Membrane-based Absorption Heat Pump Water Heaters

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The Foundation for The Gator Nation

Outline

- Motivation
- Operation principle
  - Closed & open absorption cycle water heaters
- Membrane-based absorption cycle
  - Theory and experiments
  - Preliminary system level tests
- Ionic liquids (ILs) for absorption cycles
  - Unique properties and prospects
- Summary

Motivation

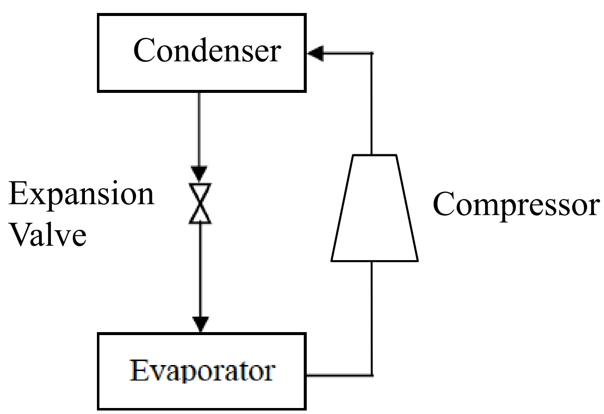
- ~50% of the water heaters shipped are gas-fired

Residential	2009	2010
Gas Storage (Total)	**3,760,657**	**3,918,510**
Not E [17]*	*3,110,419*	*3,463,780*
E-qualifying [18]*	*650,238*	*454,730*
Gas Tankless (Total)[19]	**380,000**	**399,000[20]**
*Not E**	*46,987*	*14,974*
E-qualifying*	*333,013*	*384,026*
Electric Storage (Total)	**3,751,994**	**3,736,597**
Not E [21]*	*3,737,260*	*3,677,472*
E-qualifying (heat pump)[22]*	*14,734*	*59,125*
Solar [23]	**31,647**	**33,462**
*Not E**	**24,751**	**23,472**
E-qualifying*	**6,896**	**9,990**
TOTAL	**7,924,298**	**8,087,569**
*Total Not E**	*6,919,417*	*7,179,698*
Total E qualifying*	*1,004,881*	*907,871*

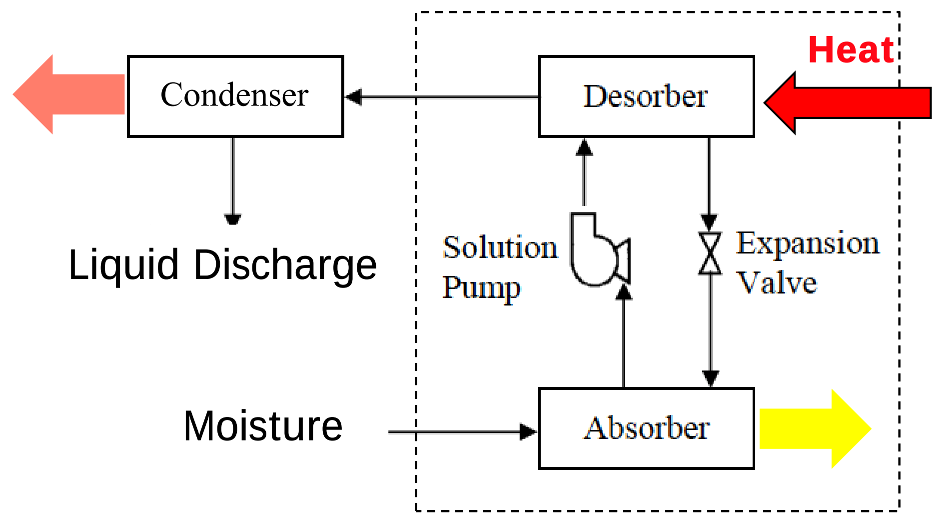
Research and Development Roadmap for Water Heating Technologies, Navigant, 2011

Operation Principle of an Absorption Cycle

Vapor compression cycle

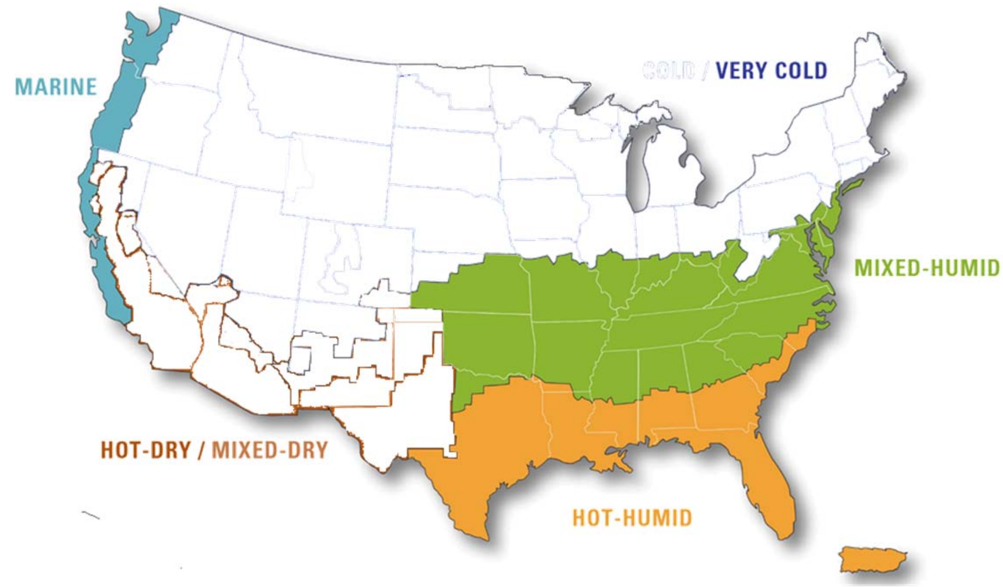


Open absorption system



Potential Application of Open System

- An open cycle can be substantially cheaper than a closed cycle
- Applicable to 3 zones, encompassing 54% of US homes



Environment	Ambient RH and Temperature	Thermal COP	Ambient Dew Point
Cold humid basement	6 ˚C, 80% RH	1.54	2.82
Humid open space	35 ˚C, 70% RH	1.72	28.7
Air-conditioned closed space	23 ˚C, 50% RH	1.63	12.06

Applicable in Buildings with Fresh Air Requirement

- Latent heat (i.e. heat of moisture) is the primary air ventilation load for much of the US (east, south, north, mid-west, north-west, and Islands)

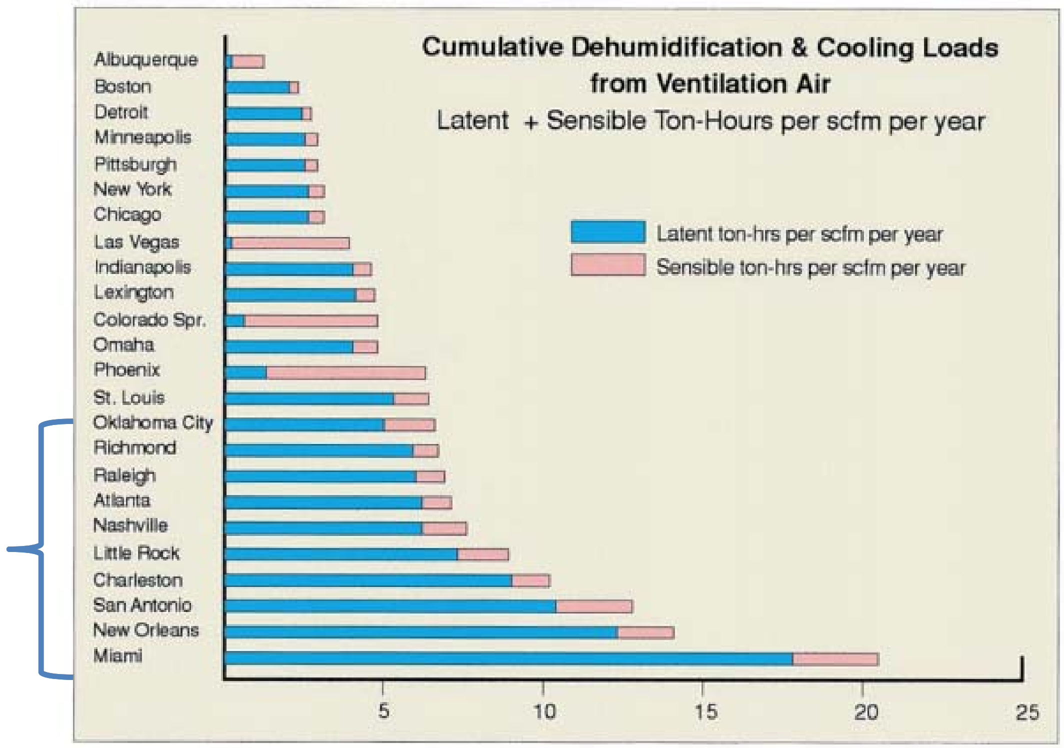
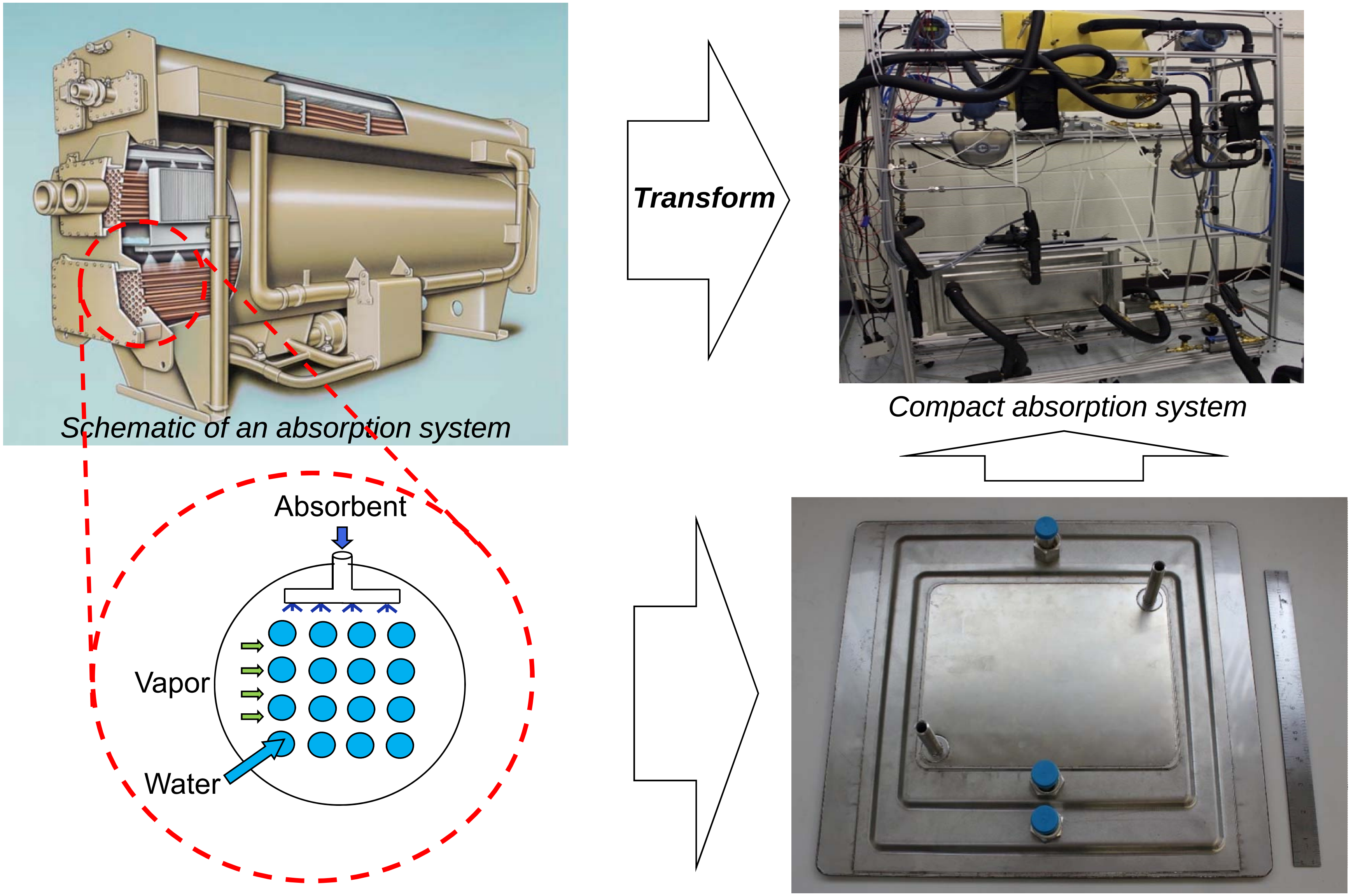


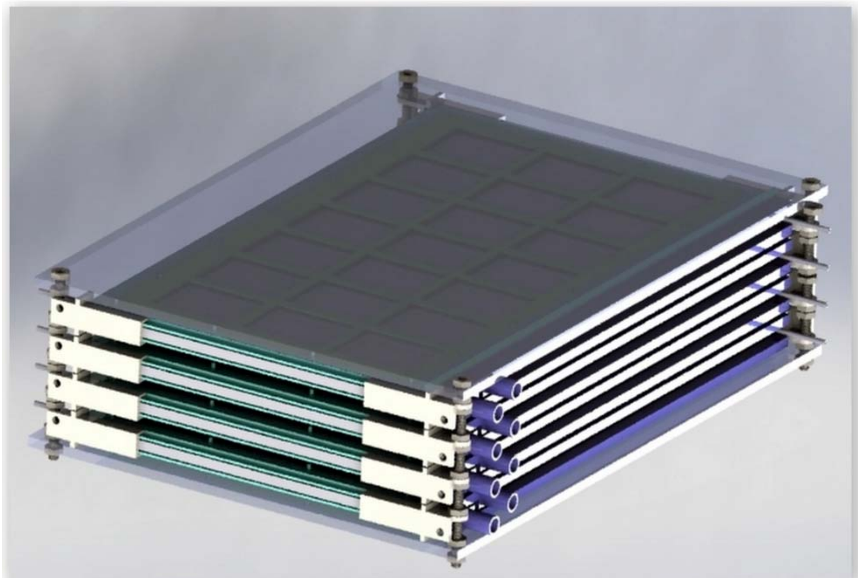
Fig. 2: Cumulative dehumidification and cooling loads from ventilation air for selected locations in the United States.

