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A thermodynamic perspective to study energy performance of vacuum-based membrane dehumidification

Duc Thuan Bui [a], M. Kum Ja [a], Jeffrey M. Gordon [b], Kim Choon Ng [a, c], Kian Jon Chua [a, *]

[a] National University of Singapore, Department of Mechanical Engineering, 9 Engineering Drive 1, Singapore, 117576, Singapore
[b] Department of Solar Energy and Environmental Physics, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, 84990, Israel
[c] Water Desalination & Reuse Centre, King Abdullah University of Science & Technology, Thuwal, Saudi Arabia

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In humid environments, decoupling the latent and sensible cooling loads - dehumidifying - can significantly improve chiller efficiency. Here, a basic limit for dehumidification efficiency is established from fundamental thermodynamics. This is followed by the derivation of how this limit is modified when the pragmatic constraint of a finite flux must be accommodated. These limits allow one to identify promising system modifications, and to quantify their impact. The focus is on vacuum-based membrane dehumidification. New high-efficiency configurations are formulated, most notably, by coupling pumping with condensation. More than an order-of-magnitude improvement in efficiency is achievable. It is contingent on water vapor exiting at its saturation pressure rather than at ambient pressure. Sensitivity studies to recovery ratio, temperature, relative humidity and membrane selectivity are also presented.

1. Introduction

Dehumidification can comprise a substantial fraction of cooling loads in hot humid environments. For example, 70–80% of the total energy consumed by a vapor-compression chiller comes from direct cooling at a relative humidity *RH* of 70–95%. Outdoor air (point O) and return air (point R) are mixed in an air-handling unit (Fig. 1). The mixed air (point M) is then passed over the cooling coil, where both sensible and latent heat are removed. To meet the required humidity for thermal comfort, the surface temperature of the cooling coil is set below the dew point temperature of the supply air. Then, the off-coil air is reheated to raise its temperature (*T*) and lower its *RH* (point S). The considerable energy consumption in both the cooling step (when the cooling coil operates at lower surface temperatures) and the reheating step diminishes air-conditioning efficiency [1,2].

This motivates decoupling moisture removal from sensible cooling [1,2]. Efforts to date have been based on solid [3–8] and liquid [4,9–13] desiccant dehumidifiers. These include three-fluid energy exchangers and other novel methods for improving heat and mass transfer [10,12]. The process is illustrated by pathway M → D → S in Fig. 1. The mixed humid air is first passed through the desiccant module, removing the water vapor. But the exothermic sorption between water vapor and desiccant warms the air stream (M → D). The air is then cooled to the desired temperature (D → S) by a conventional vapor compressor chiller. The desiccant is regenerated thermally after each cycle. The Coefficient Of Performance (*COP* - see Eq. (1) below) of desiccant dehumidification is low because of the excessive energy to regenerate the desiccant at high temperature [4,7,8,14].

This study relates to the strategy of Vacuum-based Membrane Dehumidification (VMD) [14–18], illustrated by path M → I → S in Fig. 1. Mixed air is first passed over a membrane surface at ambient pressure. A vacuum pressure is applied to the opposite side of the membrane to create a driving force for water permeation. An advantage of VMD is that air is dehumidified isothermally (M → I). The dried air is cooled to the thermal comfort level with minimal energy consumption (I → S). No thermal regeneration is needed for continuous operation.

Substantial efforts to develop suitable highly permselective polymeric [17–22], inorganic [14,19,23], liquid [24,25] and mixed matrix [26,27] membranes have been explored. However, precisely how membrane permeance and selectivity affect the *COP* of VMD remains to be elucidated, where, for dehumidification [14,15,18]

* Corresponding author.
E-mail address: mpeckje@nus.edu.sg (K.J. Chua).

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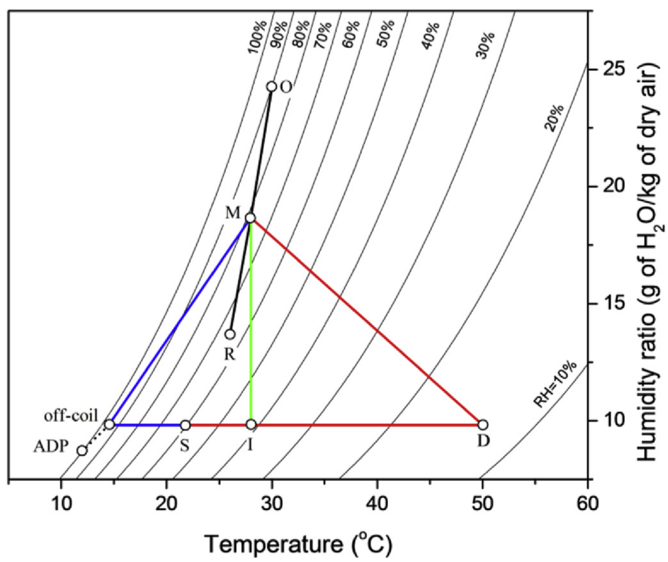

Fig. 1. Psychrometric chart. Air-conditioning processes are indicated, from mixed air (point M, mixing return air at point R and outdoor air at point O) to supply air (point S). With a conventional air-handling unit, the path is M → off-coil → S. Using a desiccant, M → D → S. Using vacuum-based membrane dehumidification, M → I → S.

$$COP = \frac{\text{latent heat removed}}{\text{energy input}} \tag{1}$$

is the principal measure of dehumidification efficiency.

