Air Dehumidification with Vacuum-Driven, Vapor-Selective Membranes for Efficient Separate Latent Cooling

Andrew J. Fix, DOE IBUILD Fellow and PhD Candidate, Purdue University

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Abstract: Cooling and ventilating buildings is estimated to account for 10% of global electricity consumption, and dehumidification for buildings is often inefficient owing to the large heat of condensation and low evaporator temperatures required to cool below the dew point of the air. Thus, separate latent cooling technologies have gained significant interest in recent years to increase the efficiency of building HVAC processes. This presentation covers my work on vacuum membrane dehumidification, including new materials and novel system concepts to achieve potential energy savings up to 50% in buildings with high ventilation rates.

1 | Introduction

- Buildings consume ~40% of all primary energy in the United States
- Greenhouse gas (GHG) emissions from HVAC are expected to grow
- Dehumidification can contribute to more GHG emissions than sensible cooling in many climates (Fig. 2)

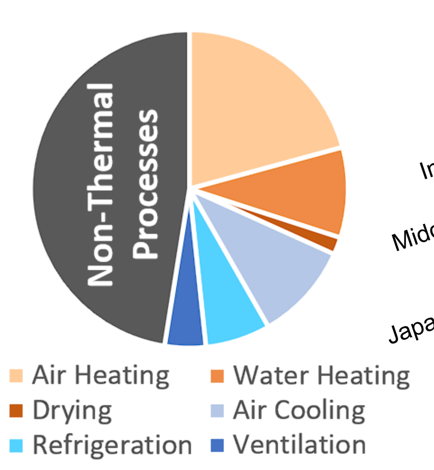

Figure 1. Commercial and residential primary energy consumption breakdown (%) for thermal processes [1].

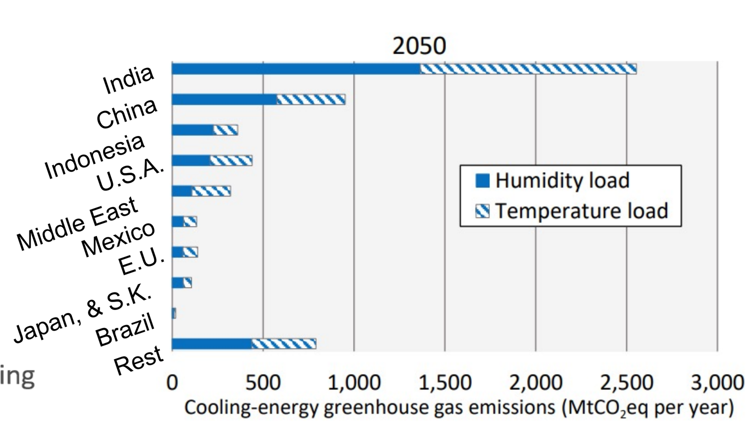

Figure 2. HVAC GHG emissions for sensible and latent cooling in 2050 assuming static emissions intensity and building efficiency. Taken from Woods et al. (2022) [2].

Membrane dehumidification can be a high-efficiency technology for separate latent cooling.

2 | Selective Membrane Materials

- Actively remove water vapor by combining selective membranes with a partial pressure difference

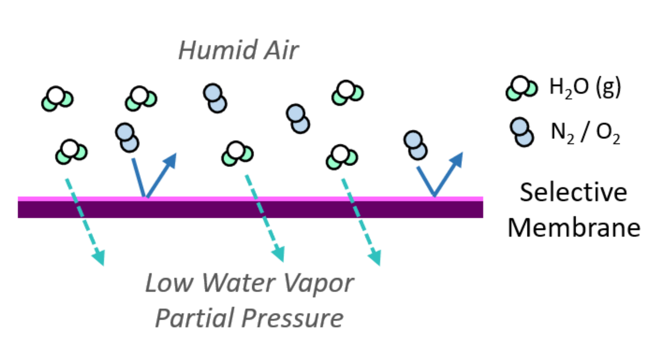

Figure 3. General representation of selective membrane dehumidification showing a thin selective layer coated onto a thicker support layer with air blocking capability.

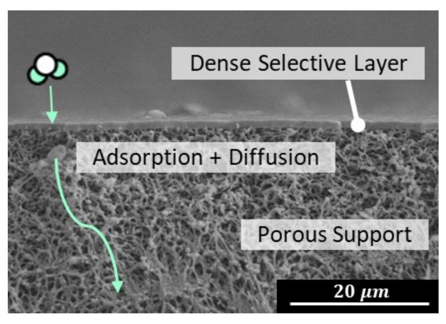

Figure 4. Pebax 1657 + graphene oxide coated on PVDF composite membrane. Taken from Fix et al. (2023) [3].