Benefits of a membrane-based absorption cycle

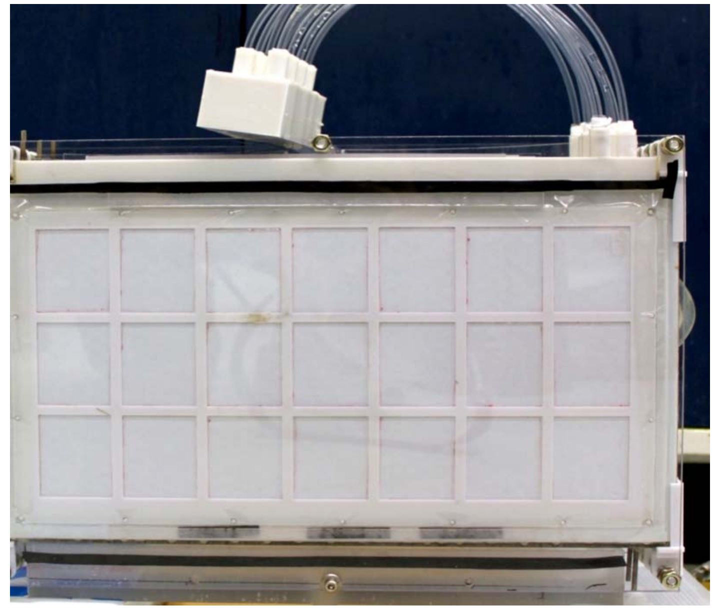
Membrane-based Closed Absorption System



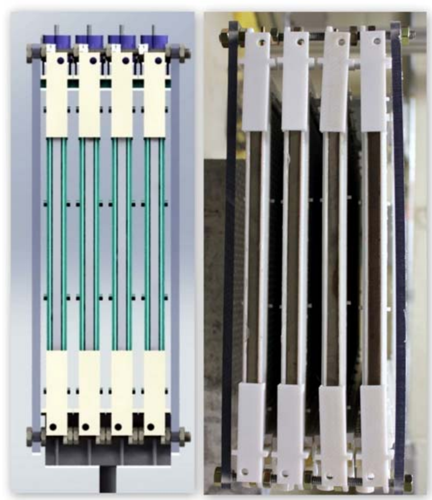
Membrane-based Open Absorption System



3D model of the absorber

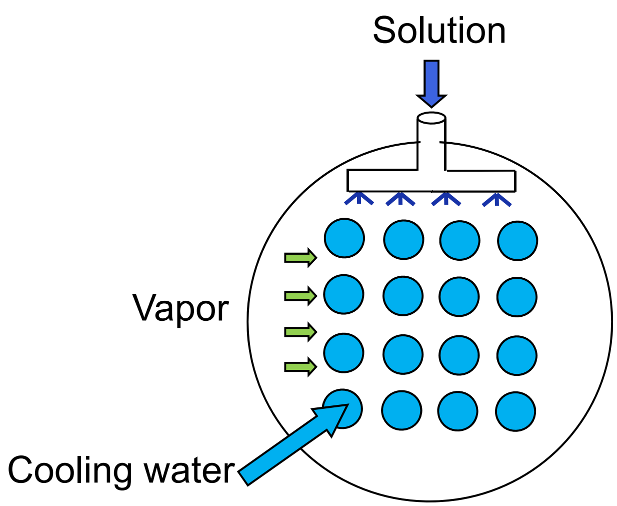


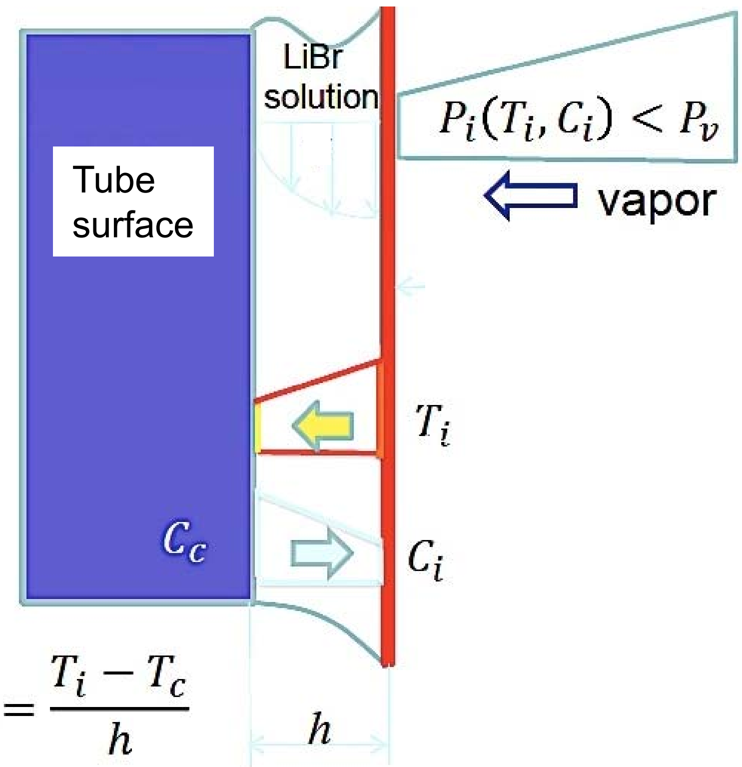
Fabricated absorber



Science of membrane-based absorption process

Absorber Heat Exchanger





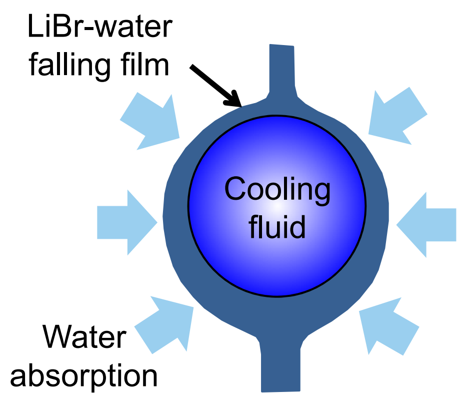
Control factors in absorption rate:

Film thickness: h; solution velocity v
Cooling water temperature T_c

$$\nabla T = \frac{T_i - T_c}{h}$$

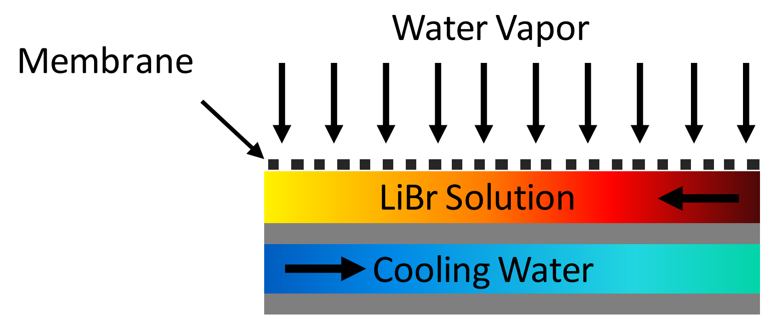
Membrane-based Absorber vs. Current Absorbers: Fundamental Physics

Conventional



- Hydrodynamics of the falling film over the tubes dictates the film thickness
  - ➢ Film thickness is not optimal for maximum absorption
  - ➢ Flow velocity is coupled with the film thickness

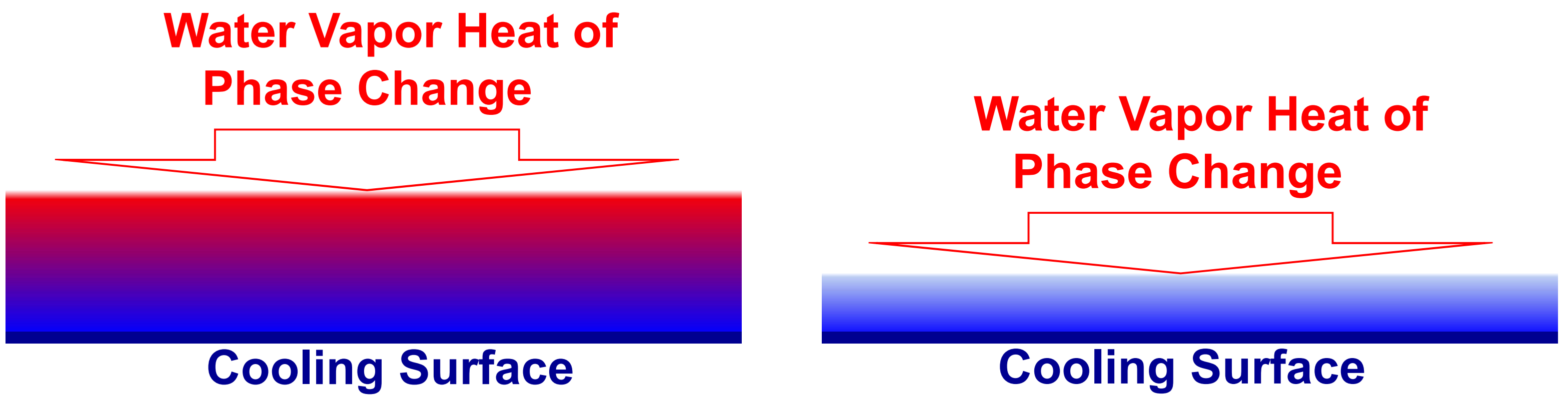
Membrane-based



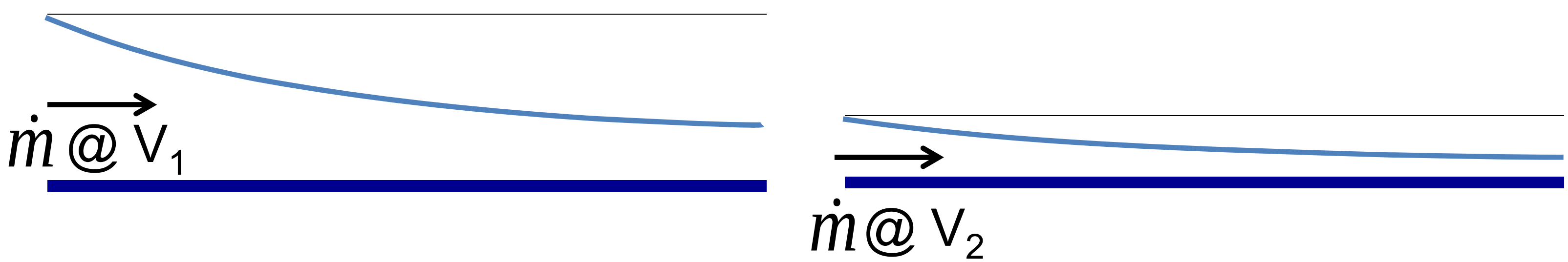
- Utilize thin absorbent films constrained by highly permeable membranes
  - ➢ Enables independent control over the film thickness and velocity
  - ➢ Enables fabrication of compact plate-and-frame absorbers

Effect of Film Thickness and Velocity on Absorption Rate

- Better cooling of the solution/vapor interface

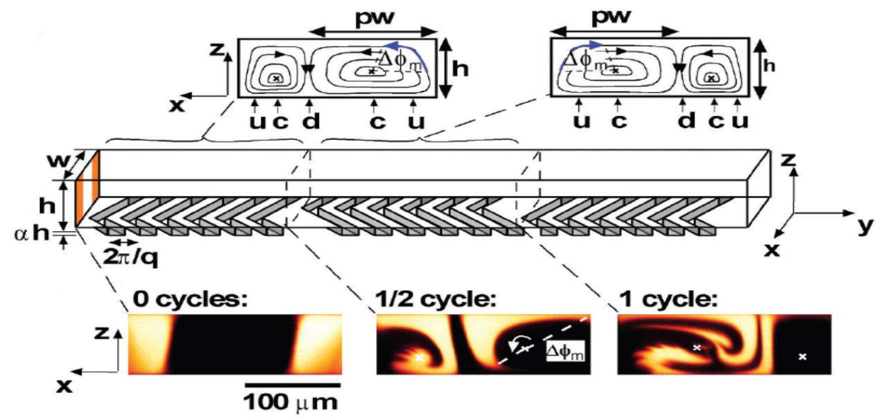


- Reduced mass transfer resistance

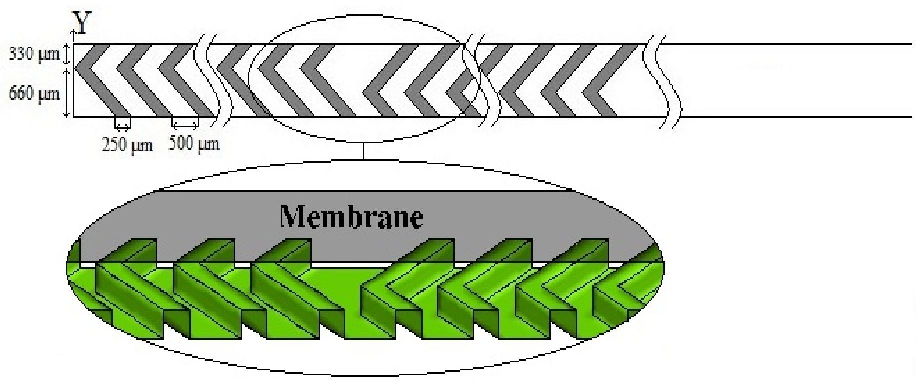


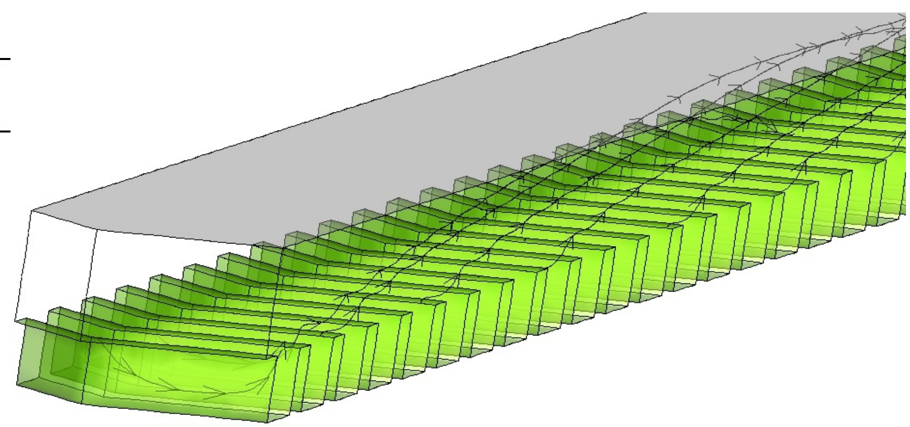
2^{nd} Generation Absorber

- Use a thick liquid layer to reduce the pressure drop
- Chaotic mixing of the solution flow
  - Overcome diffusion limitations
- Using surface microstructures to generate vortices

