Thermally driven industrial ionic liquid absorption heat pump dryer

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Outline/Agenda

- Introduction
- Research
- Experimental Tests/Results
  - Cycle
  - System
- Conclusion

Introduction

- Industrial Drying Processes
  - Processes
    - Cement
    - Paper, Lumber
    - Textiles
    - Food
    - Pharmaceuticals
  - Consumption
    - Wide range of estimates
    - 10 – 20% of Industrial energy in OECD countries (972 – 1944) TWh

Introduction

- Industrial Drying Processes
  - Temperatures
    - Low (<100 °C)
    - Medium (100 °C – 400 °C)
    - High (>400 °C)
  - Technologies
    - 50+ Types
    - Tailored to products/process
  - Quality
    - Product moisture release rate
    - Visual (discoloration, cracks, etc.)
    - Structural
- Clear incentives to reduce energy use
    - User Level – Process Economics (Cost/efficiency)
    - Societal Level – Infrastructure/Carbon footprint

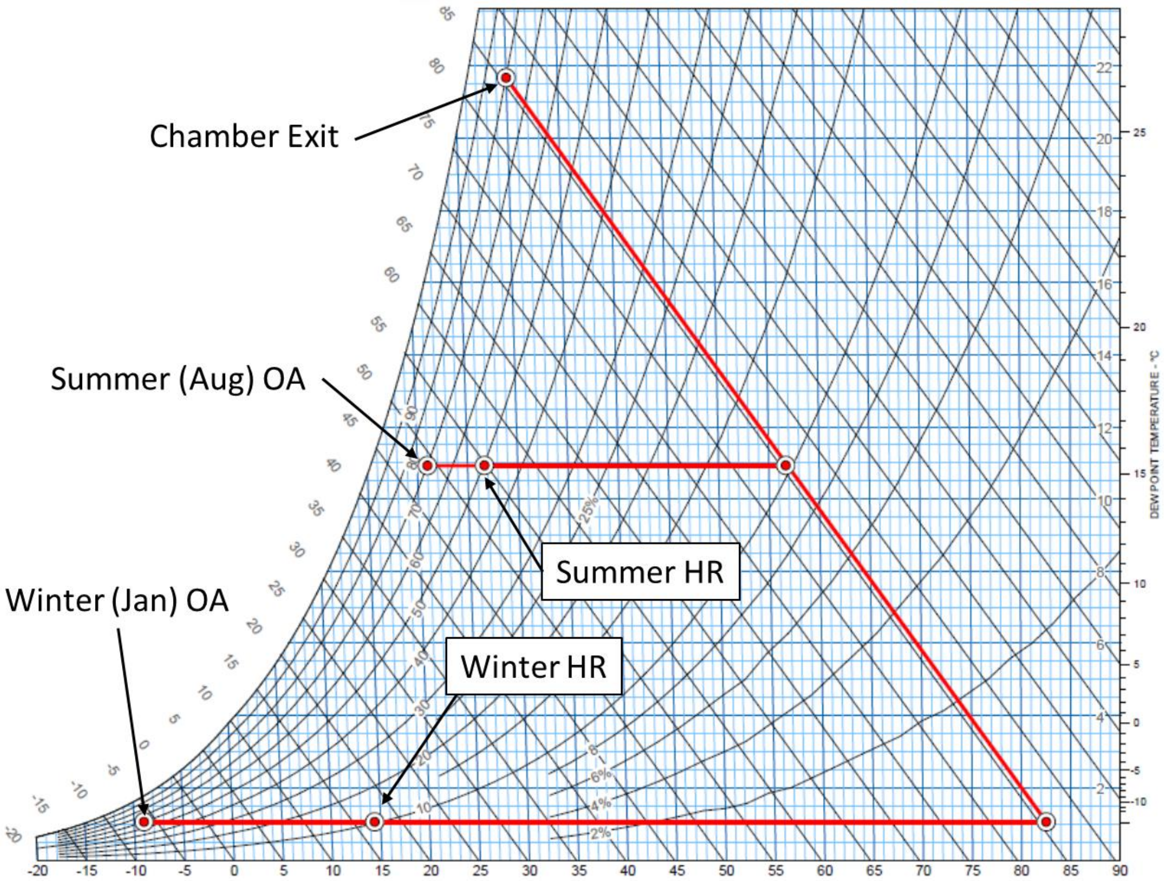
Lumber Drying - Current

- Lumber Drying
  - Low temperature – 43-82 °C (110–180 °F)
  - GHG Emissions
    - ~ 0.48% Global Total (2018)
    - 24.8 MMTCO_2e – US
  - Commercial Technologies
    - Direct Heating Dryers
    - Heat Pump Dryers

Lumber Drying - Current

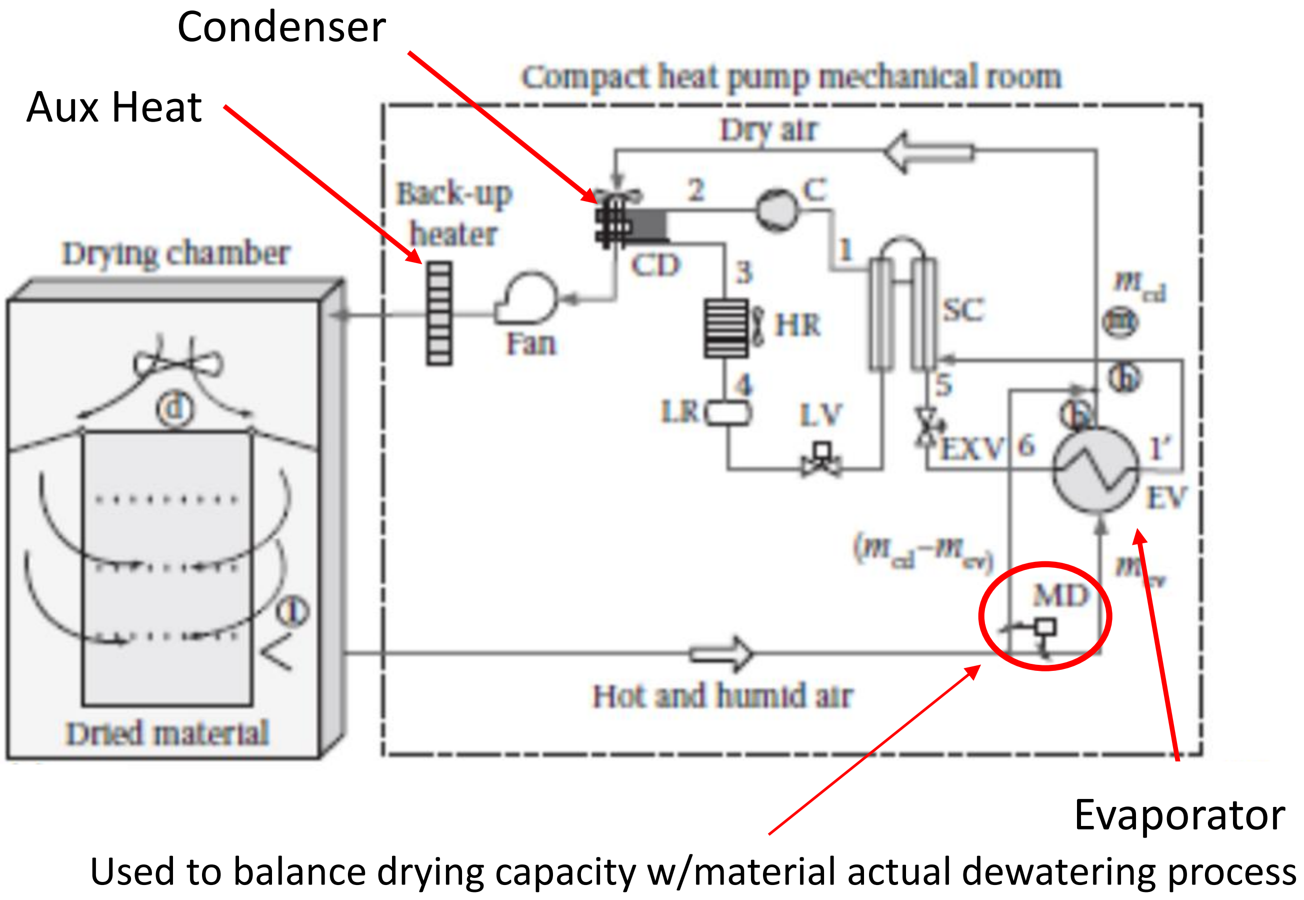
- Direct Heat Kilns ~ 90% (US – 2016)
  - Single Pass
  - Fuels
    - Biomass, NG, other
  - SMER (kg H_2O/kWh) – Wisconsin
    - 0.69 – 0.89
      - Winter/Summer
      - No Heat Recovery
    - 0.92 – 1.06
      - Winter/Summer
      - Heat Recovery