- Coat a thin hygroscopic layer on a porous substrate
  - Water vapor adsorbs onto the surface
  - Water vapor diffuses through the polymer
  - Water vapor desorbs on the low vapor pressure side
- Best performing selective layer materials
  - Pebax polymer familiar
  - Polyvinyl alcohol (PVA) + triethylene glycol (TEG)
  - Graphene oxide (GO)

3 | Vacuum Membrane Dehumidification and AMX Concept

Vacuum Membrane Dehumidification

- Vacuum pump connected to module
- Pump creates artificial vapor pressure difference across the membrane
- Large pump compression ratio

Dual Module Humidity Pump [4]

- Two modules, compressor between
- Works like a heat pump, but for vapor
- Low compression ratio = lower power consumption than other membrane dehumidification systems

Active Membrane Energy Exchanger [5]

- Combine dual module vacuum dehumidification with sensible cooling
- Process intensification
- Enhances membrane performance
- Improves cooling system coefficient of performance (COP)

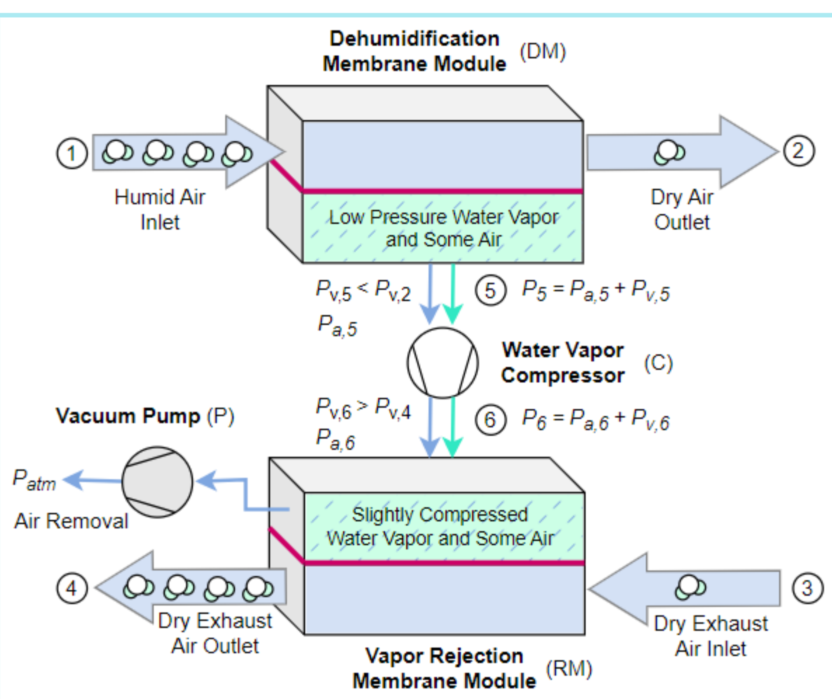

Figure 5. Dual module humidity pump concept, where humidity is removed in the top module, pressurized, and rejected in the bottom module to an exhaust stream. The design enables a low pressure ratio and, thus, lower power consumption.

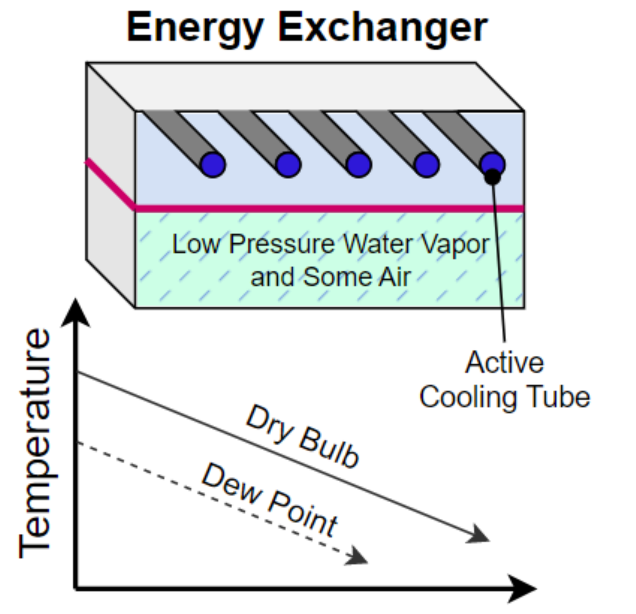

Figure 6. Active membrane energy exchanger (AMX) concept, in which vacuum membrane dehumidification is combined with active heat exchangers for simultaneous cooling and dehumidification [5].