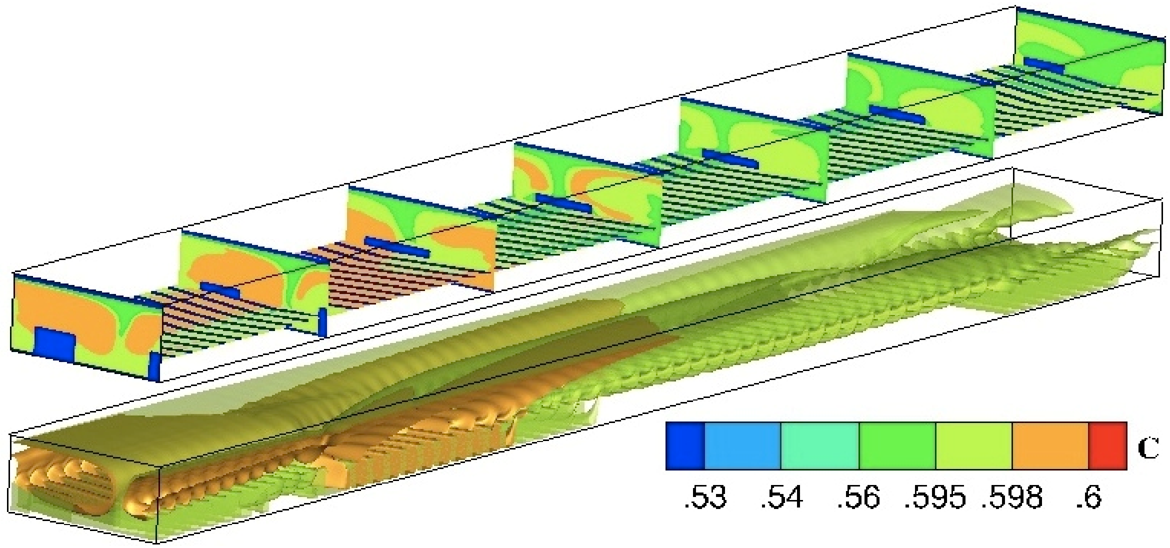


A. D. Stroock et al., Science, 2002

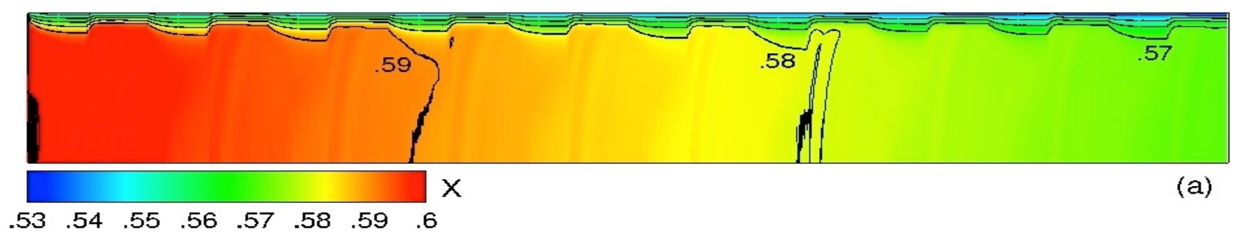




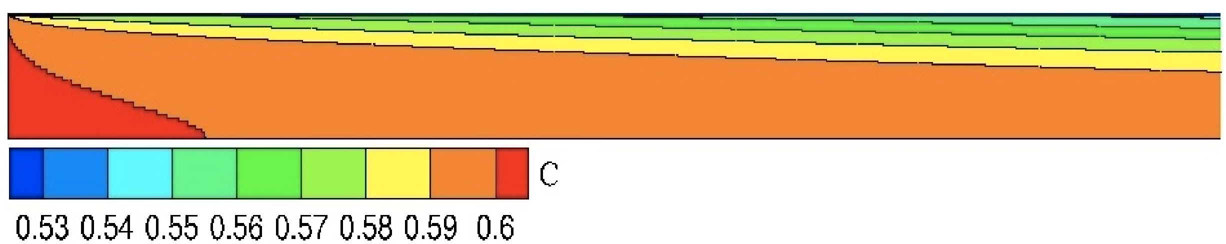
2nd Generation Absorber



With mixing

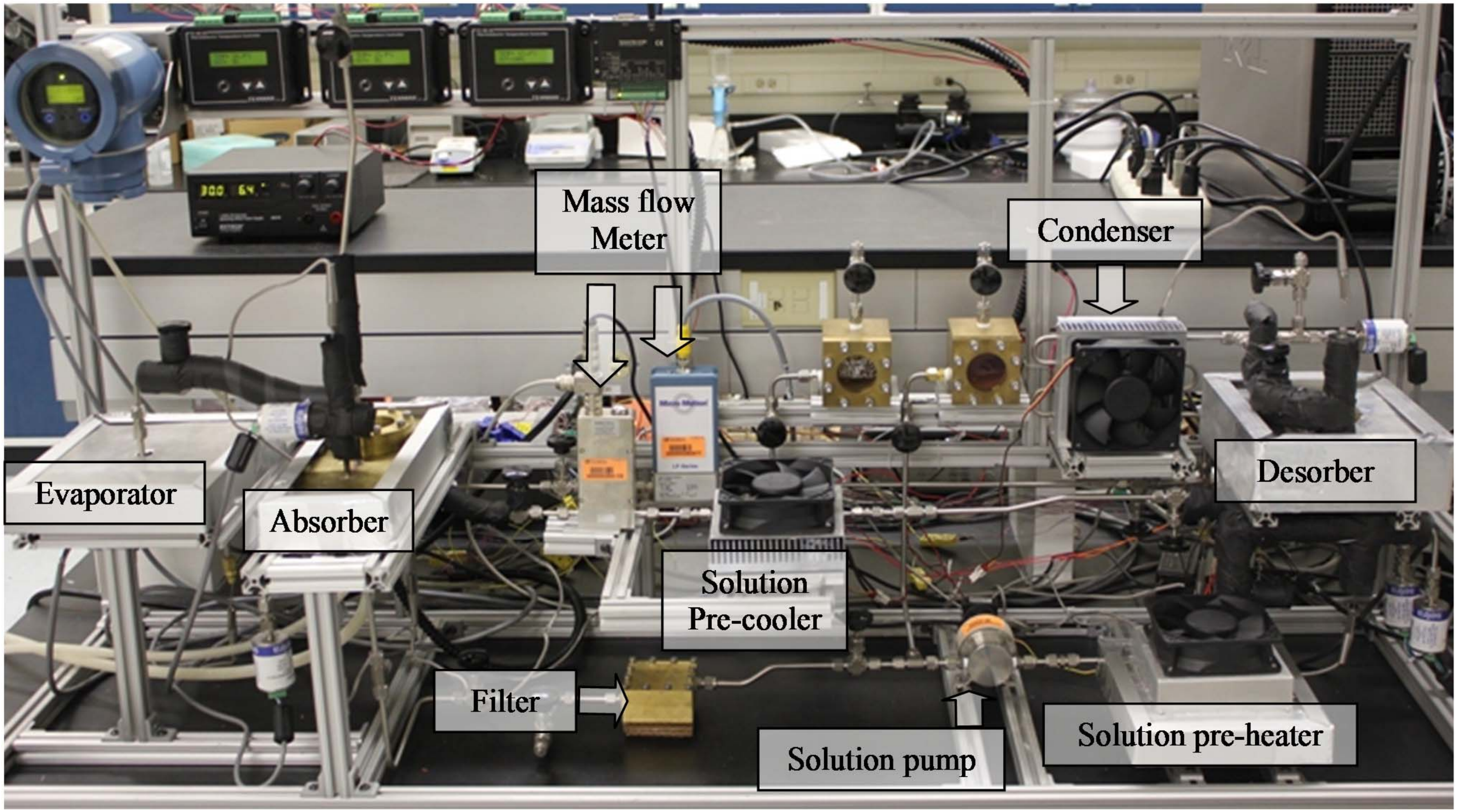


Without mixing

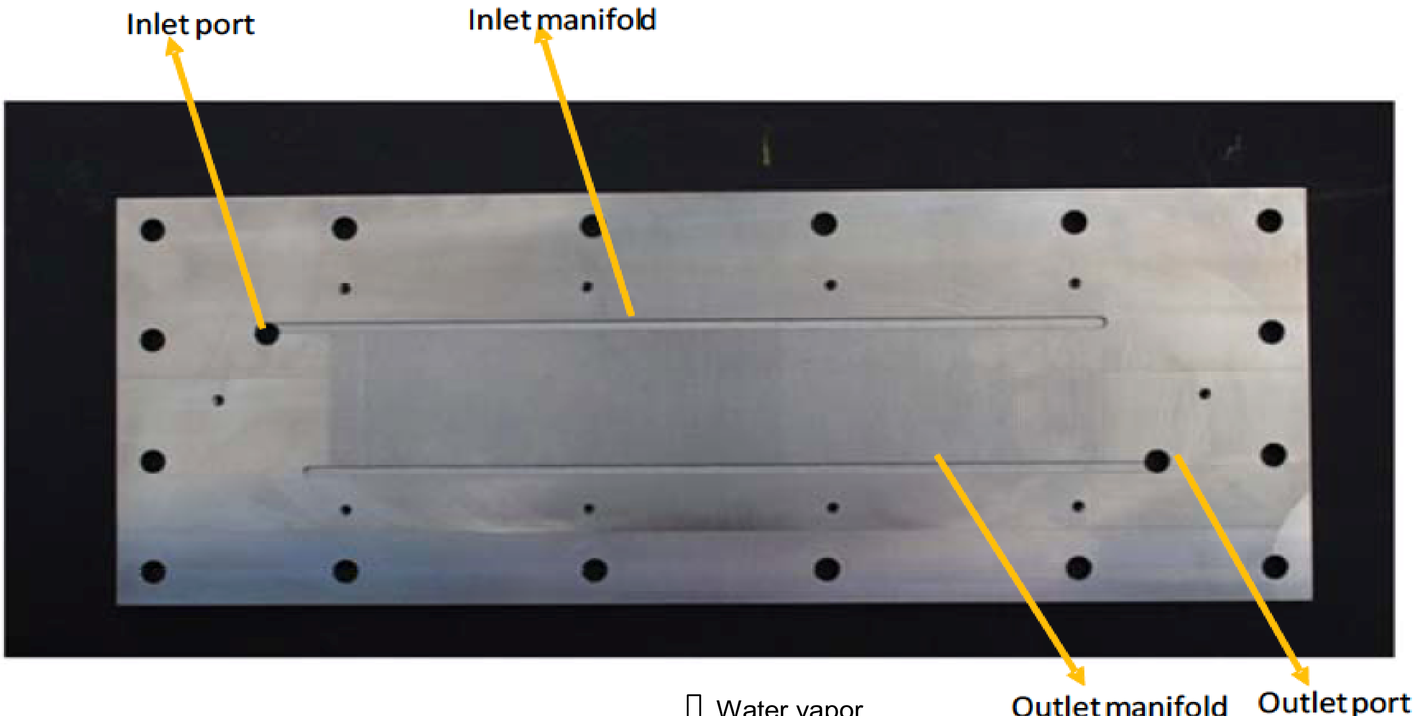


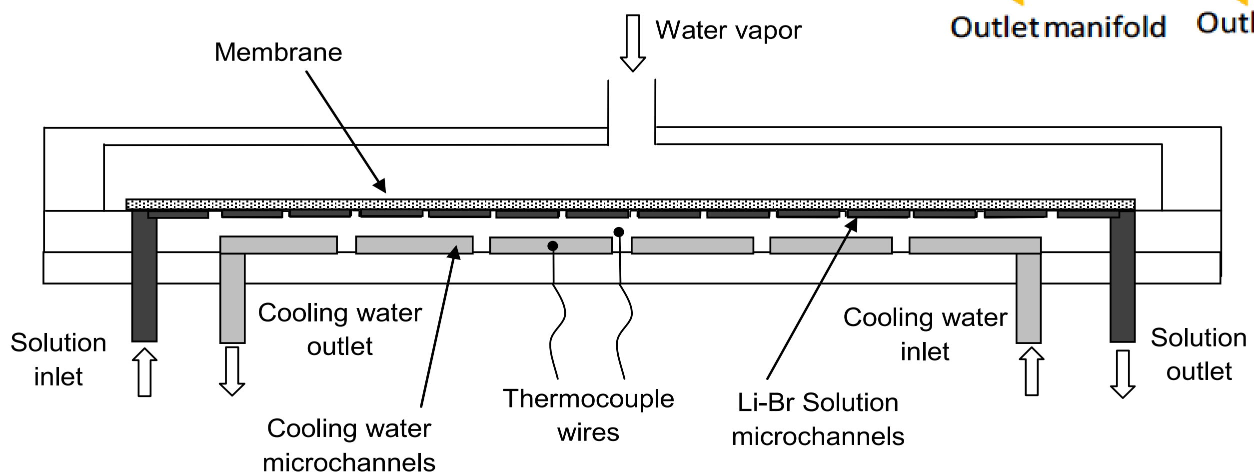
Scaled by a factor of 100 in the x-direction