Climate impacts performance



Lumber Drying - Current

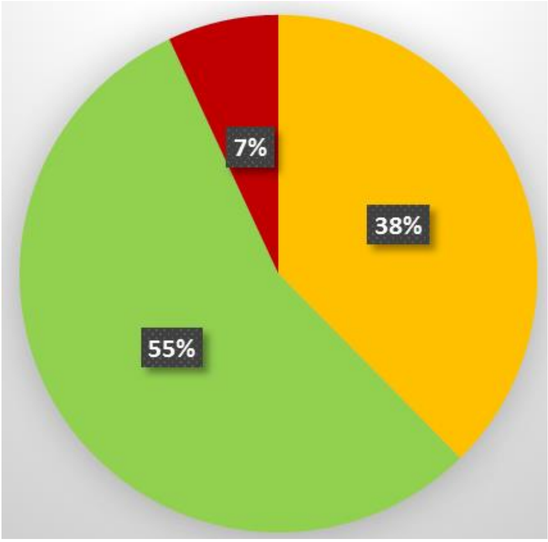
- Heat Pump (HP) Kilns
  - Recirculatory
    - 40 – 60% greater efficiency
    - SMERs up to 1.4
  - Electricity driven
  - Lower Capacity Kilns (< 225,000 bf)
- Moisture Removal
  - Evaporator
  - Saturation Conditions
    - Removed as Liquid
- Reheat
  - Condenser heat recovery
  - Electric Aux Heat (as necessary)



Lumber Drying – Change Barrier

Impact of Biomass on Process Economics

- Free byproduct
- Renewable

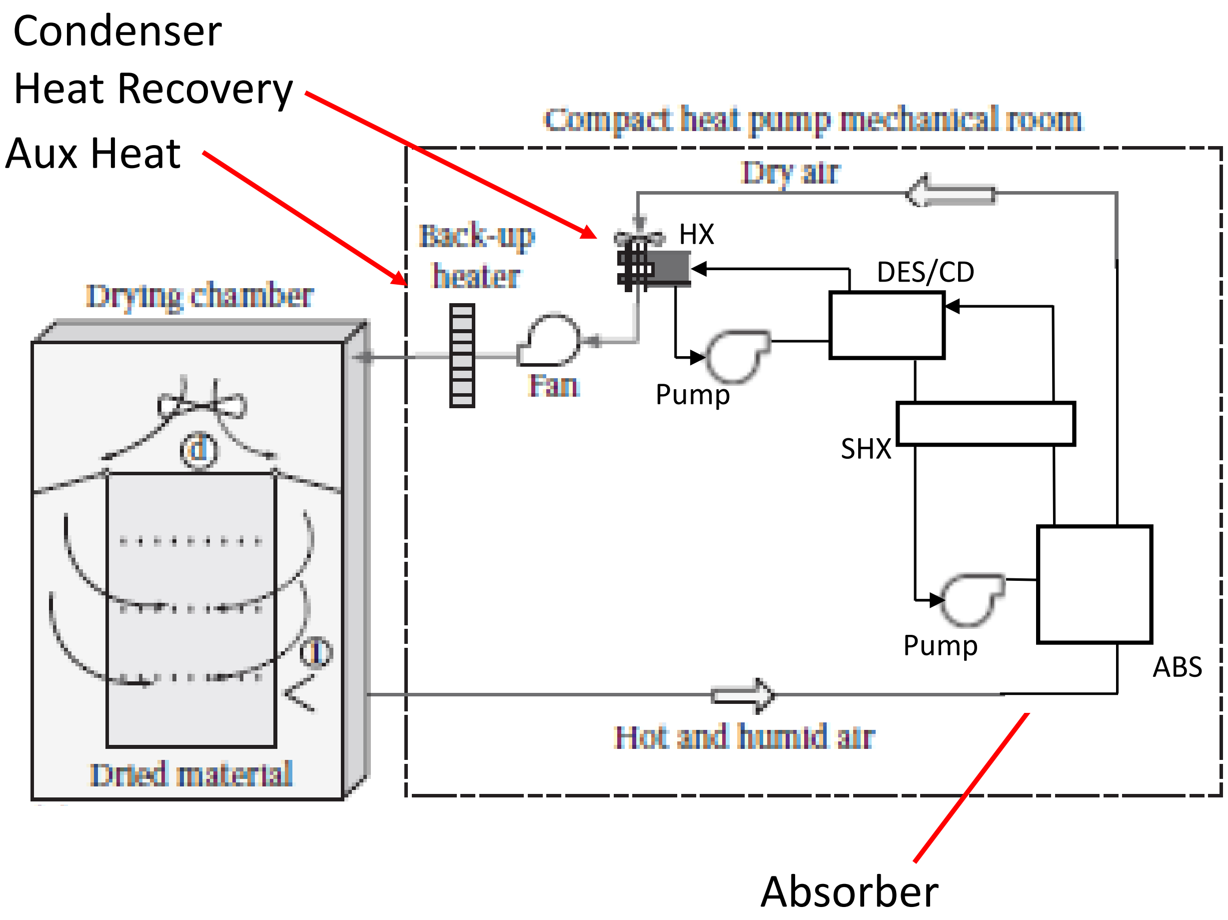


Georgia-Pacific Annual Energy Use by Source (2018)

