High Efficiency Heat Pump Industrial Drying with Water Vapor-Selective Membranes

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Outline

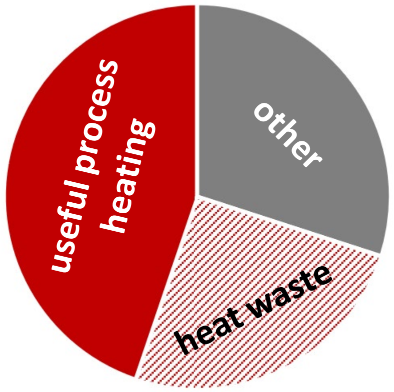
- Background and Motivation
- Modeling Framework
- Results and Discussions
- Future Work

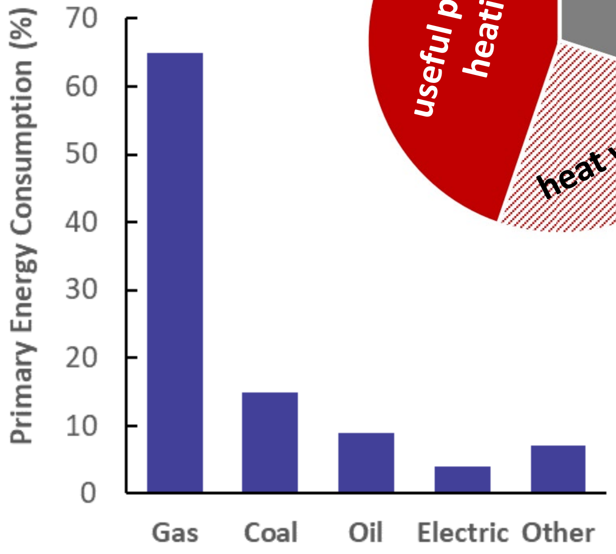
Industrial Drying

- 70% of all process energy = process heating
- Industrial drying consumed 1.78 Quads of energy in 2010 (1.8% of all US energy)
  - Electricity powers a small fraction of drying processes
- Industry accounts for 23% of carbon emissions in the U.S.
- Strong push in the U.S. to electrify processes

Summary of Process Energy Use

(DOE AMO, 2014)





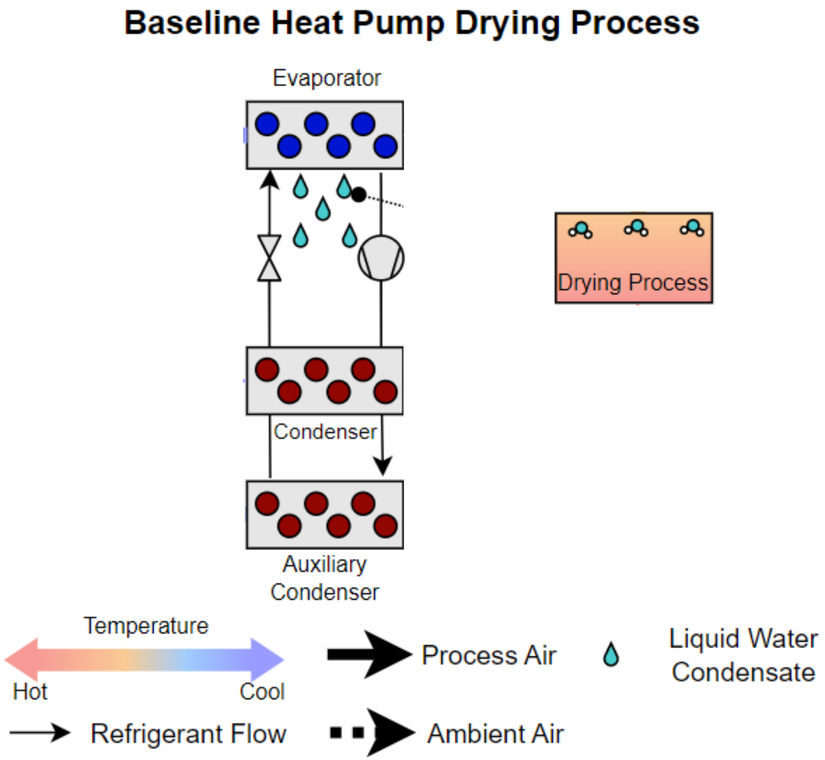
Energy Sources for Industrial Drying

(DOE)