4 | Modeling and Experimental Methods

- System-level models developed in Engineering Equation Solver based on first and second laws
- Key building load information from EnergyPlus
- Computational fluid dynamics simulations in ANSYS and STAR-CCM+ [7]

- Fabricated several membrane materials, including Pebax + GO and PVA + TEG
  - Scanning electron microscopy imaging
  - ASTM permeance tests
  - ISO permeance tests
  - Solubility characterization
- Demonstrated 3 iterations of membrane module prototypes
- Built a complete test bench for steady-state performance analysis

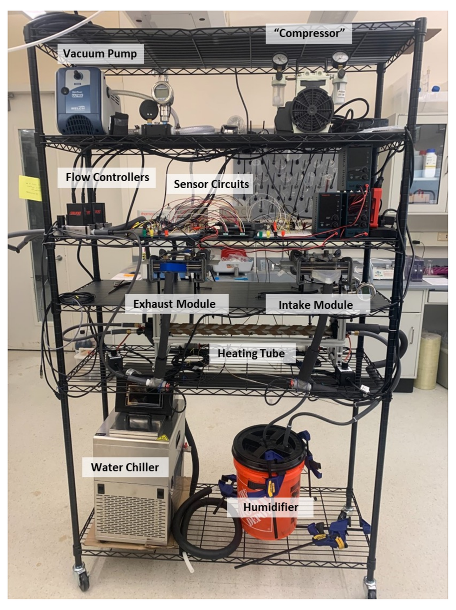

Figure 7. Experimental test bench.

5 | Results

Thermodynamic System Models

- Up to 50% energy savings during extreme conditions and 20% annual savings
- Cooling integration design can increase cooling COP and use waste heat for additional savings
- Greatest potential in humid climates and buildings with high latent loads (e.g., restaurants)

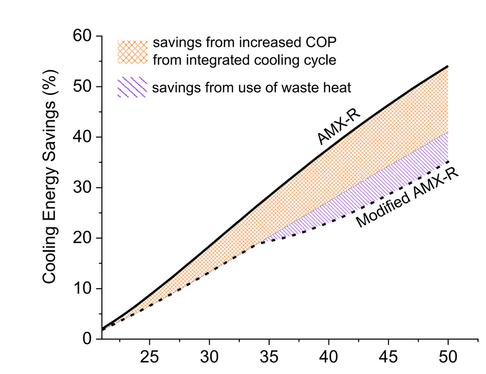

Figure 8. Breakdown of the energy savings benefits of the AMX over the standard dual module and baseline systems for an ambient 50% relative humidity [6].

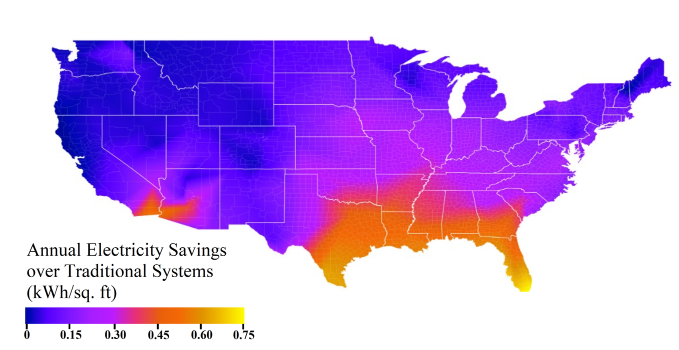

Figure 9. Annual cooling electricity savings map for the AMX-R relative to a VC system developed using EnergyPlus simulations for the "Medium Office" building simulated in 114 cities (up to 20% annual savings) [6].