Introduce HP Efficiencies using Biomass

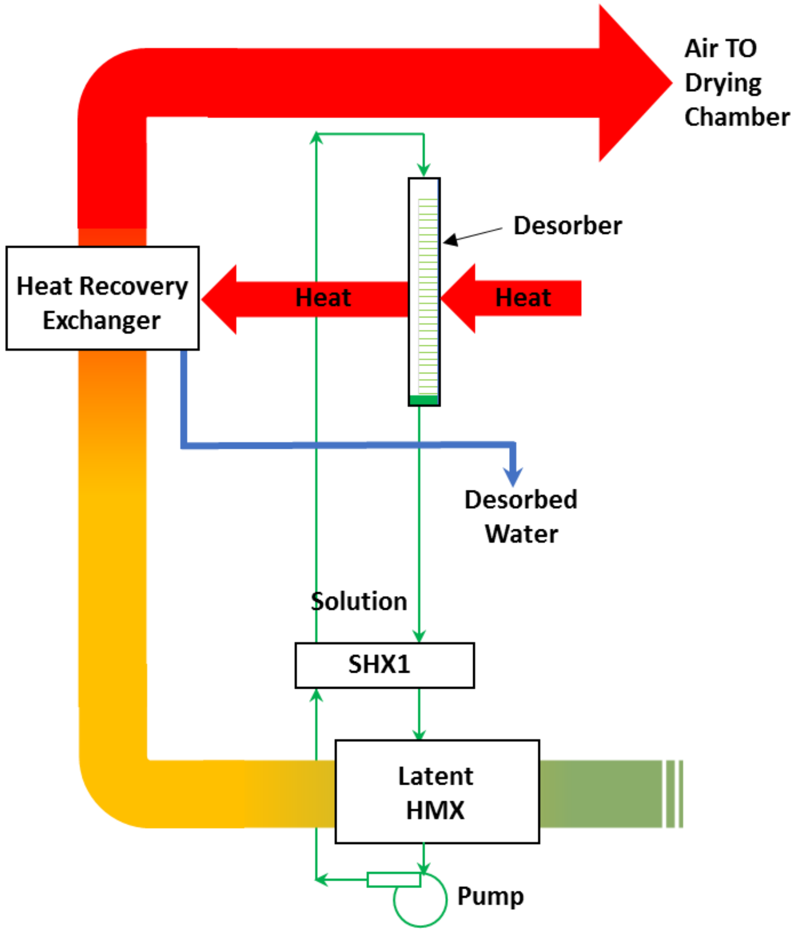
Heat Pump Dryer – Absorption

- Recirculatory Drying (AHPD)
- Heat powered (biomass)
- Moisture Removal
  - Absorber
  - Inlet Conditions
    - Removed as Vapor
- Reheat
  - Air Heated in Absorber
  - Condenser heat recovery (82 °C)
  - Aux Heat (as necessary)



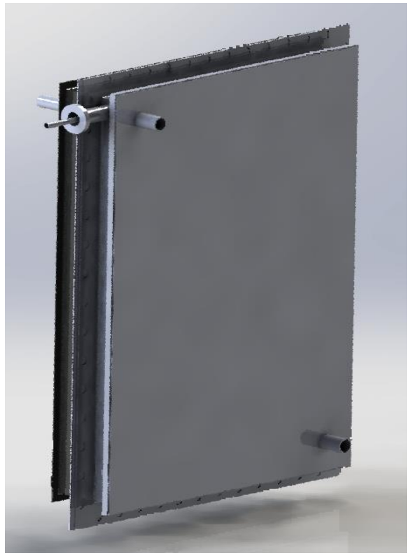
Semi-Open Absorption Cycle

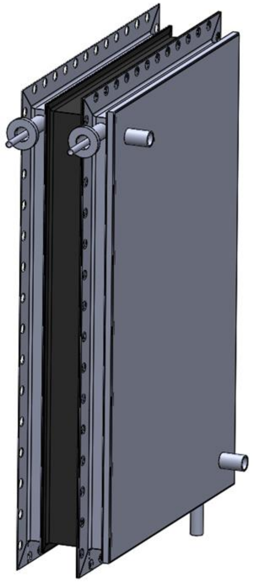
- Semi-Open Cycle
  - Introduced 2017
  - Chugh & Gluesenkamp
  - HPWH
- Characteristics
  - Single- or double-effect
  - Ionic liquid desiccant
  - Heat driven
  - Open Absorber
    - Inter-cooled
    - Adiabatic



Semi-Open Absorption AHPD

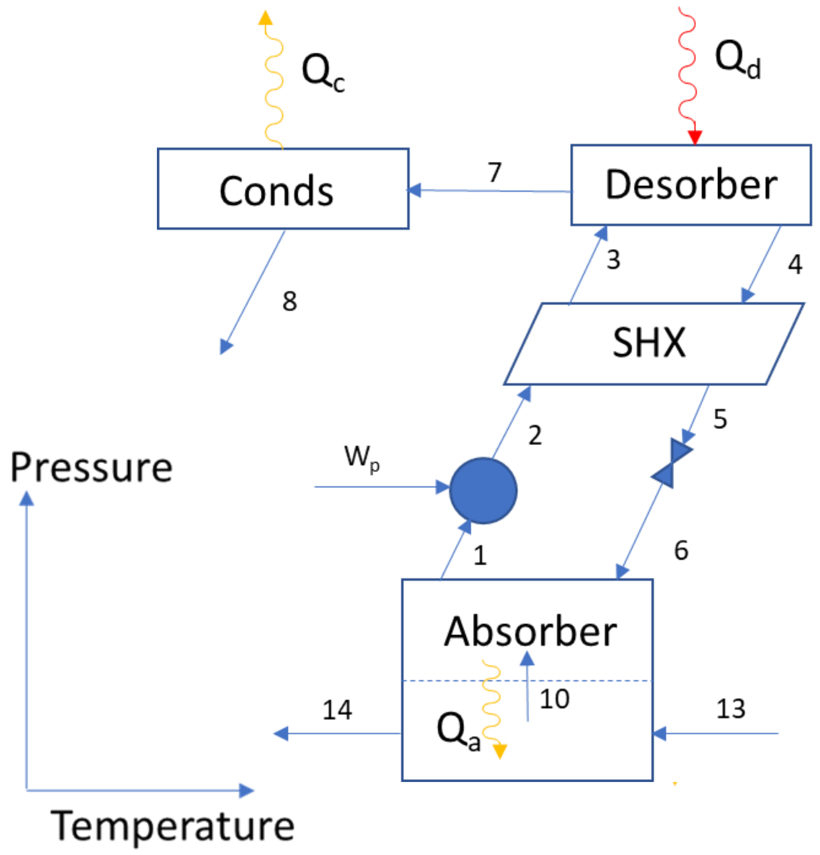
- Desorber/Condenser
  - Single effect
  - Double effect
  - Stainless Steel
  - Scalable
    - Plate & Frame Architecture
- Absorber
  - Adiabatic
  - Polymer
  - Scalable
    - Plate & Frame Architecture