Heat Pumps for Drying

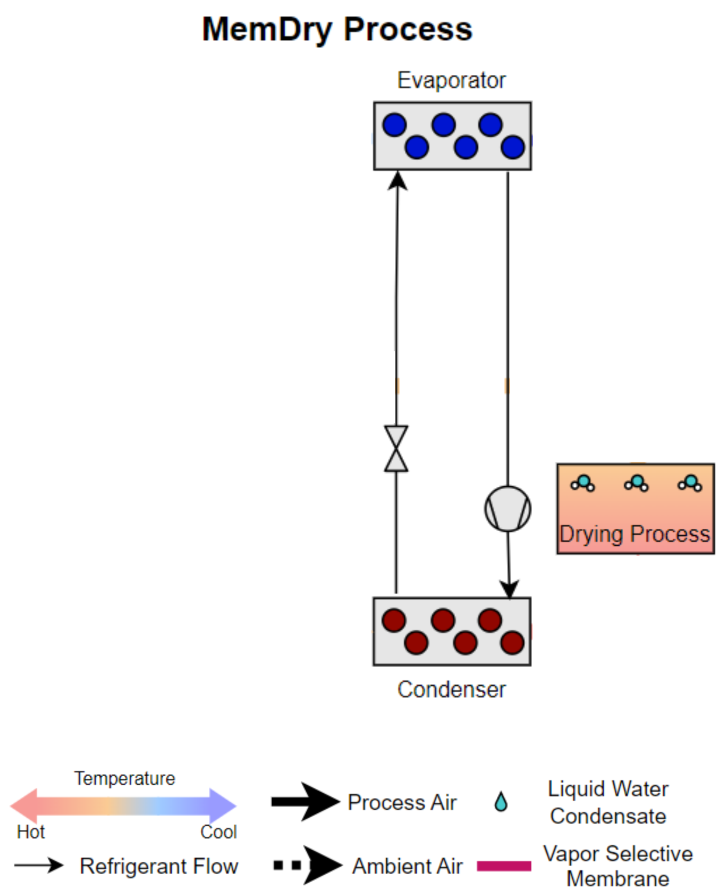
- Heat pump systems for drying:
  - Open systems (constantly feeding in outdoor air to the system)
  - Closed systems (recirculate the air)

- Primary limitations of heat pump dryers:
  - Cannot reach comparable temperatures to combustion heating
  - Condensation dehumidification is energy intense and lowers heat pump COP



Proposed System: MemDry

- Vacuum Membrane Dehumidification
  - Materials selectively allow water vapor transport while blocking air
  - No phase change, lower energy input
  - Isothermal
- Proposed Cycle: **MemDry**
  - High efficiency, dual module humidity pump design for dehumidification
  - Use condensation energy to enable higher evaporator temperature (higher COP)
  - Minimize reheating energy

