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Membrane processes for heating, ventilation, and air conditioning

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ABSTRACT

This article reviews literature on using membranes in heating, ventilation, and air conditioning (HVAC) applications. Membranes enable the separation of one species from another, and membranes allowing the selective permeation of water vapor can be used to condition air in buildings, potentially more efficiently than conventional HVAC equipment. After a brief background on membrane technology, this review focuses on the following processes: vacuum membrane dehumidification; membrane energy recovery ventilation; liquid desiccant dehumidification; liquid desiccant regeneration; evaporative cooling; and humidification. It highlights the design, modeling, and experimental research on these topics, and suggests areas for further research.

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1. Introduction

The temperature and humidity of the air in buildings needs to be controlled to maintain human comfort, prevent mold growth, and ensure building durability. This requires the addition and removal of sensible and latent energy, meaning that the air in buildings requires heating, cooling, dehumidifying, and humidifying to varying degrees depending on the location of the building and how the building is used. Research in the heating, ventilation, and air conditioning (HVAC) field has improved the methods for conditioning this air, but it is typically done in the same manner as it was decades ago: heating with direct combustion (usually natural gas in the United States), vapor compression heat pumps, or electric resistance heaters; and cooling and dehumidifying with vapor compression air conditioners.

There are some concerns about these current practices; concerns that must be addressed in any sustainable energy future. In the United States, conditioning air accounts for 48% of the primary energy used in buildings [1]. Cooling and dehumidification, mostly from vapor compression systems, accounts for a significant portion of the peak electric demand in hot climates. Regulations are also phasing out refrigerants (CFCs, HCFCs) because they damage the ozone layer or contribute to climate change. Controlling humidity with vapor compression systems is also becoming more difficult as energy improvements often reduce the building's sensible load (e.g., from improved insulation), but do not affect the latent load (e.g., from required ventilation or internal gains) [2].

Researchers are pursuing alternatives to these conventional practices, especially for cooling and dehumidification [3]. Advancements in artificial membranes enable new possibilities in this area. While traditionally used for industrial separations, such as reverse osmosis and gas separation [4–6], membranes provide a means to selectively transfer water vapor from one fluid to another.

The coupling between latent and sensible energy enables a variety of potentially energy-efficient HVAC processes. While the membrane itself does not save energy, it can enable or improve processes that do. Membranes provide a means to remove moisture from the air without cooling the air to the dew-point temperature. This could mean the elimination of environmentally harmful refrigerants from cooling systems. They also make energy recovery processes possible, where moisture is exchanged between two separate airstreams. Membranes can also improve absorptive and evaporative processes, which are used in technologies like absorption chillers, liquid desiccant dehumidifiers, and evaporative coolers; technologies that are energy-efficient, but have yet to reach their market potential.

Over the past 15–20 years, researchers have explored these uses of membranes in HVAC processes. Interest in this area remains high, as illustrated with recent research grants from the US Department of Energy through their Advanced Research Projects Agency focused on Energy (ARPA-E) [7], which funds researchers working on high-risk, innovative energy ideas. In 2010, 16 projects received funding through an HVAC-focused program (Building Energy Efficiency Through Innovative Thermodevices). Membranes were a key focus in six of these 16 projects.

The purpose of this review is to summarize the literature on membrane HVAC processes. It begins with background on membrane technology, which is not meant to be comprehensive, but instead to highlight topics and literature relevant to this article. Then, it describes the HVAC applications, mostly for cooling and dehumidification, and assesses research on designing, modeling, and testing these membrane processes and devices. The review concludes with future research needs and directions.

2. Membrane technology background

A membrane is a selective barrier between two phases and is typically used to separate one species from another. Membranes can be made of many materials, but polymers are most common. Fig. 1 shows a generalized schematic of a membrane process. The *feed* stream is supplied to one side of the membrane, the *permeate* permeates across the membrane, and the *retentate* is retained on the feed side of the membrane. In some cases, a *sweep* stream helps carry away the permeate.

The permeate is transferred across the membrane because of a chemical potential gradient, which can be from gradients in pressure, concentration, temperature, or electric potential. The first two are most important for the processes discussed in this review.

The key function of a membrane is selective separation. Membranes are characterized by their *permeability* and their *selectivity*. The permeability is the amount of a species crossing the membrane, per unit area and per unit driving force. The selectivity is the amount of the more permeable species crossing the membrane relative to others. A higher permeability means less membrane area for a given transfer rate, and a higher selectivity means a purer product stream, which can be either the permeate or the retentate.

For HVAC processes, water vapor is usually the permeate, and thus the membranes need to be permeable to water vapor and selective to water vapor over other species. We can achieve these characteristics with two membrane types: *dense* membranes and *porous* membranes. We can also distinguish membranes by their form: *flat sheet* or *hollow fiber*.

2.1. Membrane type: dense and porous

Membranes are typically separated into dense and porous categories based on their pore structure. Dense membranes have pores on the order of 0.1 nm and porous membranes have pores on the order of 0.1 µm. In dense membranes, water vapor adsorbs onto the polymer and diffuses through the polymer matrix on the molecular level. In porous membranes, the water vapor diffuses through the air/vapor mixture within the pore space. There is some transition region between these two where both mechanisms are important [8]. However, the two can be separated in this review because the pores used in the membrane processes of interest are not near this transition region.

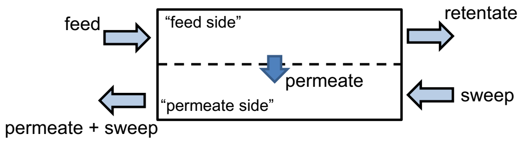

Fig. 1. Generic membrane process. Useful product stream can be retentate or permeate. Sweep is optional.