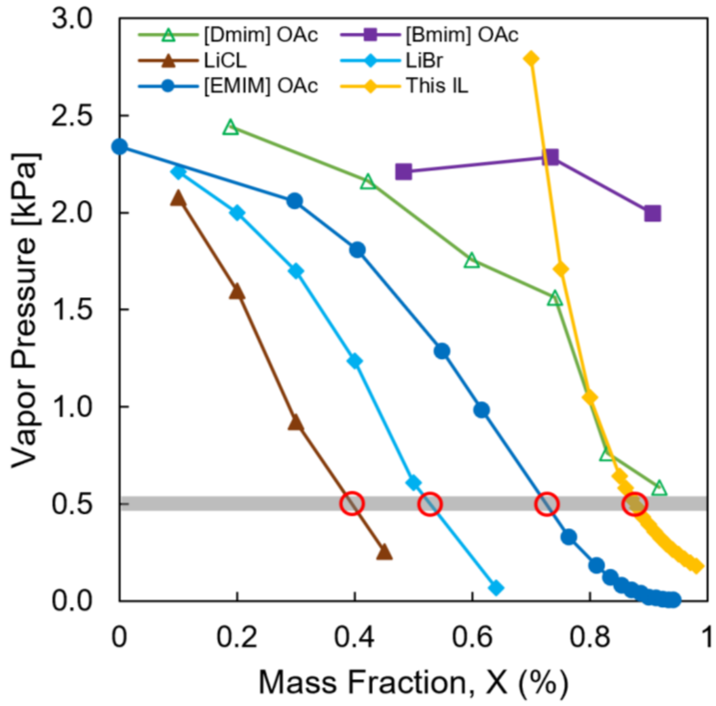
Theoretical Model

- Model
  - Energy (1st Law)
  - Mass
  - Fluid Properties
    - Air – EES Property Routines
    - Ionic Liquid – Experimental
  - Absorber Properties
    - Heat and mass transfer resistances
    - Experimentally derived
  - Single & double effect
- EES Software



Theoretical Model – Ionic Liquids

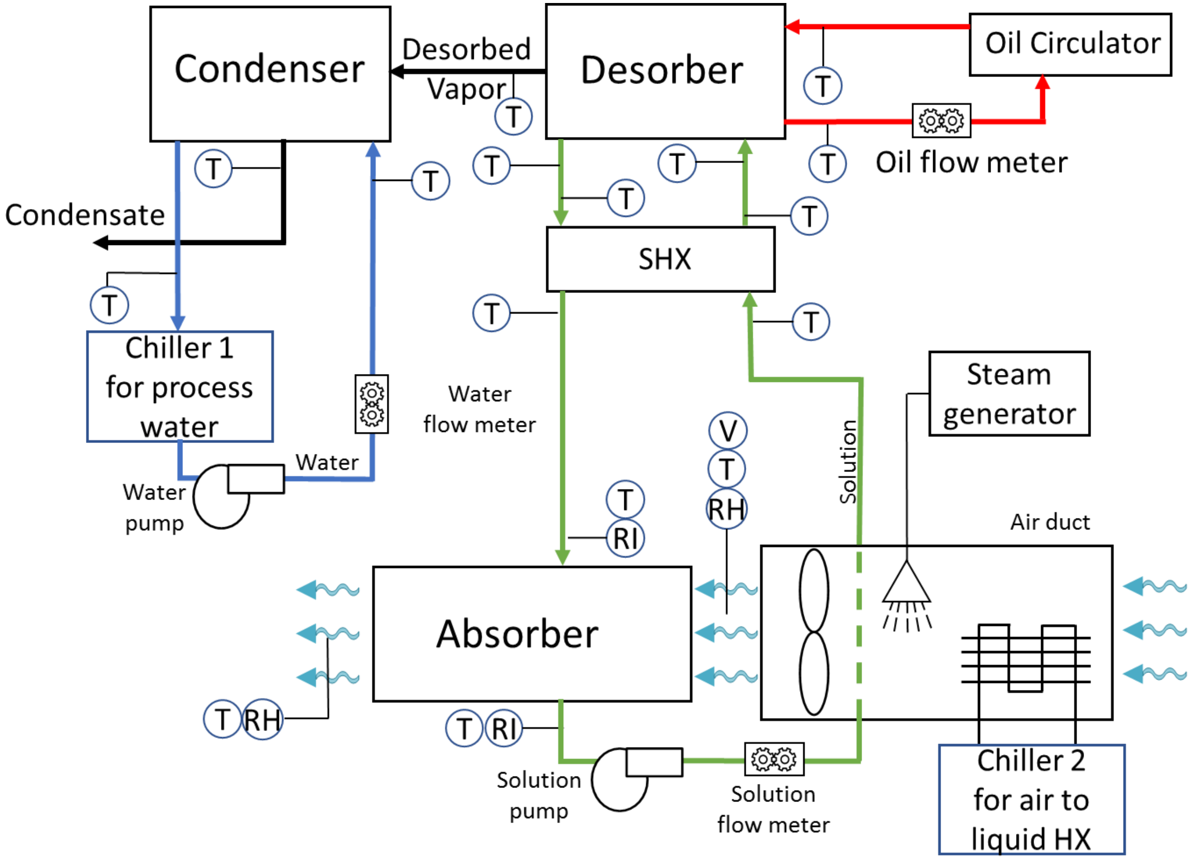
- Ionic Liquids
  - Non-crystalizing
    - Minimize control requirements
    - Increased operating envelope
  - Environmentally safe
  - < $50/kg in quantity
- Data
  - Not available (typically)
    - Vapor Pressure
    - Thermal capacity
    - Viscosity
    - Density



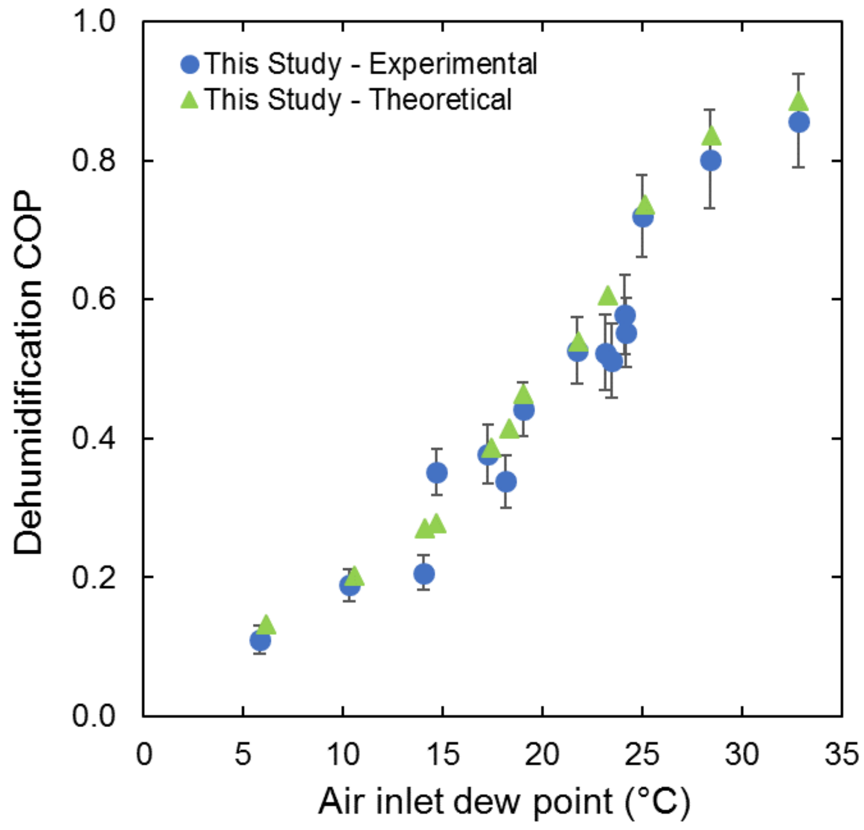
Desiccant	Viscosity (Pa-s)	Stability Limit (°C)
LiCl (20 °C, 40%)	0.0096	NA
LiBr (20°C, 53%)	0.0051	NA
[EMIM]OAc (20°C, 73%)	0.0233	~100
This IL (20°C, 87%)	0.0283	~150