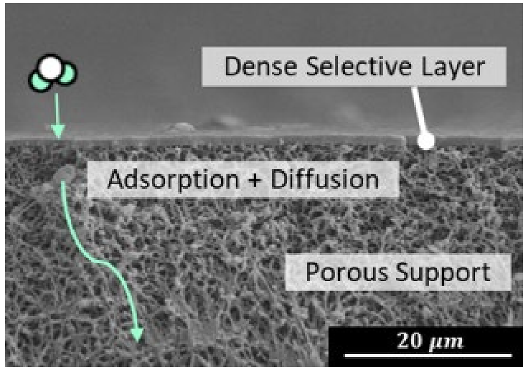


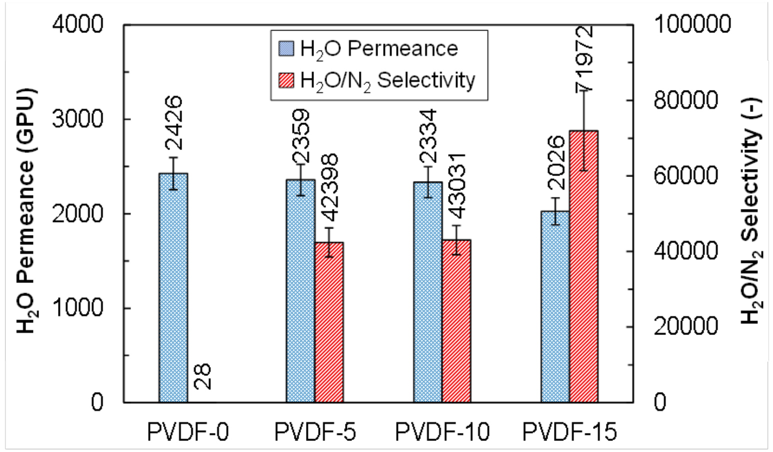
Membrane Materials

- Material properties are not needed for the generalized model presented today
- Coat several layers of Pebax 1657 + GO onto a porous PVDF substrate
- Dense (non-porous), hygroscopic polymer layer blocks air particles
  - Water vapor adsorbs onto surface
  - Diffuses through the polymer
  - Desorbs on the low vapor pressure side

Pebax 1675 and GO Membranes

(Fix et al., 2023) & (Warsinger Lab, ACS Conference)



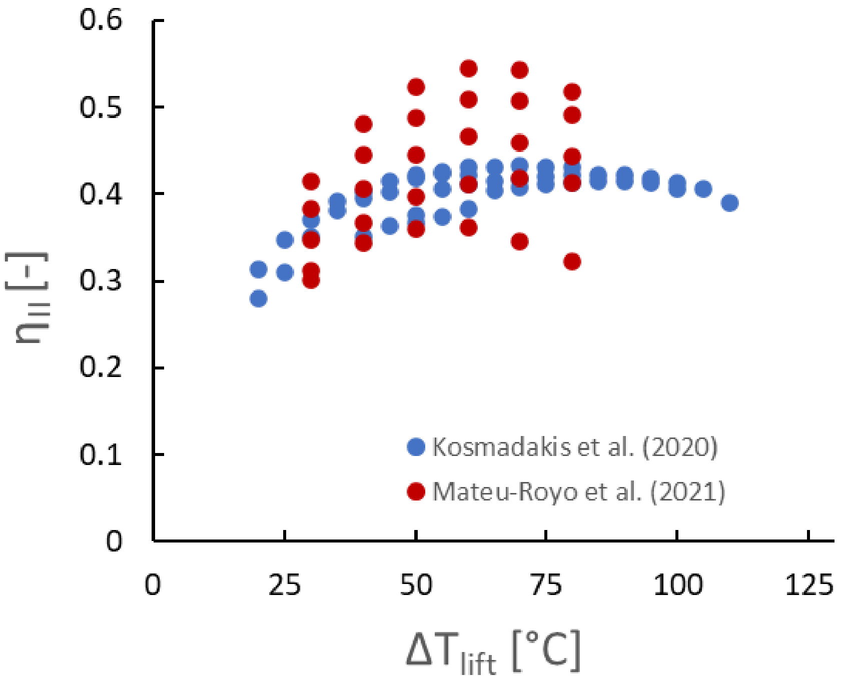


Modeling Framework

Heat Pump Model

- Reviewed high-temperature heat pump cycle models for a range of second law efficiencies, η_{II}
- Average ~0.4
- Applied two cases:
  - Ideal: $COP = \frac{T_H}{T_H - T_C} = \frac{T_H}{\Delta T_{lift}}$
  - Practical: $COP = \eta_{II} \frac{T_H}{T_H - T_C} = \eta_{II} \frac{T_H}{\Delta T_{lift}}$