The vacuum pump is a critical part of a VMD system. It creates a continuous driving force for water vapor permeation. It also pumps and discharges permeate vapor from the membrane module to ambient pressure. It is essentially the only source of energy consumption in VMD. The key practical limitation in VMD systems to date has been requiring a pump that can handle large volumes of water vapor at high compression ratio (~100) [16].

Here, a fundamental thermodynamic approach to answer three important questions is developed. (1) What are the energy efficiency bounds of VMD imposed by thermodynamics? (2) How do the key physical variables affect VMD *COP*? (3) How can substantial improvements in VMD *COP* be realized? Our findings are vital for designing an efficient membrane vacuum system for dehumidification and gas separation.

2. Vacuum-based membrane dehumidification

2.1. Thermodynamic analysis of ideal gas separation

The incoming humid air, along with the outgoing dry air and water vapor (Fig. 2), can be treated as ideal gases for the temperatures and pressures of common cooling applications. The minimum work input for the complete separation of water vapor from humid air at constant pressure (p) and temperature is the reversible limit [28]:

$$W = -nRT\,(X_a lnX_a + X_w lnX_w) \tag{2}$$

where n is the total number of moles, R is the gas constant, and X_a and X_w are the mole fractions of dry air and water, respectively. Namely, for input humid air with a moles of dry air and x moles of water vapor, for which $X_a = a/(a+x)$ and $X_w = x/(a+x)$:

$$W(x) = -RT\left[a\ \ln\left(\frac{a}{a+x}\right) + x\ln\left(\frac{x}{a+x}\right)\right]. \tag{3}$$

The impact of distinct separation strategies will now be analyzed. The most efficient dehumidification scheme - an isothermal process at constant atmospheric pressure (1 atm) - is considered first. The separation and condensation processes can be analyzed separately (Fig. 2). Because condensation proceeds at ambient temperature, cooling can be very efficient, representing only a negligible fraction of the total energy consumption.

In a partial separation process, only Δx mol of water vapor are removed. This reduces $W(x)$ by $\Delta W(x)$, which is the minimum work for the reversible separation:

$$W_{min} = \Delta W(x). \tag{4}$$

The latent heat removed (ΔH_{lt}) is proportional to Δx. Hence, the maximum dehumidification *COP* is

$$COP_{max} = \frac{\Delta H_{lt}}{W_{min}} = \frac{(heat\ of\ condensation)\Delta x}{W_{min}} = \frac{45000\left(\frac{J}{mol}\right)\Delta x}{\Delta W(x)} \tag{5}$$

Actual systems operate irreversibly at finite flux. This prompts consideration of how *COP* depends on Recovery Ratio (*RR*):

$$RR = \frac{water\ vapor\ removed}{water\ vapor\ input} = \frac{\Delta x}{x}. \tag{6}$$

Higher *RR* means drier product air, greater flux, and therefore lower *COP*. Fig. 3 (a) plots W_{min} as a function of *RR*. Fig. 3 (b) shows corresponding results for COP_{max}. In the limit of vanishing *RR*, COP_{max} approaches ~5.4 (expanded in Supplementary Information 1 (a), which rigorously accounts for the proper limit when two variables each approach 0 but their quotient approaches a finite non-zero value). In the opposite limit of *RR* approaching 1, COP_{max} approaches ~4.2.

Dehumidification has also been proposed as an alternative to desalination for producing potable water from ambient air. The principal energetic measure is then Specific Energy Consumption *SEC* (typically in kWh/kg), which is proportional to 1/*COP*:

$$SEC = \frac{\text{energy input}}{\text{mass of water removed}} = \frac{heat\ of\ condensation}{COP} = \frac{2500\left(\frac{J}{kg}\right)}{3600\left(\frac{J}{kWh}\right)\cdot COP} \tag{7}$$

where the conversion factor in the denominator of Eq. (7) ensures that the units of *SEC* are kWh/kg.

The minimum energy for water reclamation increases from 0.13 to 0.17 kWh/kg over the full range of *RR* values (Fig. 3 (b) and Supplementary Information 1 (a)). In contrast, the corresponding *SEC* limit for seawater desalination is more than two orders of magnitude lower [29,30]. Vacuum-based membrane systems have also been developed for thermally-driven desalination [31] (in contrast to electrically-driven reverse osmosis).

The latent heat and minimum work for calculating COP_{max} strongly depend on the air's water content. The resulting variation of COP_{max} with input *RH* (as $RR \to 0$ and $RR \to 1$) is shown in Fig. 4.

2.2. Thermodynamic analysis of vacuum-based membrane dehumidification

The isothermal separation of water vapor from air requires membranes with high water vapor permeability and selectivity. A cross-flow membrane dehumidifier is shown in Fig. 5 (a). Its pressure profile is drawn in Fig. 5 (b). Humid air is passed over the