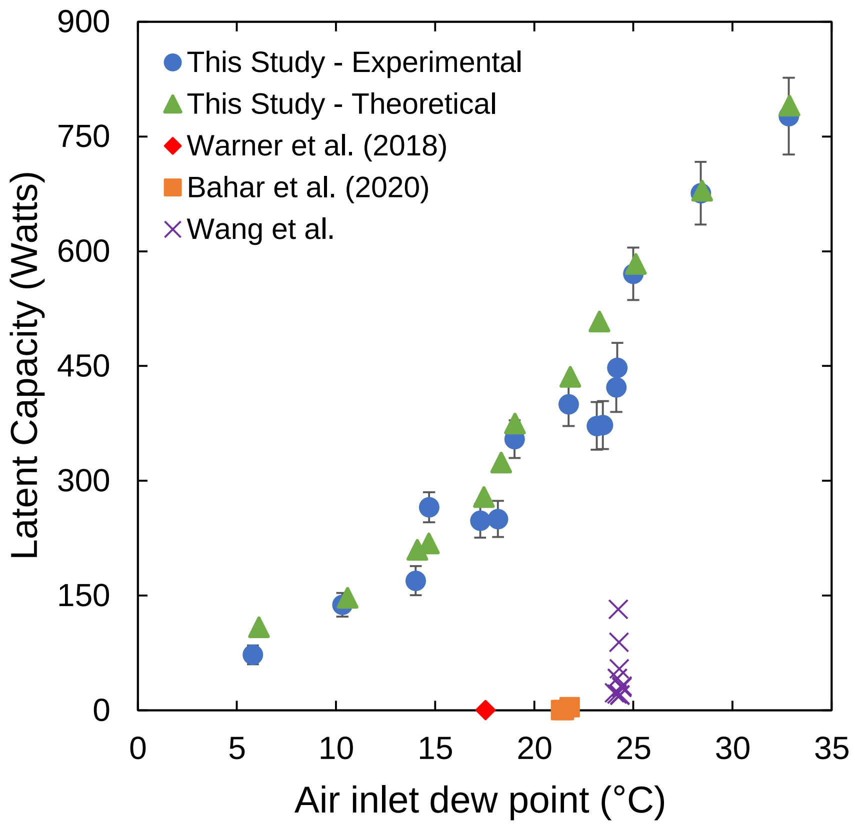
Theoretical Model - Validation

- Test System
  - Single-effect
  - ~ 1kW capacity
- Test Parameter (Consistent)
  - Solution flowrate (0.3 lpm)
  - Airflow rate (155 cfm)
  - Oil flow rate (2.85 lpm)
  - Oil inlet temp (148 °C)
- Inlet Conditions
  - T_{dp} ~ 5 – 32 °C