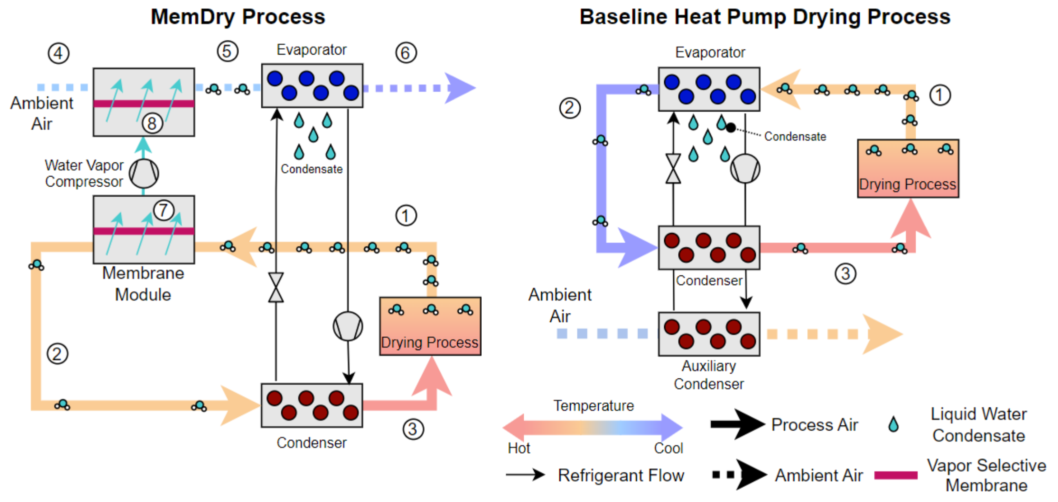
Review of Modeled Second Law Efficiency for High-Temperature Heat Pumps



Modeling Framework

Membrane Model

- No material properties needed – thermodynamic model only
- Assume perfectly selective (no air)
  - Our membranes ~70,000 (very high)
- Set vacuum vapor pressures based on a pinch point difference
  - E.g. $P_{\text{v,vac}} = P_{\text{v,supply}} - \Delta P_{\text{v,pinch}}$
  - Assume membrane module is big enough to accommodate this setup



Variable/Input	Ideal Scenario	Practical Scenario
Pinch vapor pressure difference, $\Delta P_{\text{v,pinch}}$	0 [kPa]	0.5 [kPa]
Compressor isentropic efficiency, η_{WVC}	1 [-]	0.70 [-]
Heat pump second law efficiency, η_{II}	1 [-]	0.40 [-]