Experimental Equipment

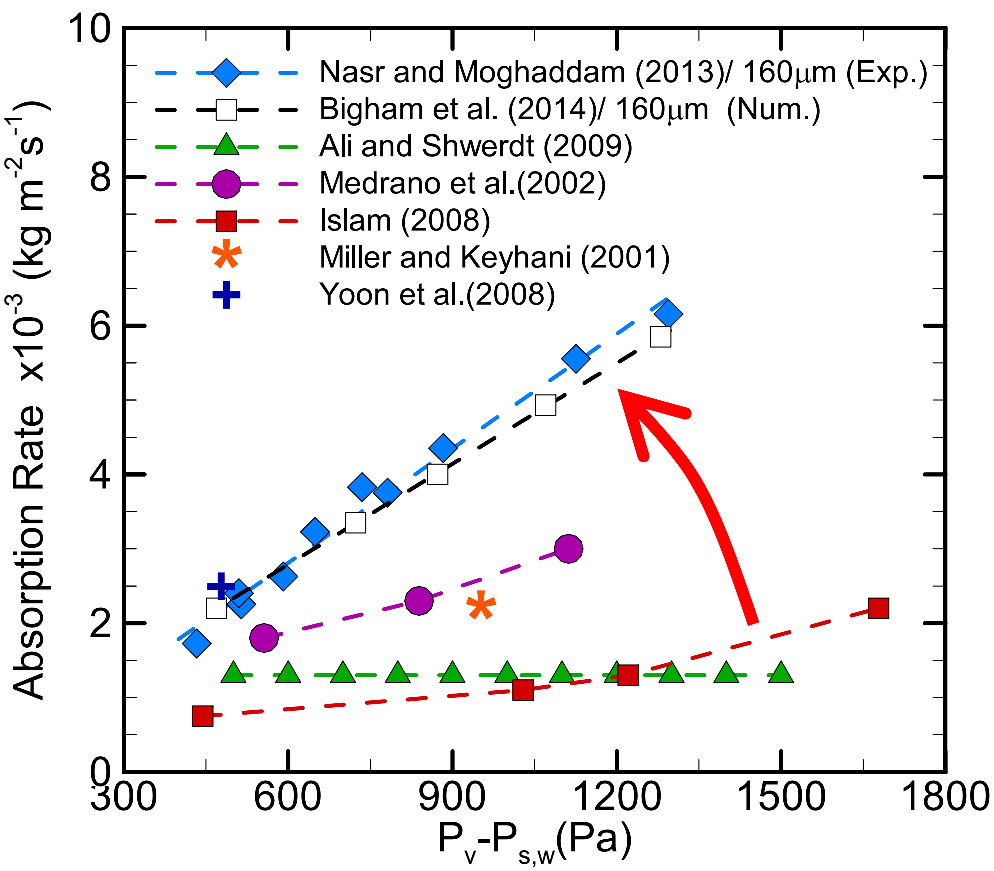


1^{st} Generation Absorber



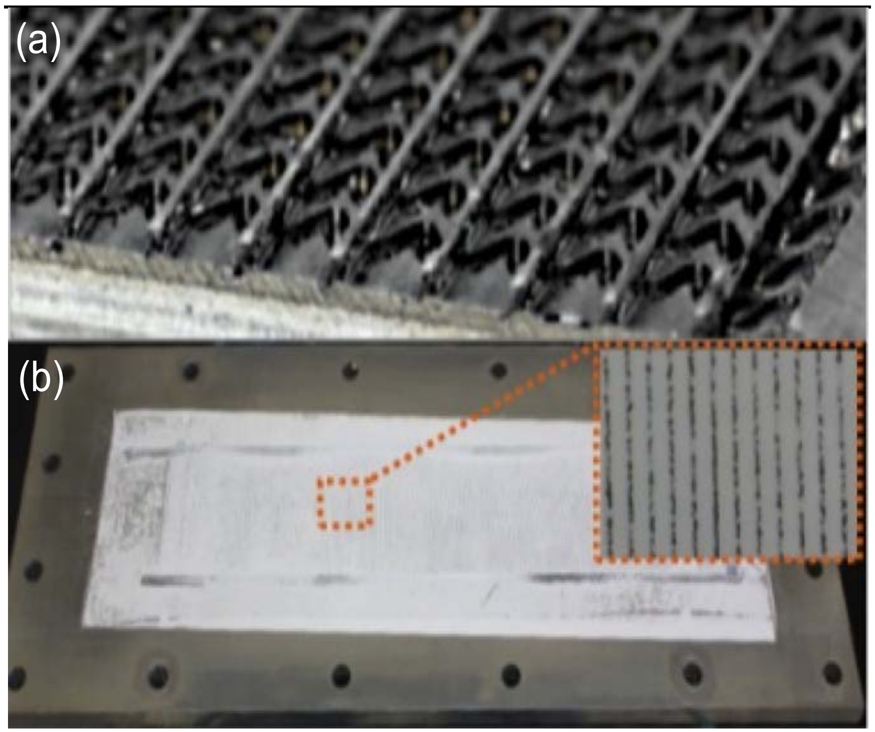


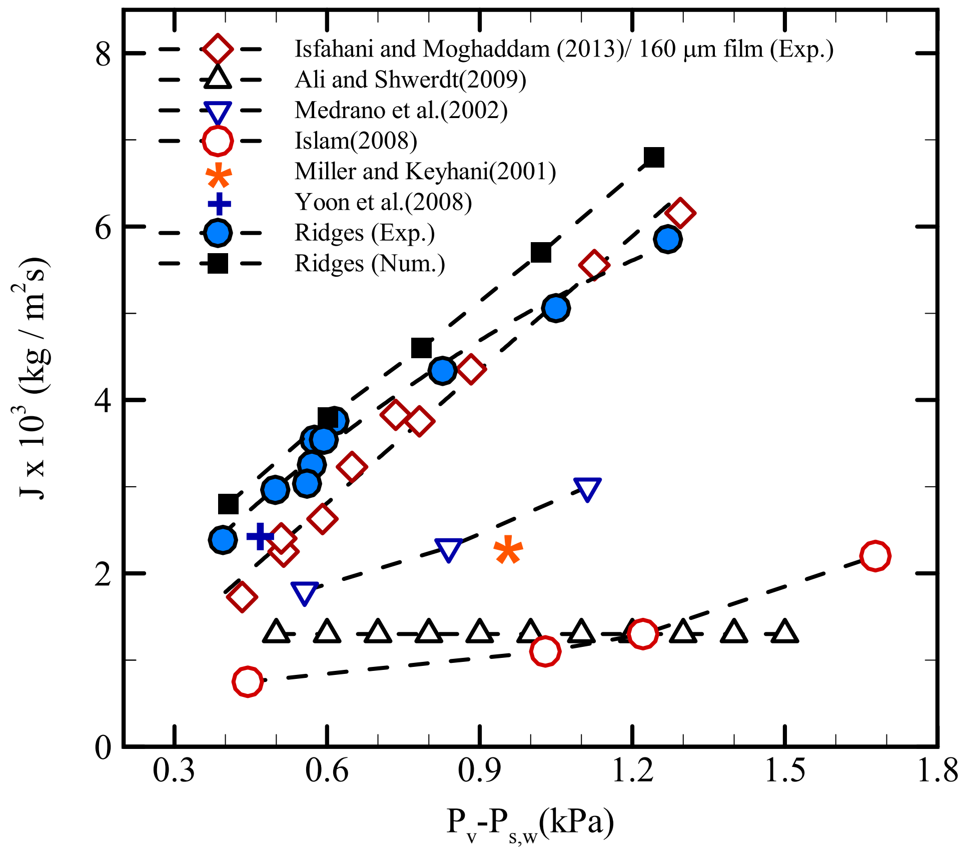
1st Generation Absorber



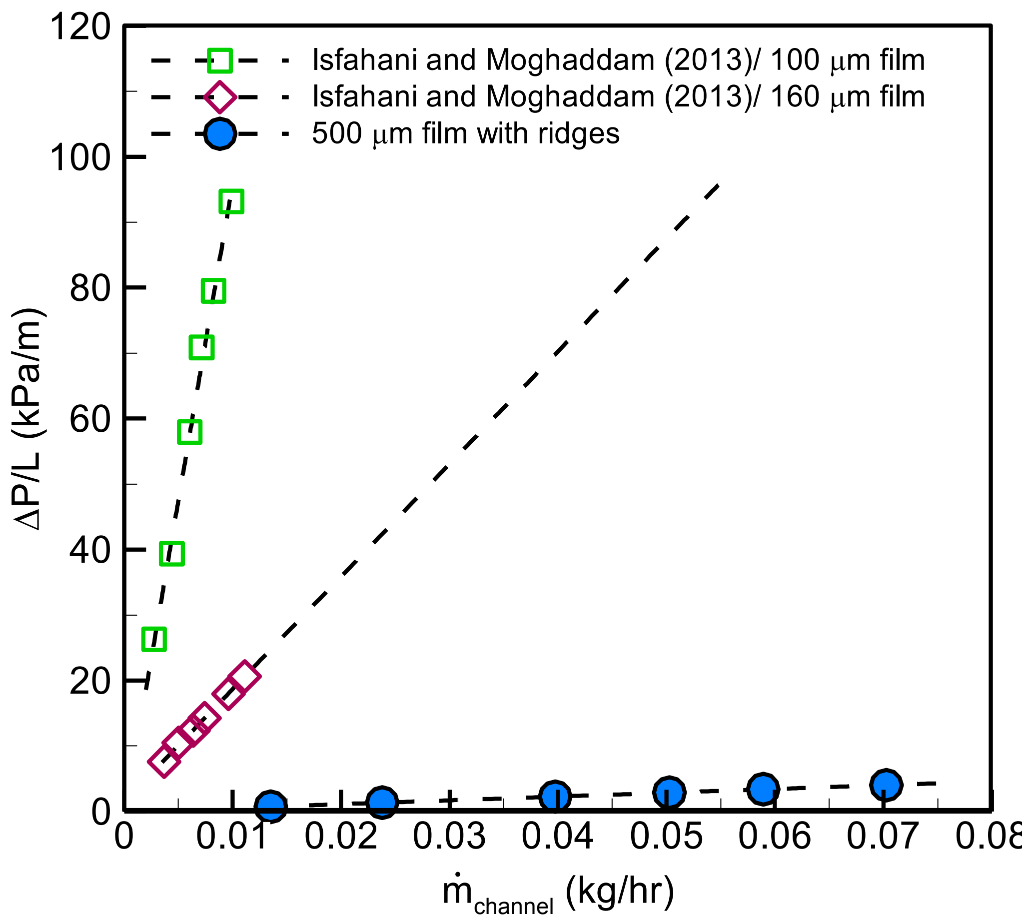
Nasr and Moghaddam, Int. J. Heat Mass Transfer, 2013