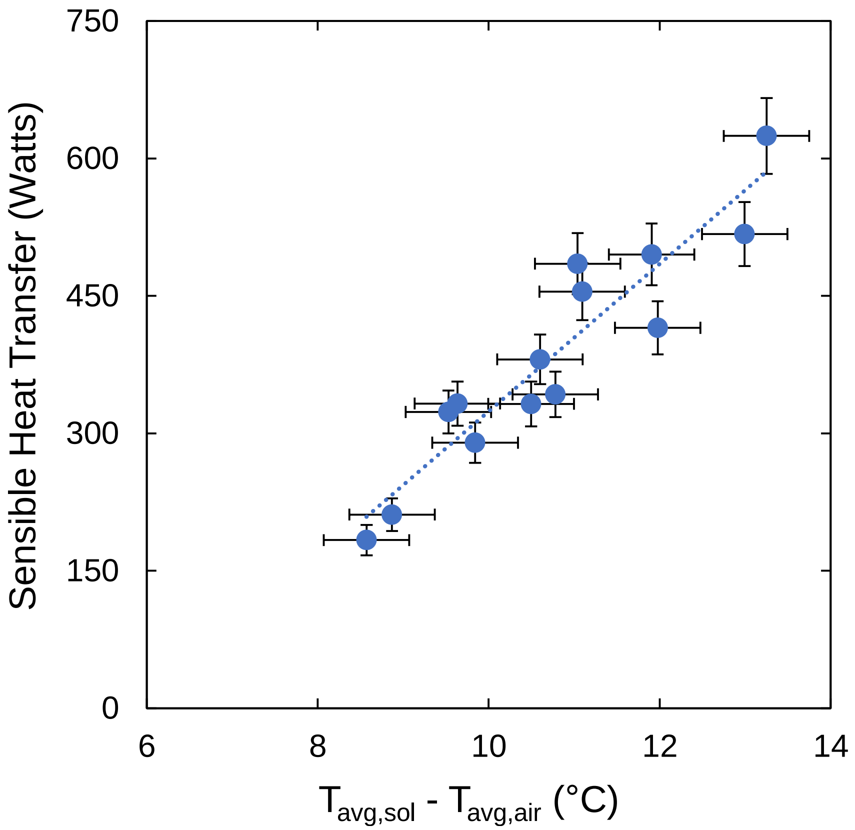
Experimental Results - Cycle



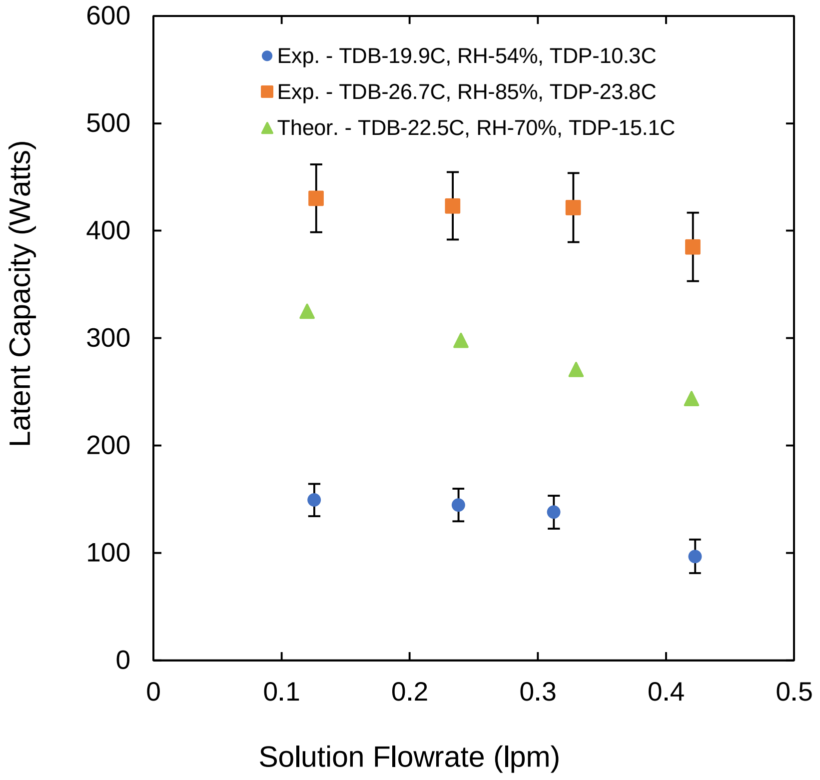


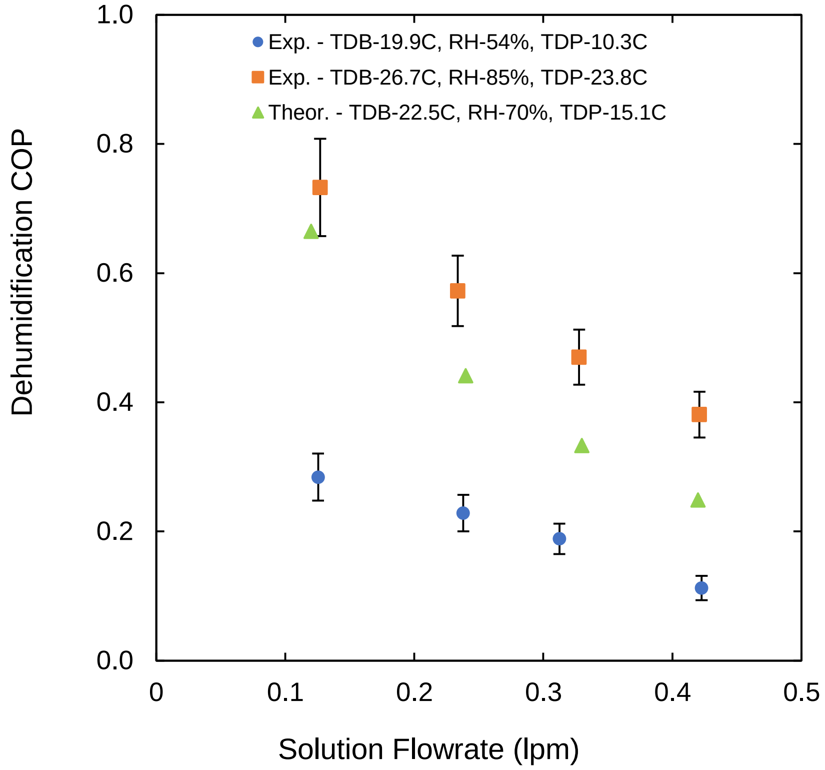
Experimental Results - Cycle

- Adiabatic Absorber
  - Process
    - Water vapor is absorbed in desiccant
      - Membrane
    - Heat of absorption is released
    - Heats process air
  - 5 – 11 °C increase