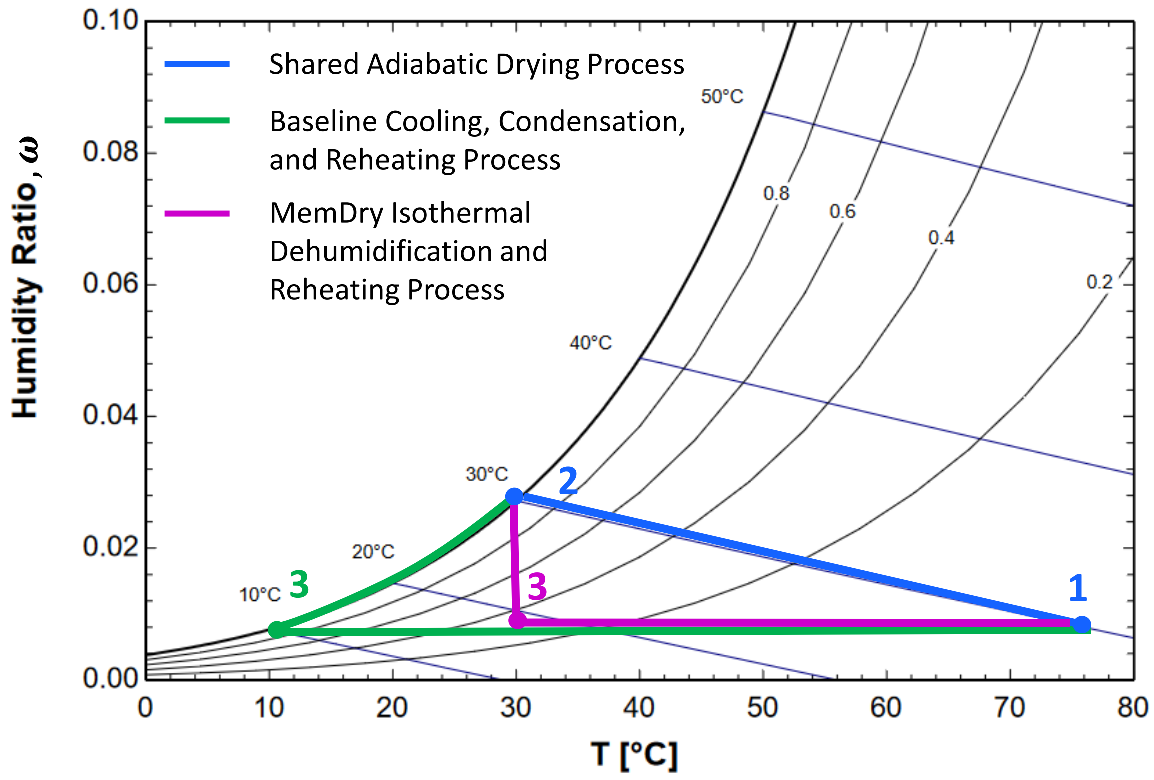
Modeling Framework

Dryer Model

- Ideal dryer
  - Adiabatic drying ($\Delta T \sim \Delta\omega \times h_{fg}$)
  - Outlet air is always saturated

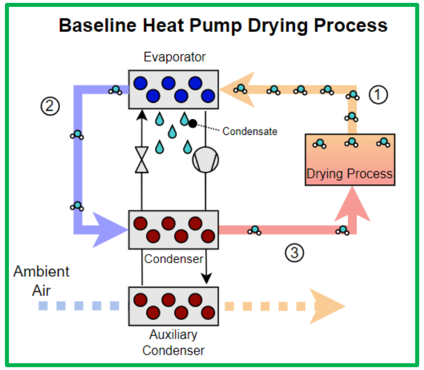
System Comparison

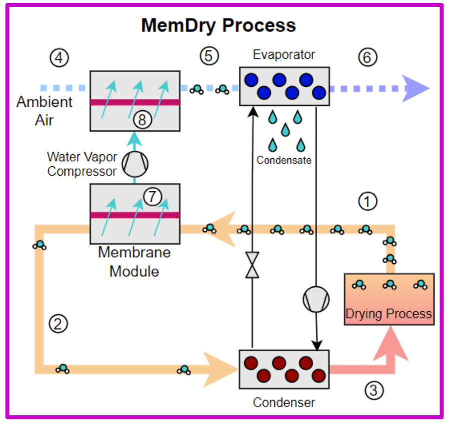
- Supply dew point and dry bulb temperature always equal
- Same condenser temperature



Results: Improving Heat Pump COP

- Why is condensation bad in the baseline but good in the MemDry?

