using solids and liquid desiccant dehumidifiers [2–5]. The overall efficiencies of these processes are low because these systems require excessive energy to regenerate the desiccant at high temperature. Additionally, the air can be contaminated with undesired desiccating particles that are potentially entrained in the air stream.

Recently, vacuum-based membrane dehumidification (VMD) has gained significant research attention [6–14]. In this process, the air passes over a membrane surface at normal pressure. A vacuum pressure is applied on the opposite side of the membrane to create a driving force for water to permeate through the membrane. Humid air is dehumidified without any temperature change. The dried air is then cooled down to the thermal comfort level with minimal energy consumption via a conventional vapor compression chiller. This isothermal dehumidification process is considered to be “green” since no heat source is needed for thermal regeneration, resulting in minimal environmental emission [8].

Over the last two decades, there have been many attempts to develop highly permselective membranes for air or gas dehumidification [9,10,14,15]. Many types of polymer [10–14,16–26], inorganic [8,10,27], liquid [6,28–30] and mixed matrix [31,32] membranes have

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been explored. Among them, dense polymeric membranes have received a significant level of attention due to their low cost, lightness, physical robustness and ease of fabrication and modification. Mass transport in dense polymer materials is based on the solution diffusion mechanism [9,10,12,16,33–35]. Water molecules selectively permeate through the membranes due to both its smaller kinetic diameter as well as greater condensability compared to other gases [13]. For low temperature working conditions in ventilation and air conditioning, stable performance of the polymeric membrane can be achieved [9,10,15].

Many of the existing works focus on making and evaluating water permeability and selectivity of new membranes [6–8,10–32,34,36]. Only a few of them evaluate the efficiency of VMD by means of theoretical analysis [7–9,11]. The energy efficiency of a dehumidification process is commonly characterized by its *COP* (dimensionless):

$$COP = \frac{\Delta H_{lt}}{W} \tag{1}$$

where, ΔH_{lt} is latent heat removed and W is work input. It is worth noting that COP is the most suitable term to describe the energy efficiency of VMD because it can have a magnitude that is greater than 1 and is commonly used in the heating, ventilation and air conditioning (HVAC) community. It is apparent that without involving any phase change, VMD potentially has higher *COP* than condensing water vapor by conventional processes. Theoretical input work were estimated from the permeate flow using the isothermal compression work equation [7–9,11]. VMD's *COP* of 2–3.5 has been reported with different membranes and operation conditions [7–9,11]. This energy efficiency is significantly higher than that of dehumidification by desiccants, which have reported *COPs* of less than 1 [4,5,8,37,38].

Hitherto, there are several theoretical energy analysis based on the isothermal compression work equation [7–9,11,39,40], but there is a lack of reports on a practical working vacuum membrane dehumidification system comprising a high performance membrane module and an efficient vacuum pump to realize system performance that approaches the theoretical COP. Thus, the motivation arises for the need to conduct a systematic energy-efficiency study of VMD through thermodynamic and experimental analyses in order to determine the limits of the technology as far as the development of a practical system is concerned. In this work, a fundamental thermodynamic approach is carried out to study and analyse the energy consumption of VMD. Accordingly, the efficiency limit of VMD is determined. A membrane module is developed based on a highly water vapor permeable thin film composite membrane. The membrane module is connected to an appropriate vacuum pump to achieve water vapor dehumidification. The effect of concentration polarization on the performance of the system is evaluated. The experimental *COP* of the system is studied and practical limit of the dry vacuum pump technology is deduced.

2. Thermodynamic analysis

A cross-flow VMD and its pressure profile are shown in Fig. 1(a) and (b), respectively. Humid air is introduced to the feed side of the membrane at ambient pressure, p_{amb}. A vacuum pressure, p_{vac}, is applied on the permeate side of the membrane to create a driving force for water vapor to be selectively sieved out of the air stream, compressed, and discharged to the ambient by a vacuum pump. The water vapor pressure of the feed air stream (p_w^f) is gradually lowered as it passes over the membrane from its input value ($p_{w/in}^f$) to its output value ($p_{w/out}^f$). Lowering p_{vac} leads to more water vapor being removed and hence a drier product air.

Water vapor permeance and selectivity are two important mass transport properties of a membrane. For a membrane with water vapor and air permeances of P_w and P_a, respectively, the membrane's selectivity, *S,* is

$$S = \frac{P_w}{P_a} \tag{2}$$

Assuming that the contents of water and air are constant on both sides of the membrane along a small length increment of *dx* (Fig. 1(b)), the respective water vapor and air fluxes are [39]:

$$\mathrm{dfw} = P\mathrm{w}(p_w^f - p_w^p)\mathrm{dx} \tag{3a}$$

$$\mathrm{dfa} = Pa(p_a^f - p_a^p)\mathrm{dx} \tag{3b}$$

where p_w^f and p_w^p are water vapor partial pressures in feed and permeate streams, respectively, and p_a^f and p_a^p are air partial pressures in feed and permeate streams, respectively. Conducting a simple mass balance, the ratio of water vapor partial pressure to air partial pressure on the permeate side is equal to the ratio of water vapor flux to air flux shown as

$$\frac{p_w^p}{p_a^p} = \frac{df_w}{df_a} = S\frac{p_w^f - p_w^p}{p_a^f - p_a^p} \tag{4}$$

From Eq. (4) and the boundary conditions for water vapor partial pressures at the entrance and exit, a 1D model was developed. Water vapor and air fluxes through the entire membrane are:

$$F_w = \int df_w dx = P_w \int (p_w^f - p_w^p)dx \tag{5a}$$

$$F_a = \int df_a dx = P_a \int (p_a^f - p_a^p)dx \tag{5b}$$

The dehumidification performance in terms of percentage of moisture removed can be computed as:

$$\text{Dehumidification performance} = \frac{P_{w/in}^f - P_{w/out}^f}{P_{w/in}^f}\cdot 100\% \tag{6}$$

The effect of membrane selectivity (*S*) on dehumidification performance as a function of vacuum pressure is shown in Fig. 2(a). At lower

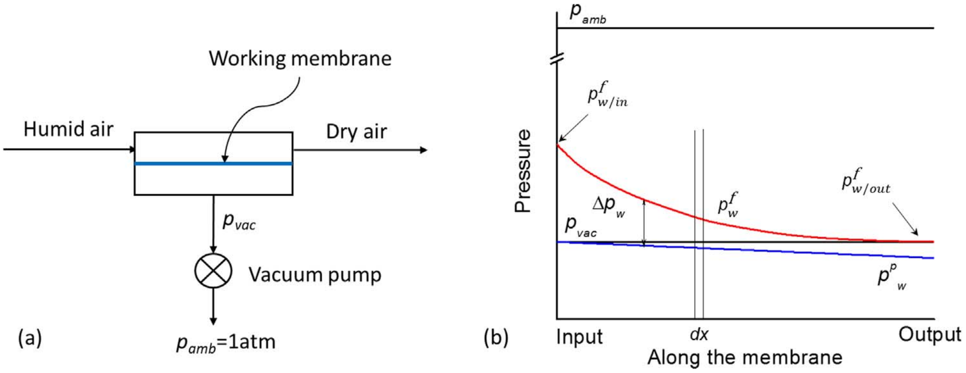

Fig. 1. Schematics of (a) cross-flow VMD; (b) the pressure profile along the membrane.