2nd Generation Absorber

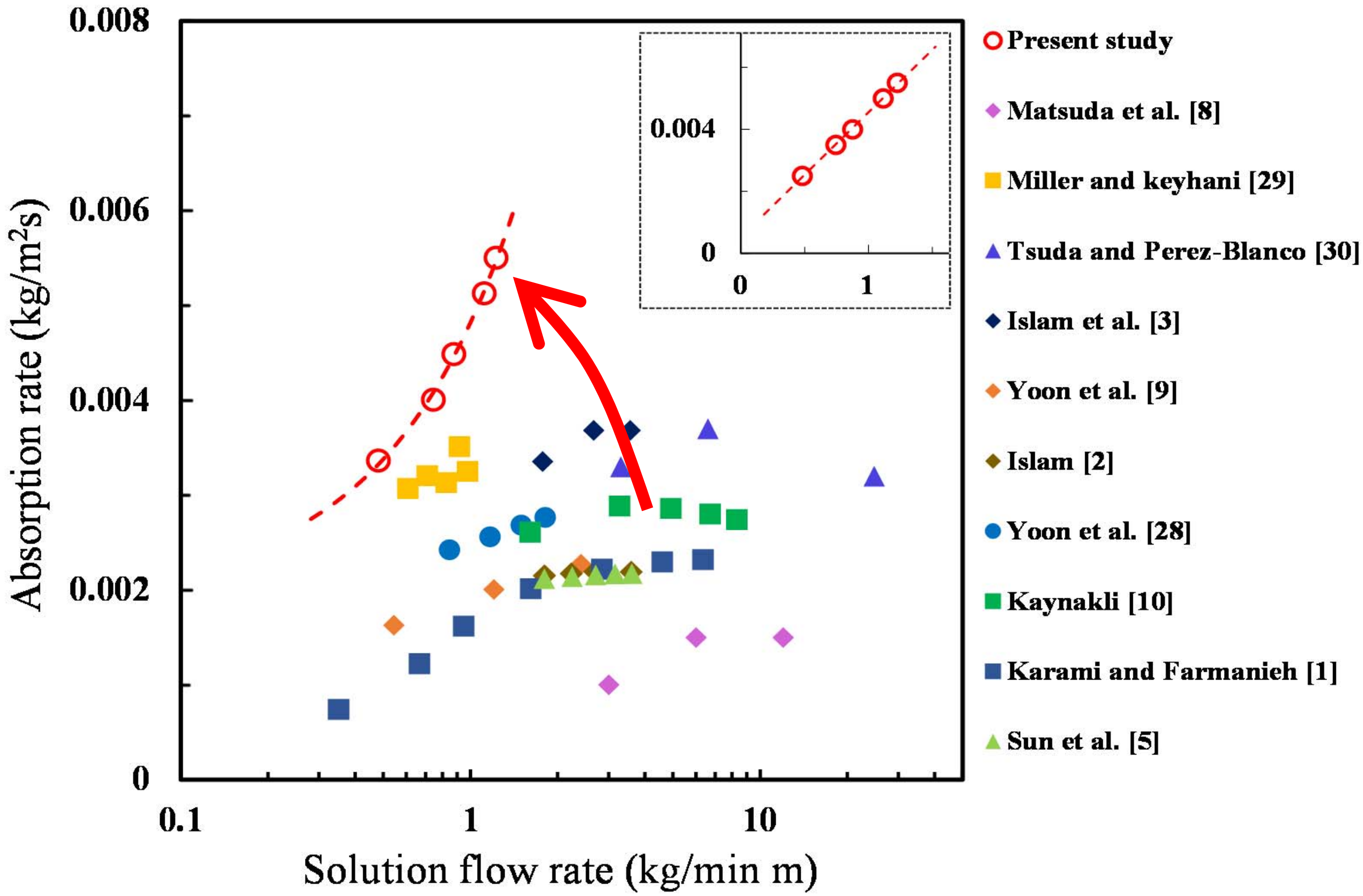




Comparison of 1st and 2nd Generations Pressure Drop

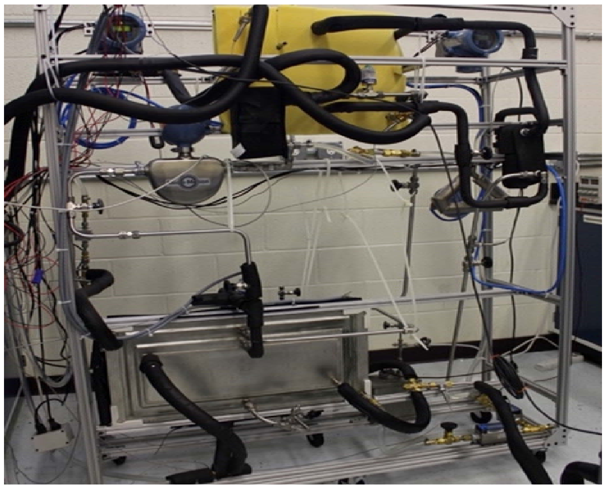


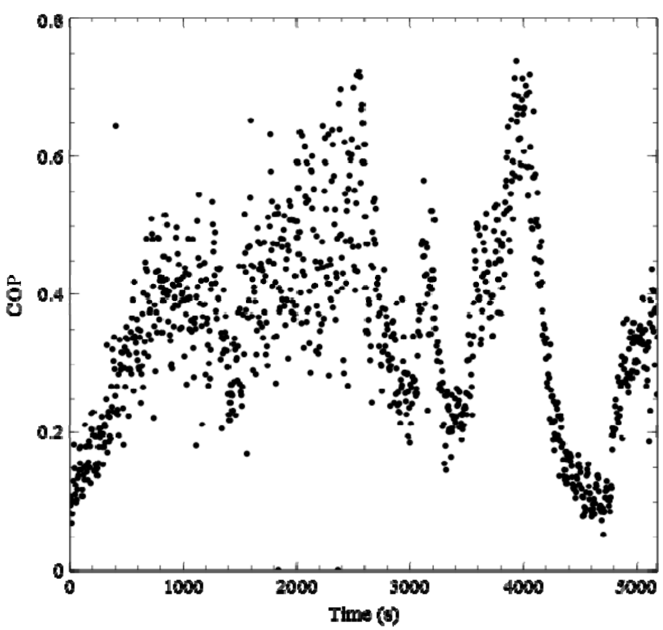
3rd Generation Absorber



Systems level testing

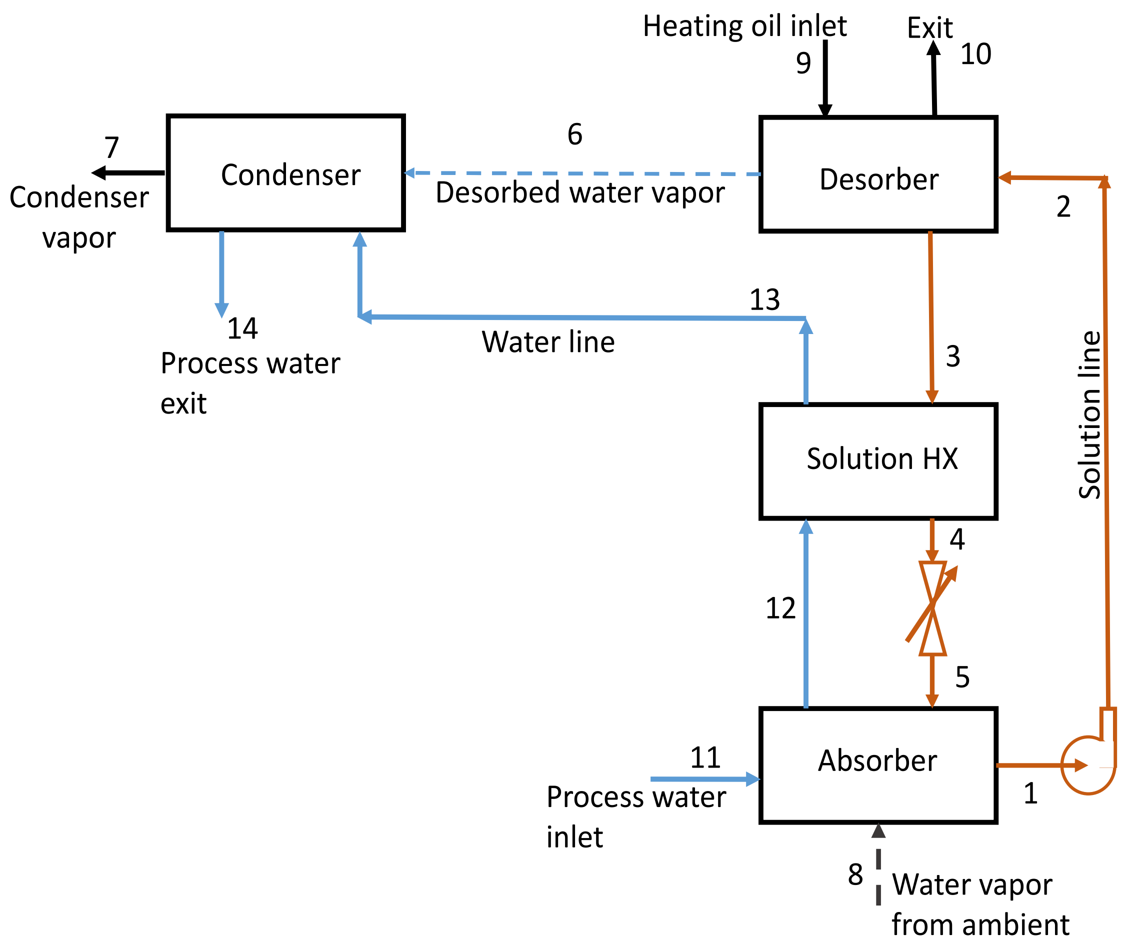
1st Generation Closed System



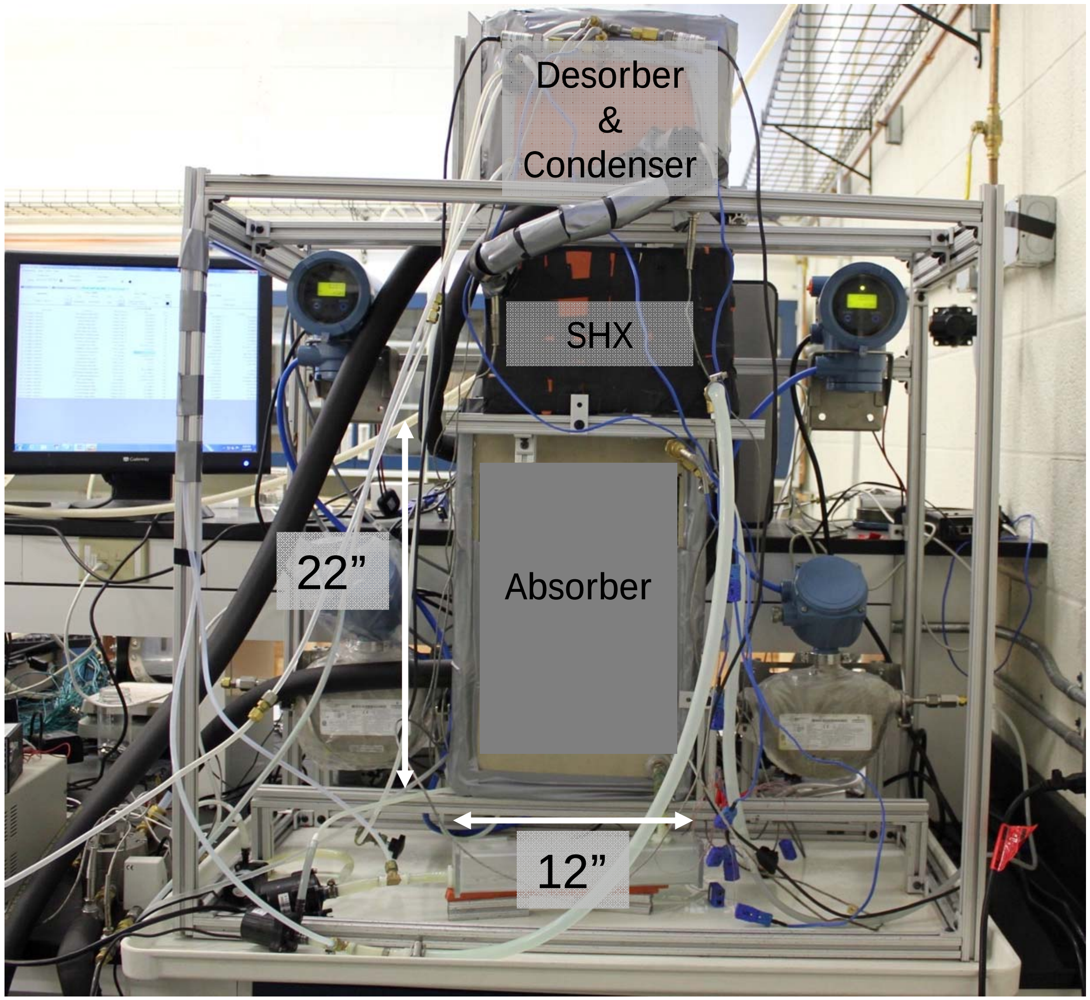


- Test conditions:
  - $T_{supl\text{-}evap}$=12 ° C
  - $T_{supl\text{-}abs}$=25 ° C
  - $COP_{heating}$=1.7
- Highly unstable
- Identified the source of instability
- 2nd generation has been fabricated
- Tests on the new system will be conducted soon

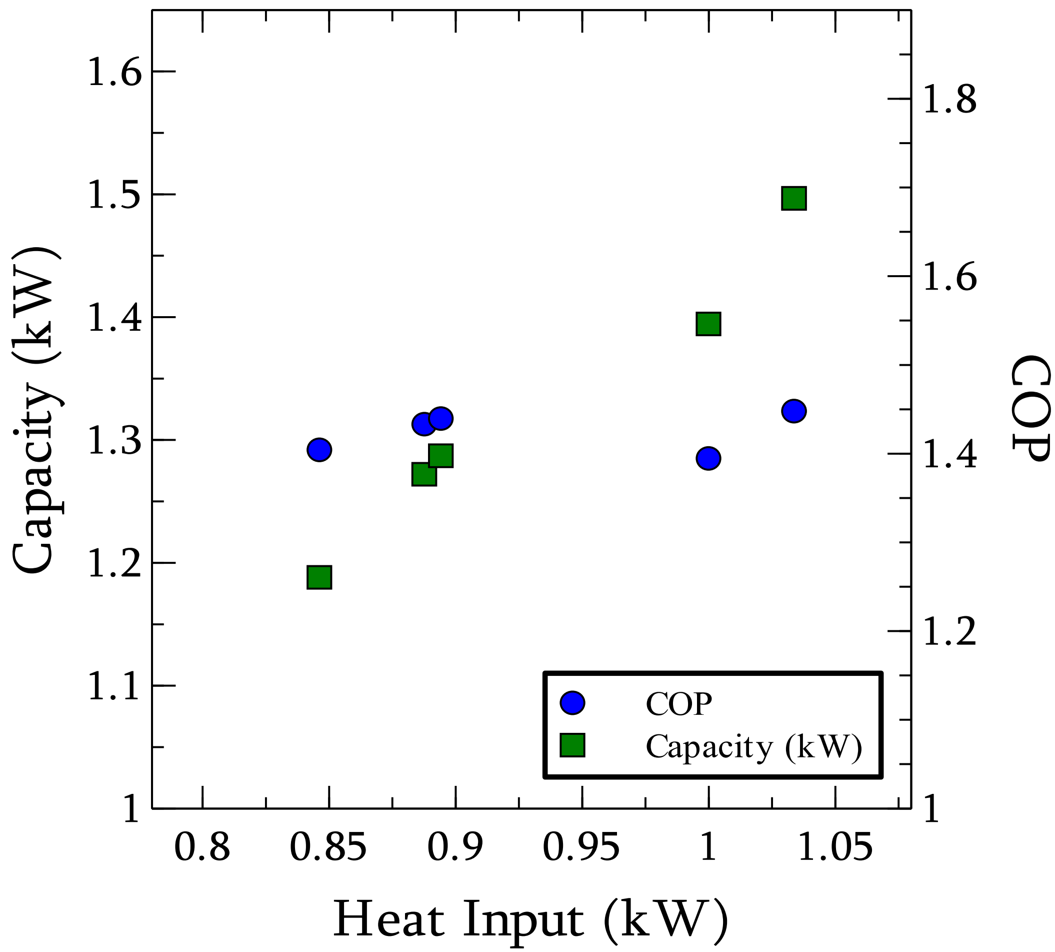
1st Generation Open Architecture Water Heater