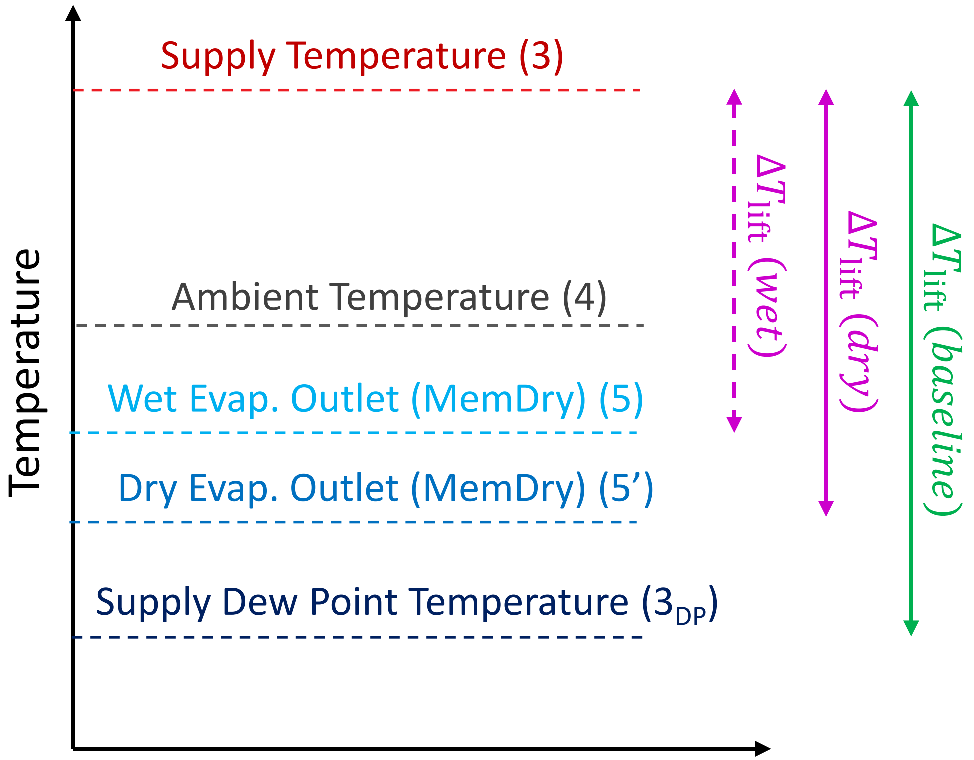




- Dew point temperature is prescribed and constant (evaporator outlet state IS set)
- Q_{evap} (dehumidification) and Q_{cond} (reheating) are both necessary purposes of the system, leading to large lift

$$COP \sim \frac{T_{supply}}{\Delta T_{lift}}$$

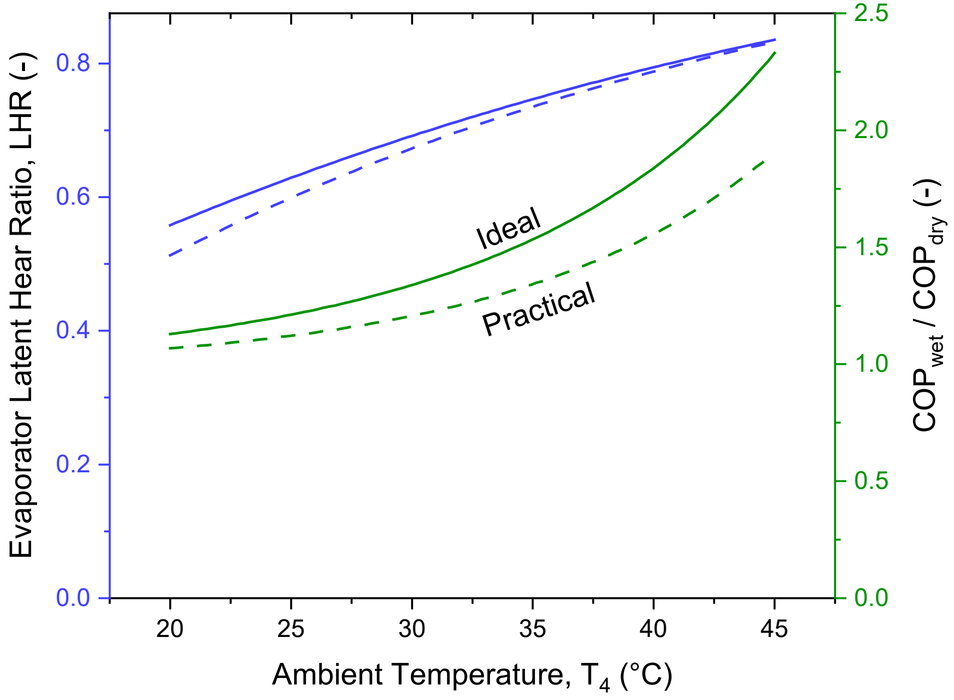
- Q_{cond} (reheating) is the main purpose
- Condensation in the evaporator is not necessary to maintain the drying process
- State 6 IS NOT set - the evaporator load just needs to be met
  - Either from sensible or latent heat



Results: Improving Heat Pump COP

- Can evaluate how adding the humidity before the evaporator improves COP (lower lift)
- COP_{dry} ~ as if the vapor was rejected somewhere else & evaporator relies only on sensible heat transfer
- COP_{wet} ~ the humidity is added to the ambient air before evaporator
- COP improved up to 2x at very hot ambient conditions

COP Improvement with Evaporator Condensation (wet)