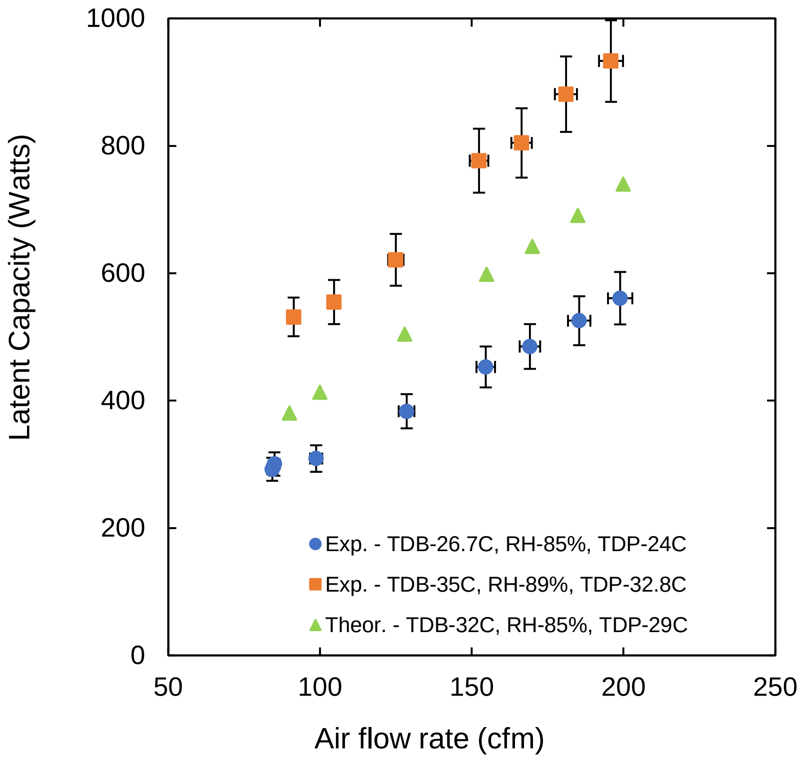


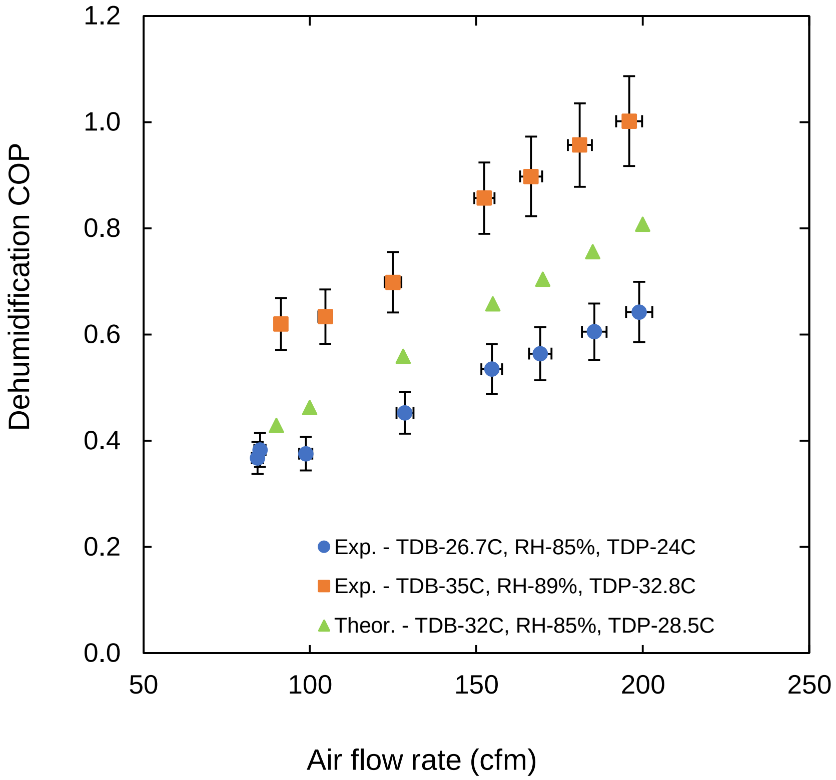
Solution flow rate impact





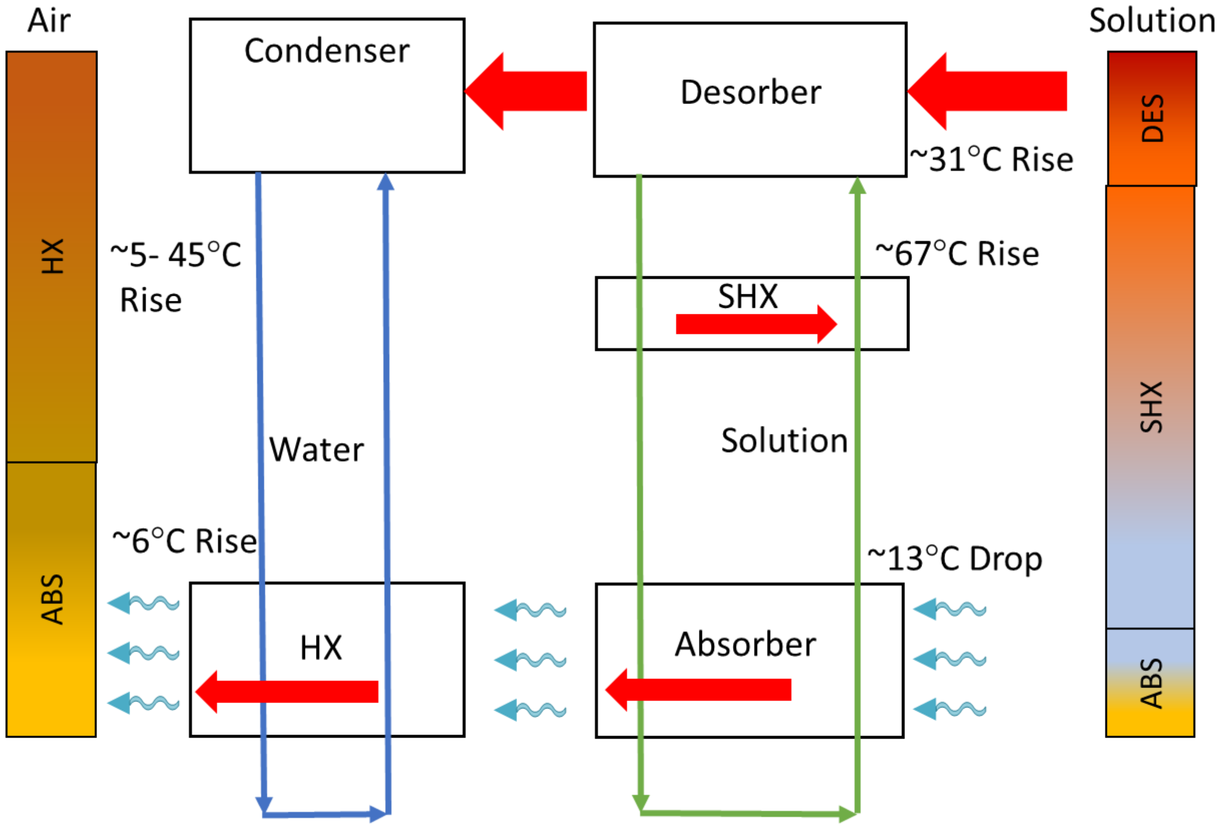
Airflow rate impact





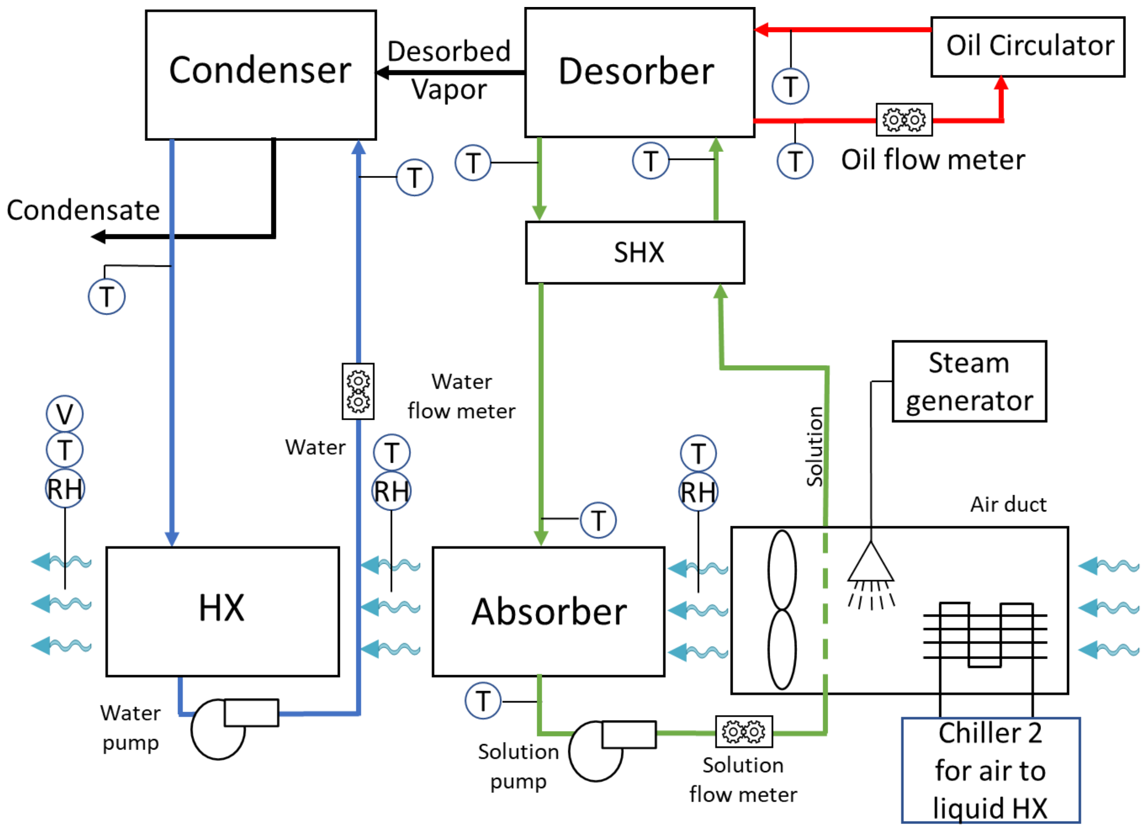
System

- Performance envelope
  - Single Effect
  - Double Effect
- Maximize heat recovery
  - Absorber
  - Condenser
- System characteristics
  - Capacity
  - COP



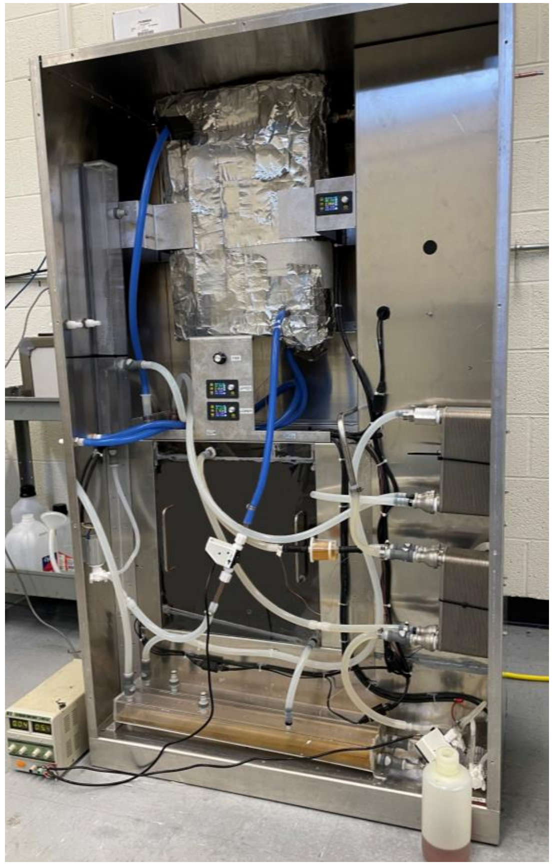
Experimental System

- Test System
  - Single-effect
  - Double-effect
  - ~ 1kW capacity
- Inlet Conditions
  - Lumber Drying Schedule