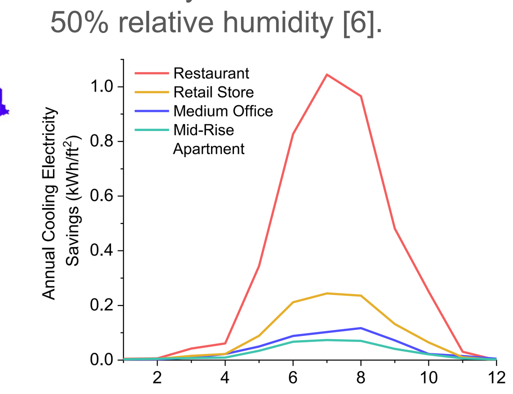

Figure 10. Annual cooling electricity savings for four different building types in Houston, Texas; simulated with EnergyPlus [6].

Materials and Prototype Demonstration

- **Simultaneous cooling benefit:**
  - As temperature ↓, solubility of the polymer layer ↑↑ and diffusivity ↓
  - Net effect = increased permeance at lower air temperatures
  - Simultaneous cooling enables higher membrane permeance while also avoiding condensation
- Latent effectiveness improves at lower flowrates (higher number of transfer units $U_m A_m / \dot{m} c_{P-h}$)

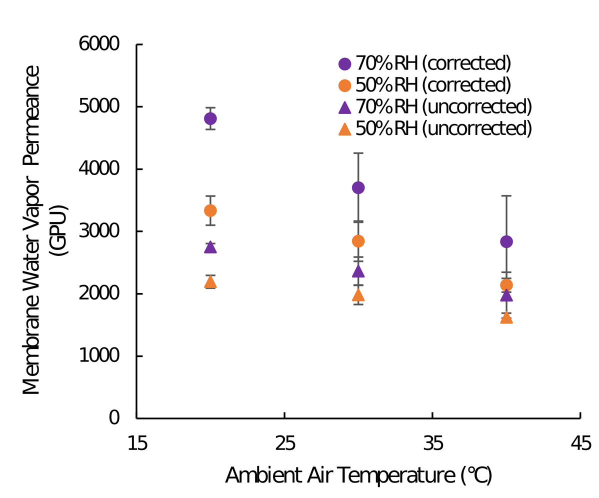

Figure 11. Water vapor permeance for Pebax 1657 + GO membranes as a function of temperature and relative humidity [3].

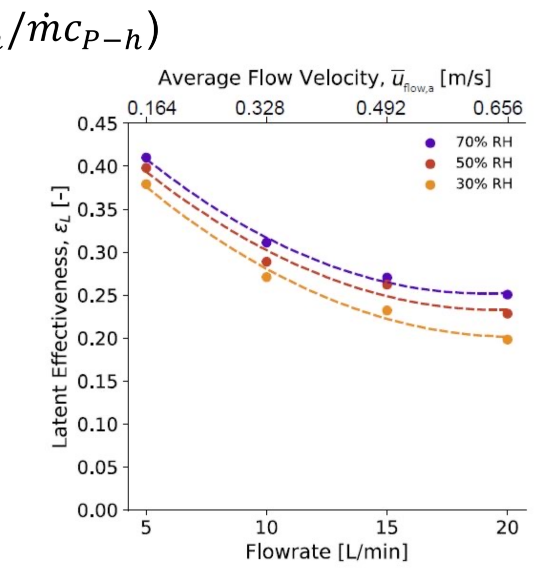

Figure 12. Latent effectiveness of the membrane module dehumidifier as a function of relative humidity and flowrate at 20°C [3].

6 | Conclusions

- Vacuum-driven, vapor-selective membranes are a promising technology for efficient separate latent cooling
- The AMX system can theoretically provide up to 20% annual savings owing to low water vapor compression ratios, improved cooling COP, and waste heat use
- The AMX also enhances membrane performance owing to increased permeance at lower temperatures

References

[1] Department of Energy (2015). *Increasing Efficiency of Building Systems and Technologies. Quadrennial Technology Review*. [2] Woods, J. et al. (2023), *Joule*, *6*(4), 726–741. [3] **Fix, A. J.**, Gupta, S., Braun, J. E., & Warsinger, D. M. (2023). *Energy Conversion and Management*, *276*, 116491. [4] Claridge, D.E. & Culp, C. (2013). Patent No. US 8,500,848 B2. [5] **Fix, A. J.**, Braun, J. E., & Warsinger, D. M. (2021). *Applied Energy*, *295*, 116950. [6] **Fix, A. J.**, Pamintuan, B., Braun, J. E., & Warsinger, D. M. (2022). *Applied Energy*, *312*, 118768. [7] Chandrasekaran, A. S., **Fix, A. J.**, & Warsinger, D. M. (2022). *Membranes*, *12*, 348.

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