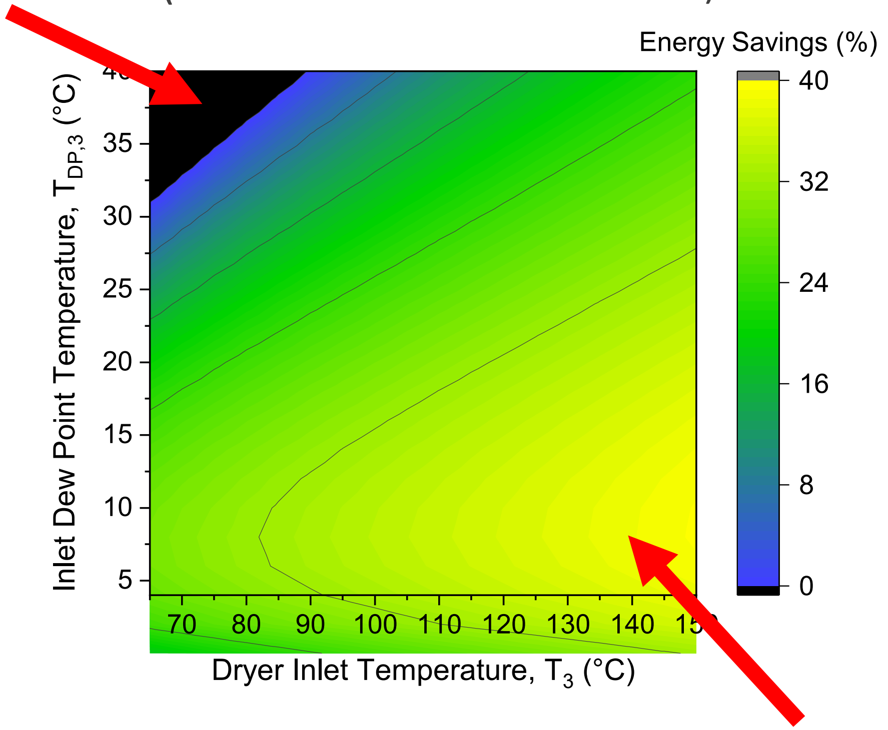


Results: Energy Savings

- Evaluate the energy savings as a function of the drying temperature and inlet humidity (dew point)
- Highest savings are at high temperature and low dew point at the dryer inlet
  - Most conducive regime for drying
- Negative savings at low temperature and high humidity at dryer inlet
  - Not good for drying

Energy Savings vs. Operating Conditions

(Ambient is 30℃ and 40% RH)

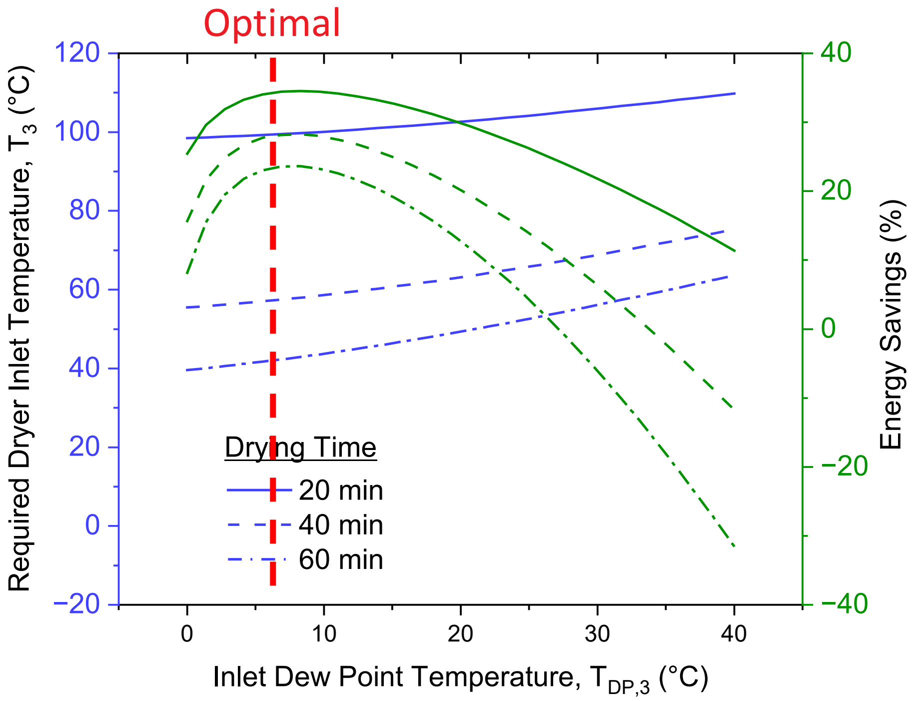


Results: Optimization

- Drying time is a function of inlet temperature and humidity
- MemDry can efficiently reduce the inlet humidity, requiring lower inlet temperature for a fixed dry time
- Optimize the tradeoff between compressor power and heat pump power.
- Reduce required drying temperature to improve feasibility of heat pumps