Experimental System

- Controls
  - Solution flow rate
    - Dehumidification capacity
  - Water flow rate
    - Condenser heat recovery
    - Condenser temp
  - Air flow rate
    - 0 – 400 cfm
- System
  - Size (consistent w/electric HP)



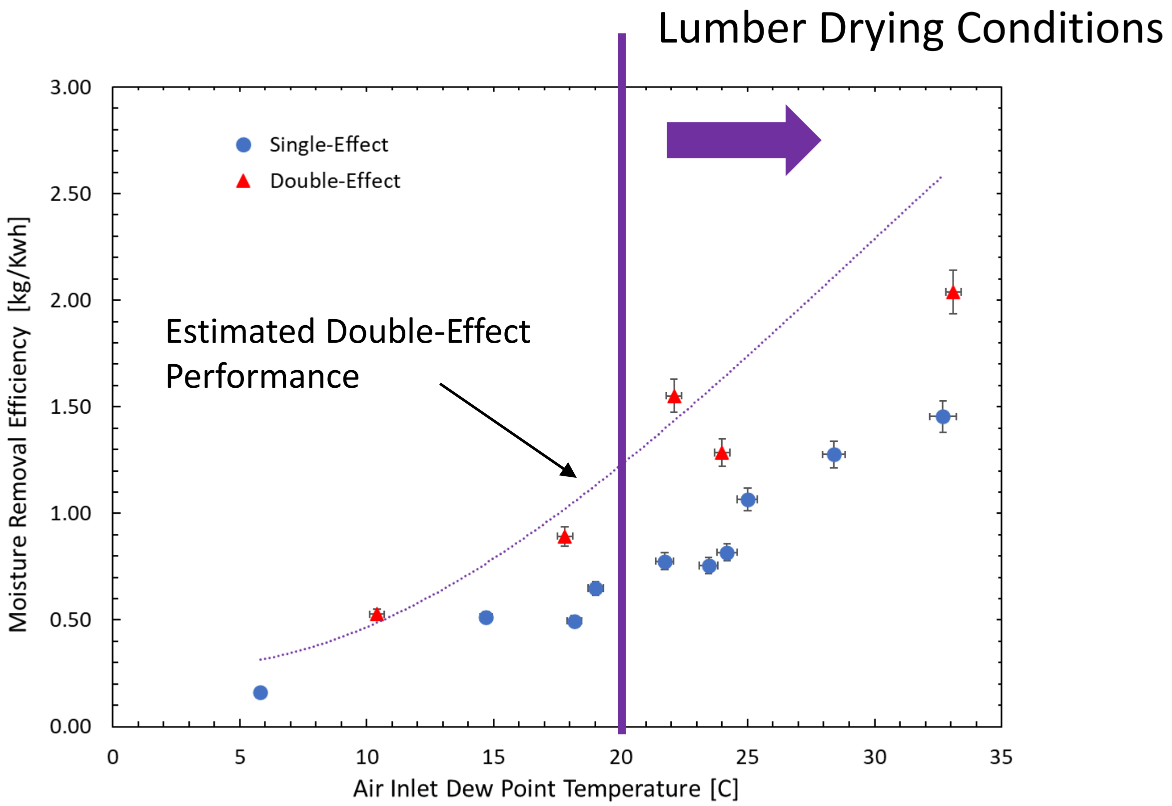
Experimental System - Status

- Establishing System Settings
  - Flowrates
    - Different drying Stages
    - Single & Double effect
- In-house testing
  - Double-effect
    - Tested in Cycle test suite
    - Wide range of parameters
  - Single-effect
    - Tested in System test suite
    - Establish flowrates for lumber test conditions
- 3rd Party testing
  - GTI Energy
  - Lumber specific parameters

Stages of drying	Warm dry air supply (Outlet of HP)		Warm humid air return (Inlet of HP)		Air Volumetric Flowrate	Representation of Lumber moisture content (%)
	T_{db} (°C)	RH %	T_{db} (°C)	RH %	(CFM)	
1	37.8	83%	29.4	95	300	>40
2	37.8	77%	29.4	90		35 – 40
3	37.8	65%	29.4	85		30 – 35
4	40.6	46%	37.8	70		25 – 30
5	40.6	15%	37.8	50		20 – 25
6	46.1	8%	40.6	30		15 – 20

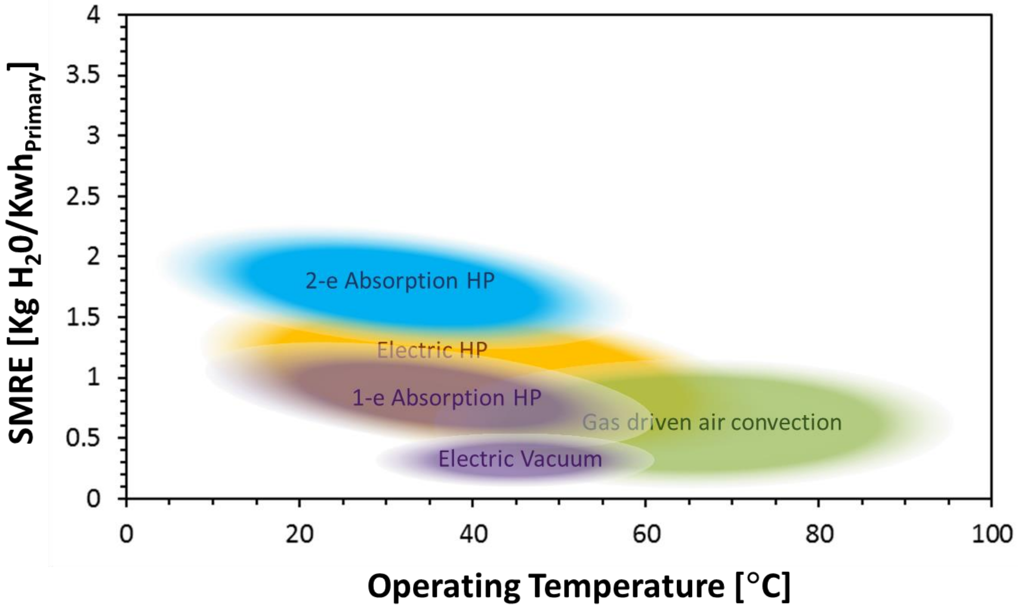
Conclusion

- Performance
  - Single-effect
    - w/o Optimization
    - ≥ Direct Heat Kiln w/HR
  - Double-effect
    - Estimated SMER
      - 1.1 – 2.5 $kg/Kwh_{primary}$
- Cycle/system testing
  - June 2023



Conclusion

- Built an experimental demonstration unit
- Demonstrated the viability of this technology
- Absorption Heat Pump Dryer
  - Eliminate "free" fuel barrier in the lumber industry
  - Provides recirculatory dehumidification drying efficiencies for large scale lumber kilns
  - Better utilization of renewable biomass resource
  - Reducing lumber drying energy consumption and GHG emissions



Acknowledgements

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Questions

Thank you

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