1st Generation Open Architecture Water Heater

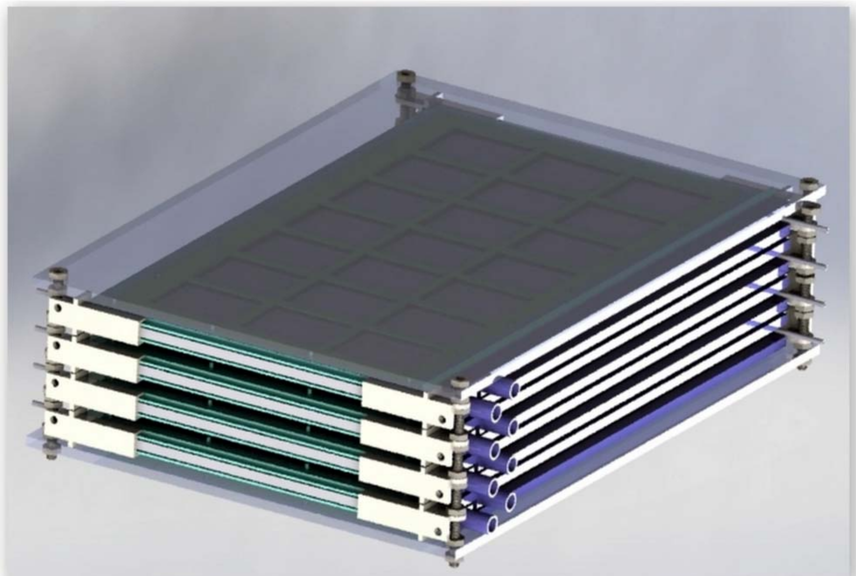


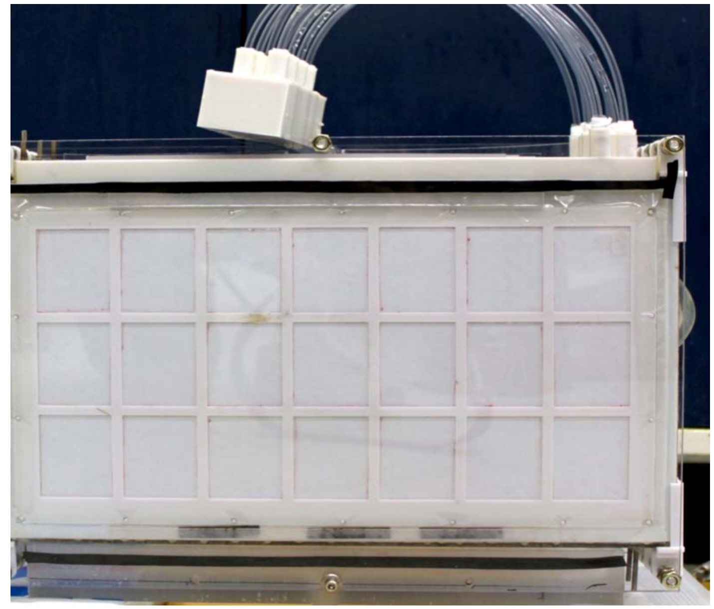
Performance Data of Open Architecture Water Heater



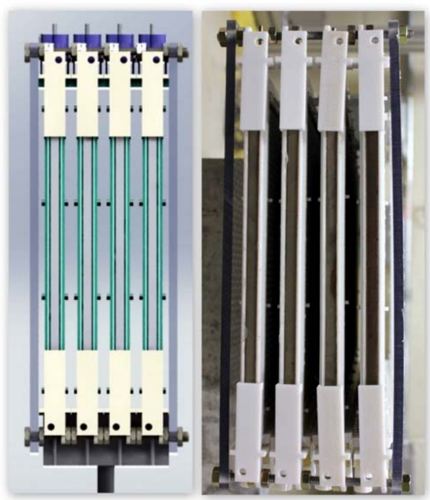
Performance of a LiBr system at ~20-23 ° C and 60-65% RH

2^{nd} Generation Open Architecture Water Heater





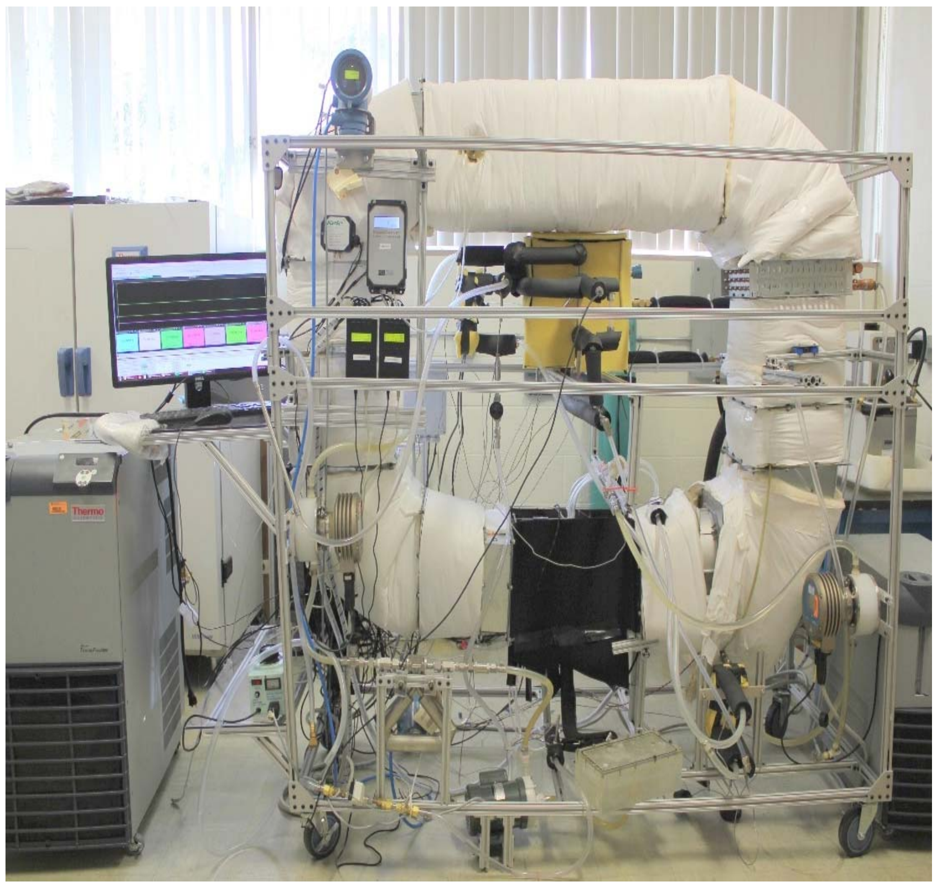
3D model



Fabricated device

Experimental Loop

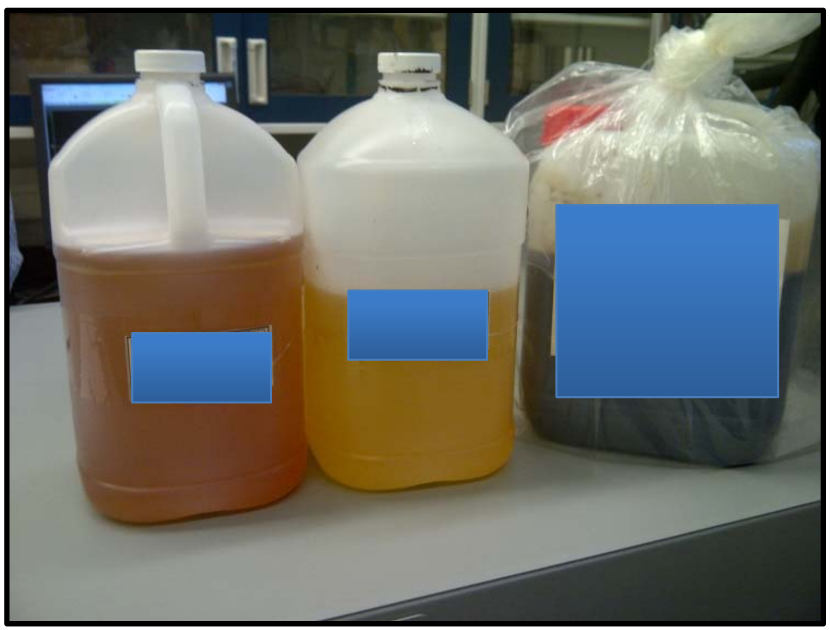
- Fully instrumented air conditioning system
- With control on temperature and humidity

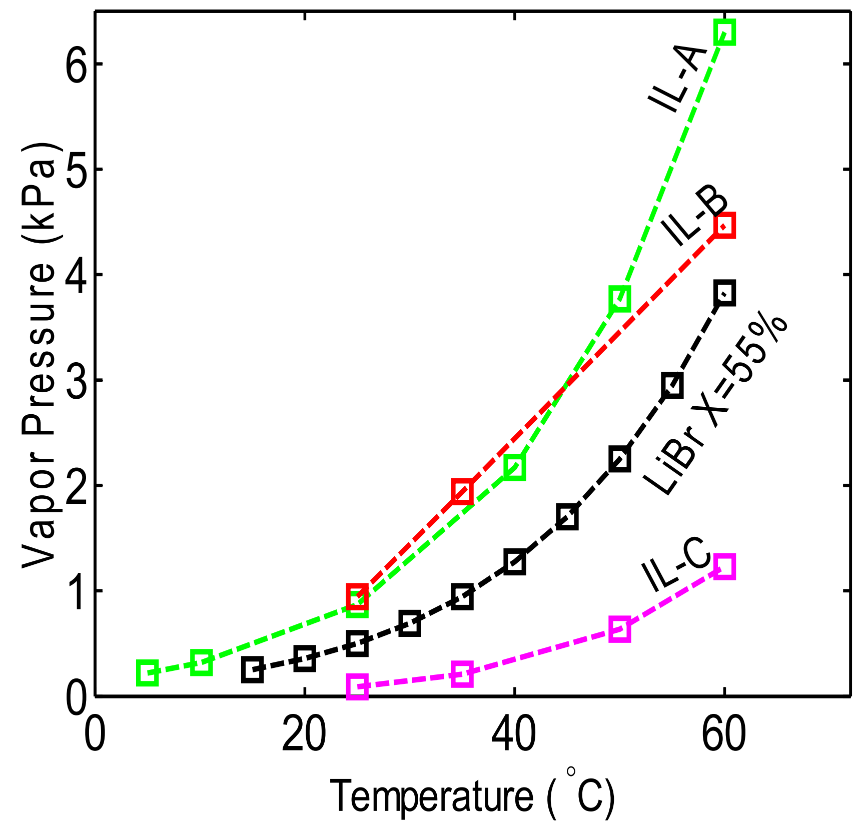


Ionic liquids

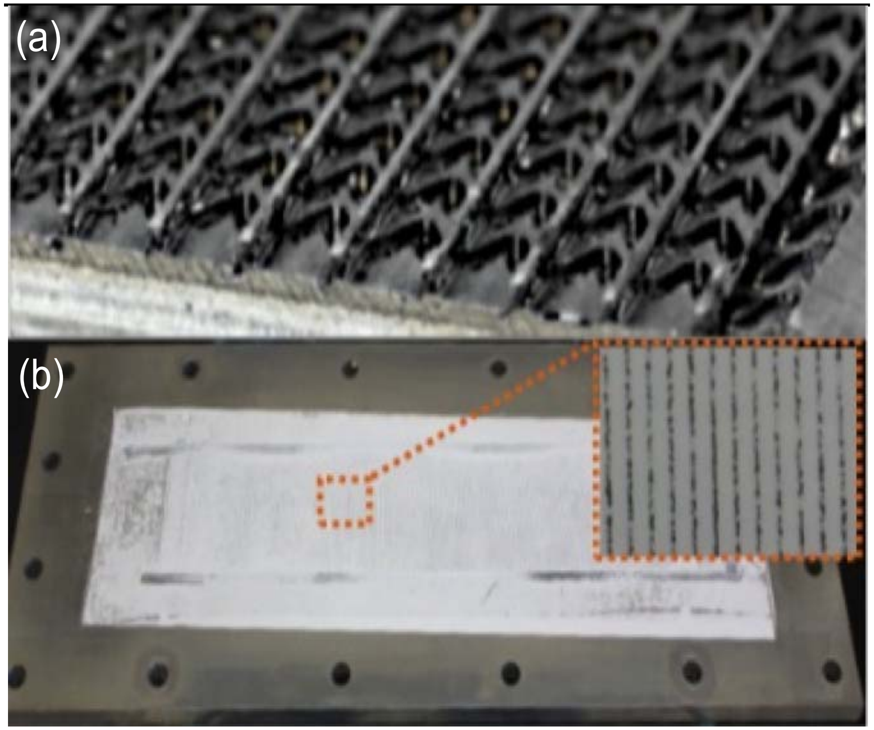
New Opportunities with Ionic Liquids (ILs)

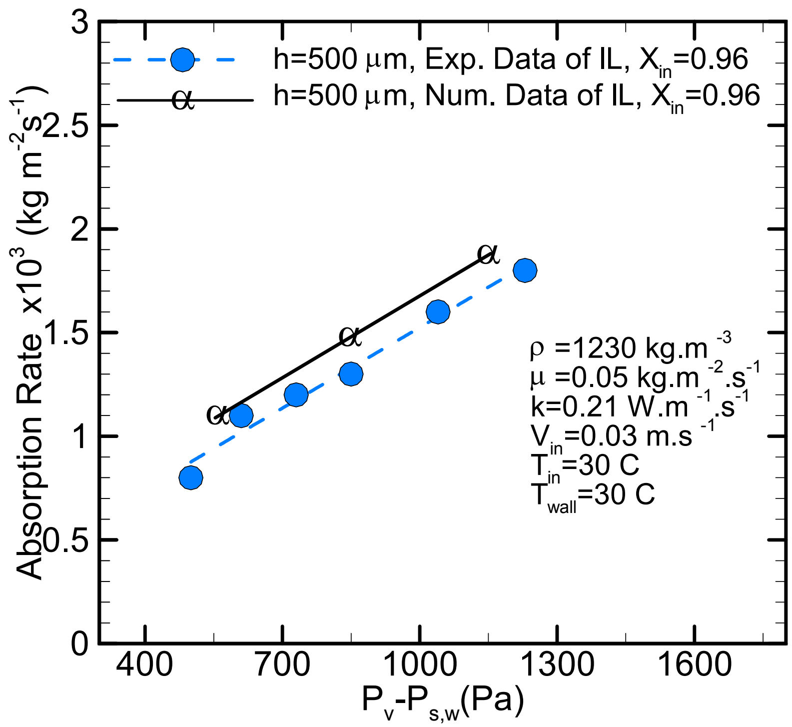
- Crystallization issue is addressed
- Less corrosive than the LiBr solution
- Low vapor pressure at high absorber temperature
- Environment friendly (green liquids!)