Energy Savings and Dryer Temperature

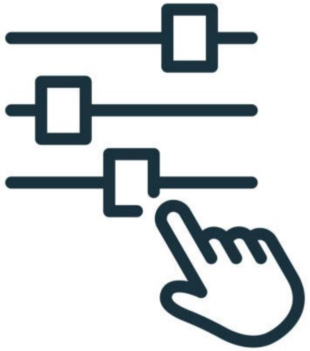
(Ambient is 30℃ and 40% RH)



Conclusions

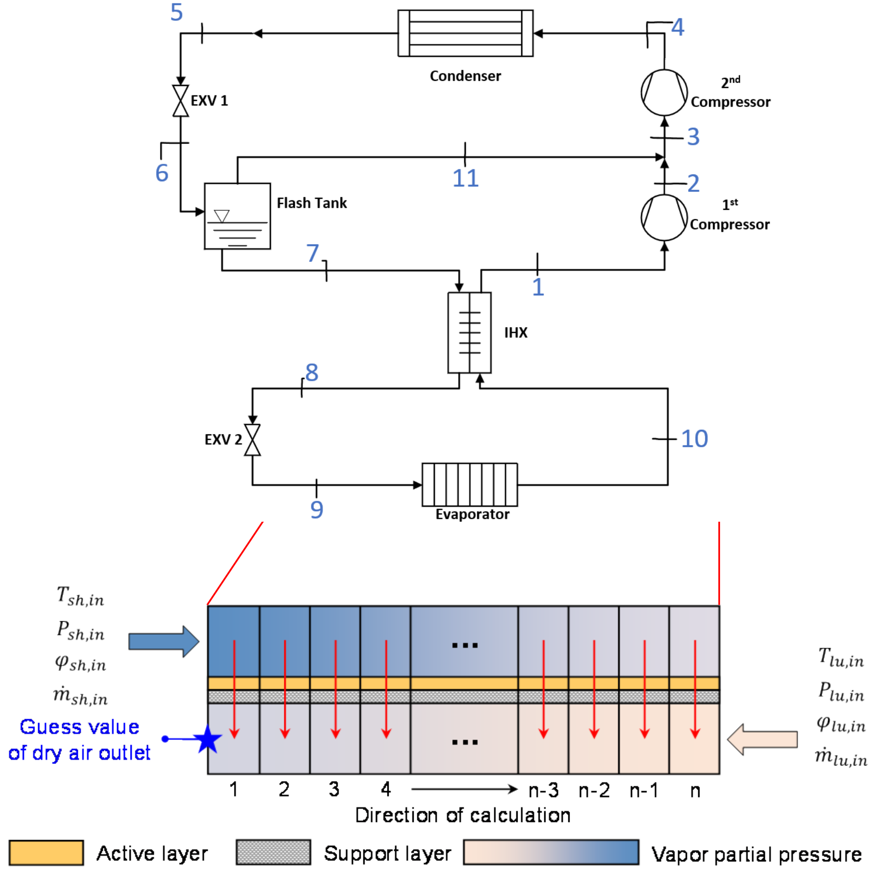
- Through clever system design, heat pump COP can be improved up to 2x by using condensation energy
- Energy savings can reach up to 40% over the baseline system
  - Largely due to avoiding condensation and reheating penalties
  - Also due to improved heat pump COPs
- MemDry provides great flexibility with drying time and drying conditions

COP ↑



Future Work

- This work is funded by DOE
- The current results are introductory and intended to provide high-level understanding of the technology
- We are currently working on:
  - Detailed heat pump modeling
  - Pilot prototype development
  - Discretized, physics-based simulations
  - Advanced materials enhancements



(a) Schematic diagram of hollow fiber membranes

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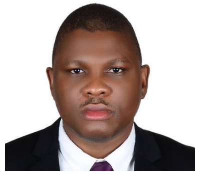

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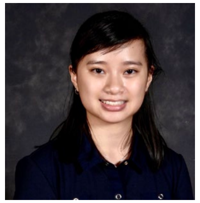

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