Preliminary Experimental Results (closed system)





Momentum, Energy and Concentration:

$$\rho u_j u_{i,j} = -p_{,i} + \mu u_{i,jj}$$

$$u_j T_{,j} = \alpha T_{,jj}$$

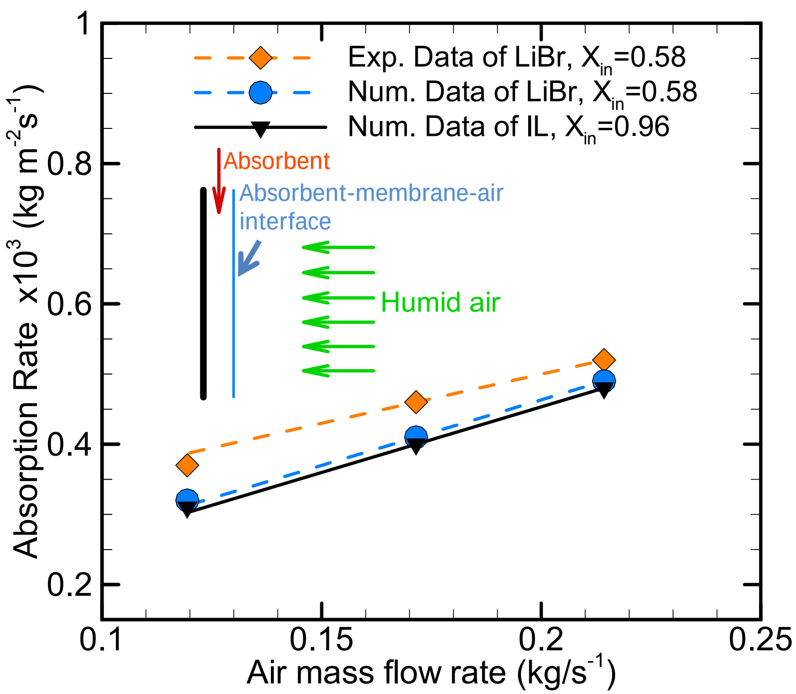
$$u_j X_{,j} = D X_{,jj}$$

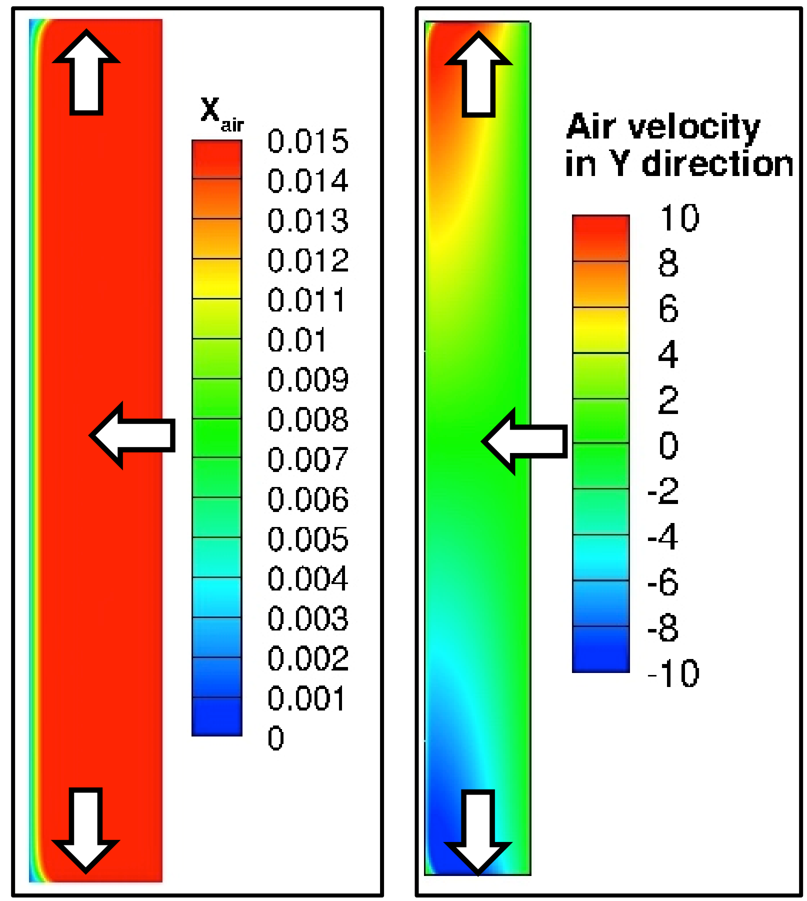
Dusty-Gas model to calculate the vapor flow rate through the membrane pores:

$$J = k_m \left(P_v - P_{s,w} \right)$$

$$k_m = -\left(M / \delta_m \right) \left[D_e^k / \left(RT \right) + PB_0 / \left(RT \mu \right) \right]$$

Numerical Analysis





Conclusions

- Absorption systems can be transformed into compact, light, and inexpensive configurations
  - 2nd generation closed LiBr system is fabricated and will be tested soon
  - 2nd generation open system with an ionic liquid is fabricated and currently being tested
- Ionic liquids enable overcoming the traditional operation limits of absorption cycles
  - Avoid crystallization
    - Robust and low cost system
    - High water output temperature

Acknowledgements

DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA

arpa·e
CHANGING WHAT'S POSSIBLE

OAK RIDGE
National Laboratory

Thank you

Publications and Patents

Publications

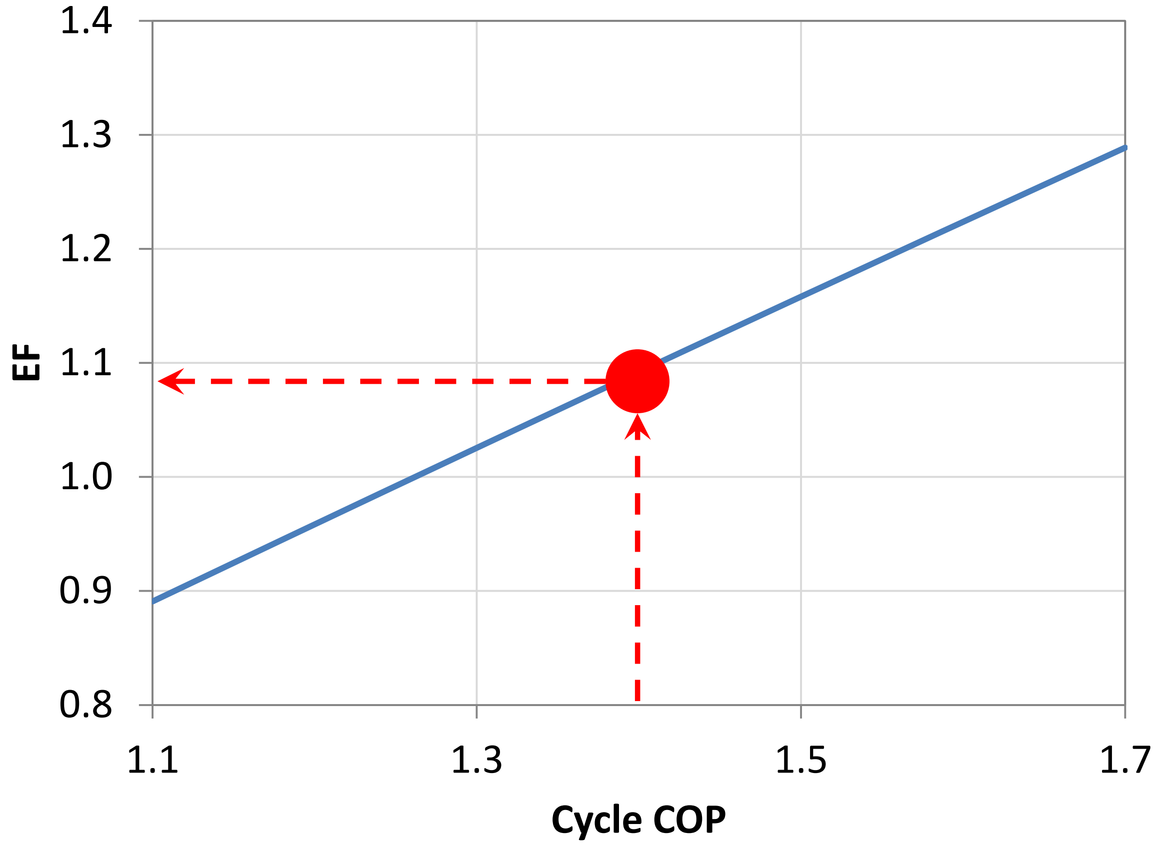
- S. Bigham, R. Nasr Isfahani, and S. Moghaddam, "Direct Molecular Diffusion and Micro-mixing for Rapid Dewatering of LiBr Solution," Applied Thermal Engineering, vol. 64, pp. 371-375, 2014.
- R. Nasr Isfahani, A. Fazeli, S. Bigham, and S. Moghaddam, "Physics of Lithium Bromide (LiBr) Solution Dewatering Through Vapor Venting Membranes," International Journal of Multiphase Flow, vol. 58, pp. 27-38, 2014.
- S. Bigham, D. Yu, D. Chugh, and S. Moghaddam, "Moving Beyond the Limits of Mass Transport in Liquid Absorbent Microfilms through the Implementation of Surface-Induced Vortices," Energy, vol. 65, pp. 621-630, 2014.
- R. Nasr Isfahani, K. Sampath, and S. Moghaddam, "Nanofibrous Membrane-based Absorption Refrigeration System," International Journal of Refrigeration, vol. 36, pp. 2297-2307, 2013.
- R. Nasr Isfahani and S. Moghaddam, "Absorption Characteristics of Lithium Bromide (LiBr) Solution Constrained by Superhydrophobic Nanofibrous Structures," International Journal of Heat and Mass Transfer, vol. 63 (5-6), pp. 82-90, 2013.
- D. Yu, J. Chung, and S. Moghaddam, "Parametric Study of Water Vapor Absorption into a Constrained Thin Film of Lithium Bromide Solution," International Journal of Heat and Mass Transfer, vol. 55 (21-22), pp. 5687-5695, 2012.

Patents

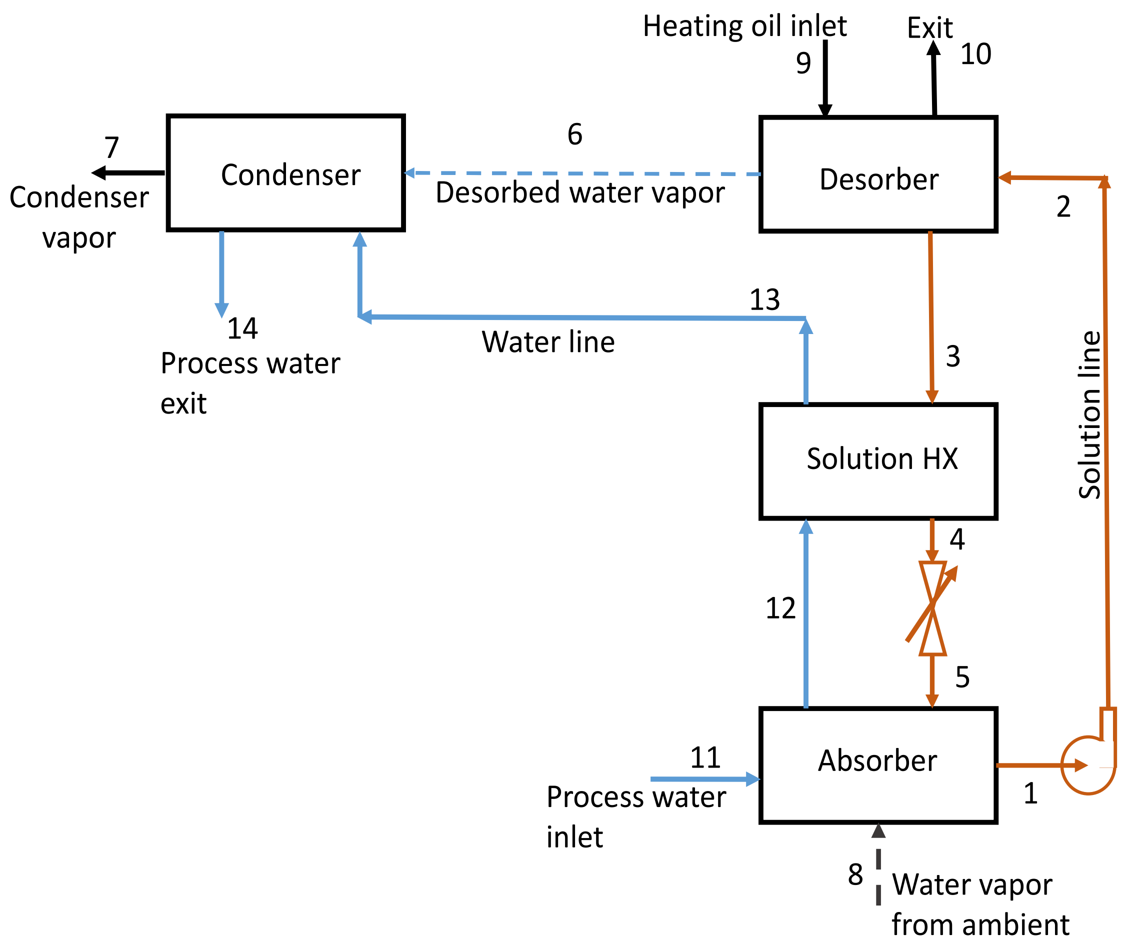
- S. Moghaddam, D. Chugh, R. Nasr Isfahani, S. Bigham, A. Fazeli, D. Yu, M. Mortazavi, and O. Abdelaziz, Open Absorption Cycle for Combined Dehumidification, Water Heating, and Evaporating Cooling, Patent Application UF-14820, 2013.
- S. Moghaddam and D. Chugh, Novel Architecture for Absorption-based Heaters, Patent Application UF-14697, 2013.
- S. Moghaddam, Thin Film-based Compact Absorption Cooling System, WO Patent 2,013,063,210, 2013.
- S. Moghaddam, D. Chugh, S. Bigham,3D Microstructures for rapid Absorption and Desorption in Mechanically Constrained Liquid Absorbents, UF Patent#14936, 2013

Energy Factor (EF)

- Projected system EF (water heating) based on absorption cycle test results

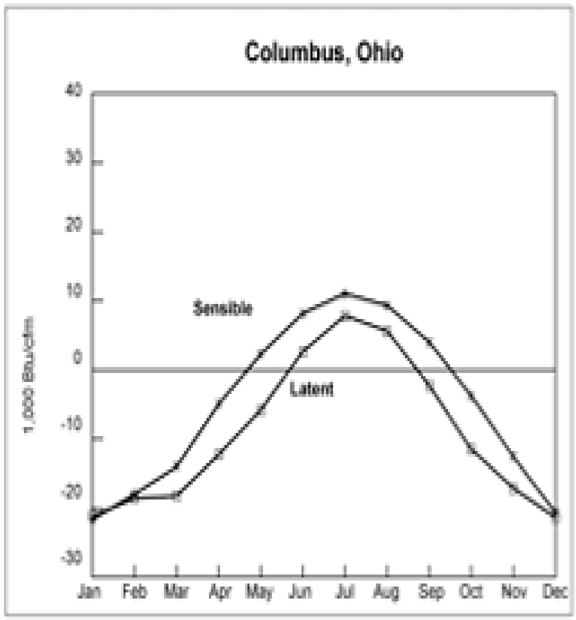


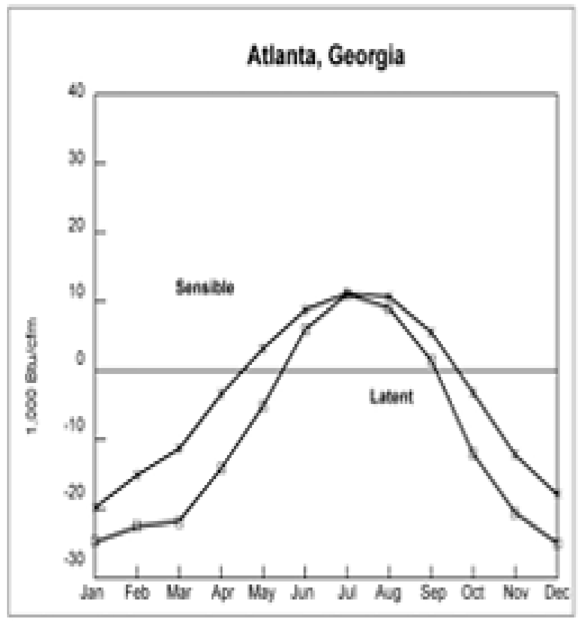
Cycle Analysis

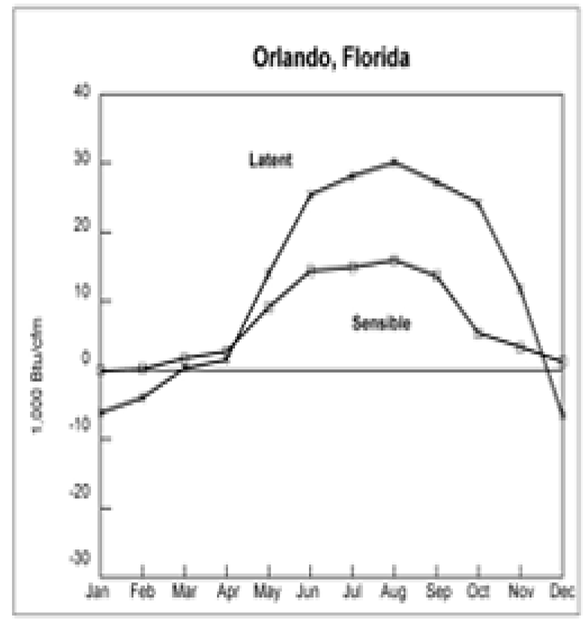


Latent vs. Sensible Heat Load

➢ Buildings latent heat significantly exceeds the sensible heat load in hot-humid climates



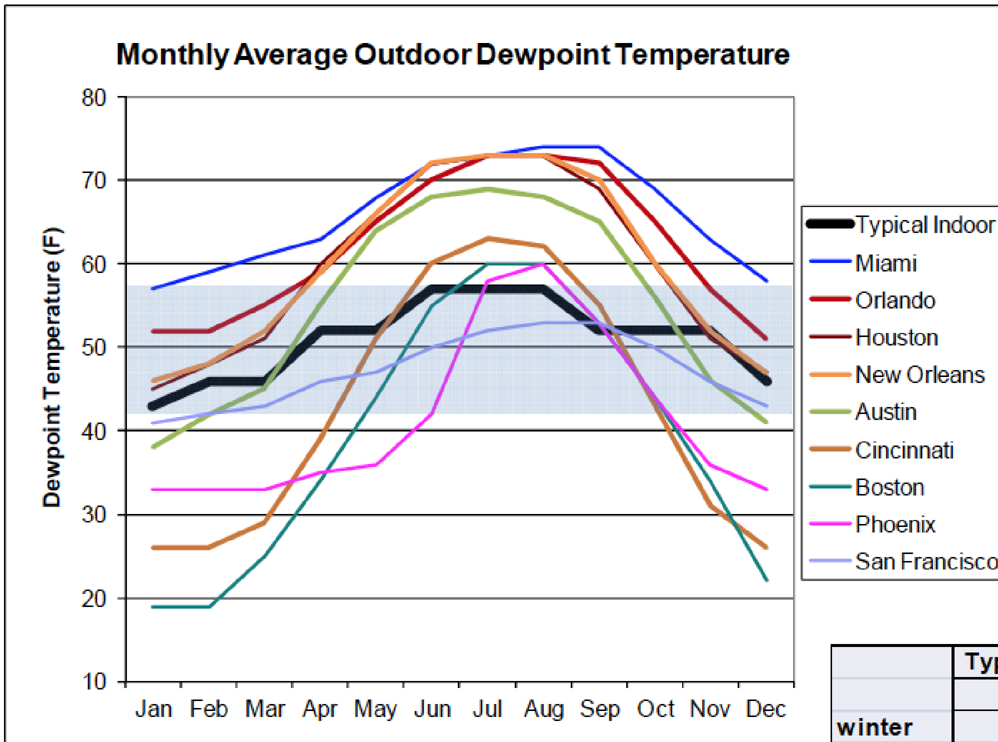




In Miami, the latent load exceeds the sensible load by 6.7:1

✓ Regional solutions

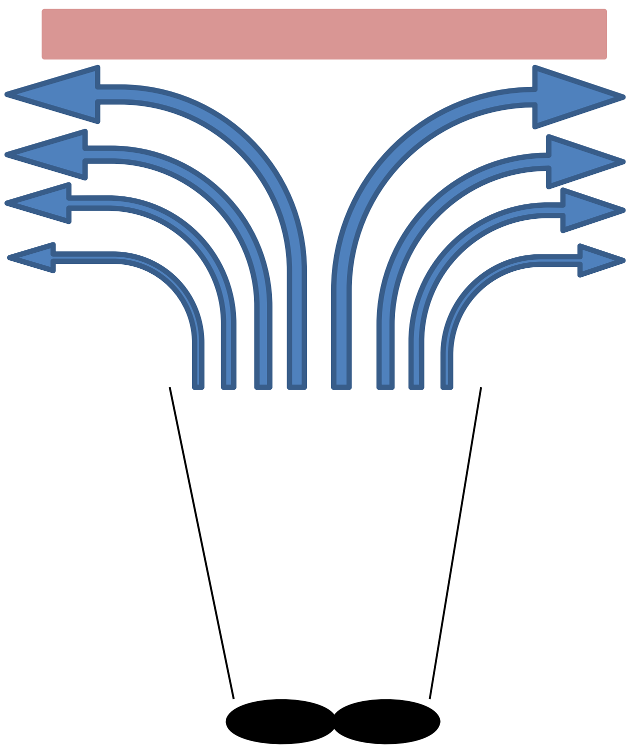
Humidity Control Challenges in Residential Buildings



	Typical Indoor (humid climate)		
	Tdb	RH	Tdp
winter	72	40	46
spring	75	45	52
summer	77	50	57
fall	75	45	52

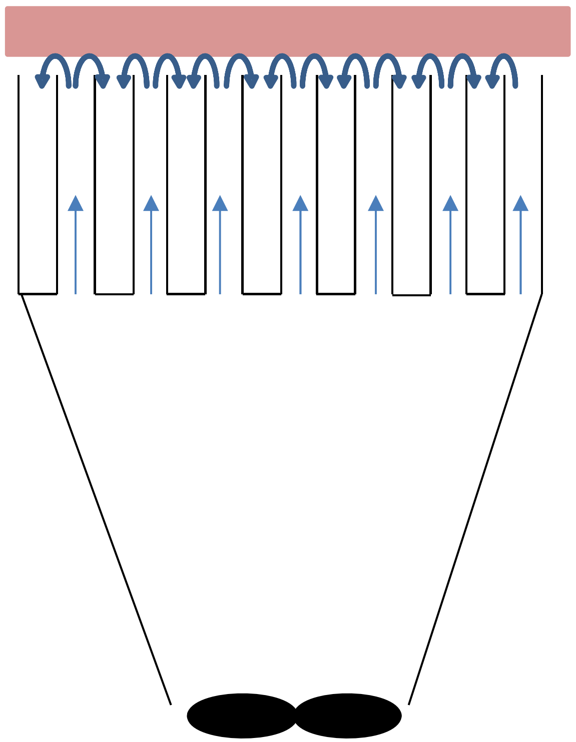
From: Armin Rudd, Residential Humidity Control Strategies, Residential Energy Efficiency Stakeholder Meeting, Austin TX, February 2012

Improvement of Air Distribution

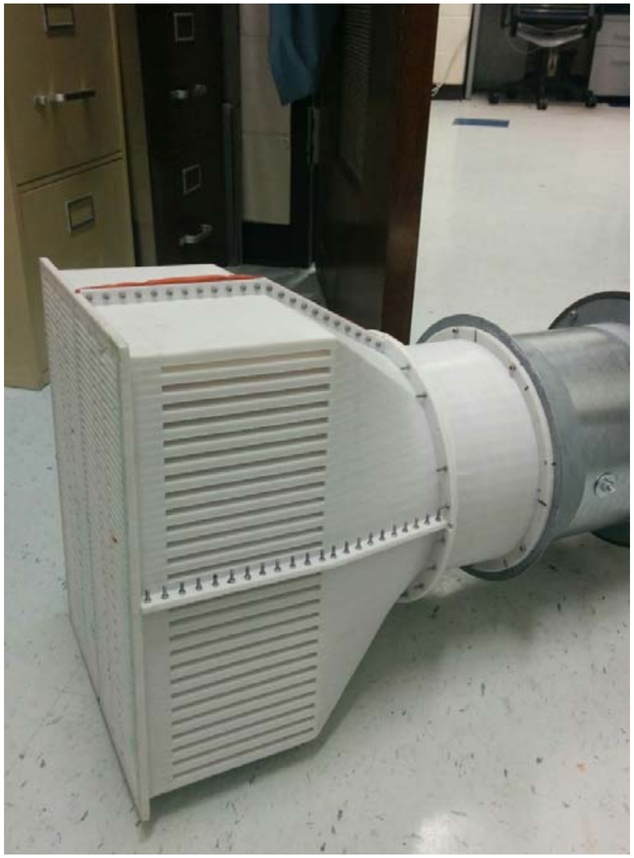


Fan

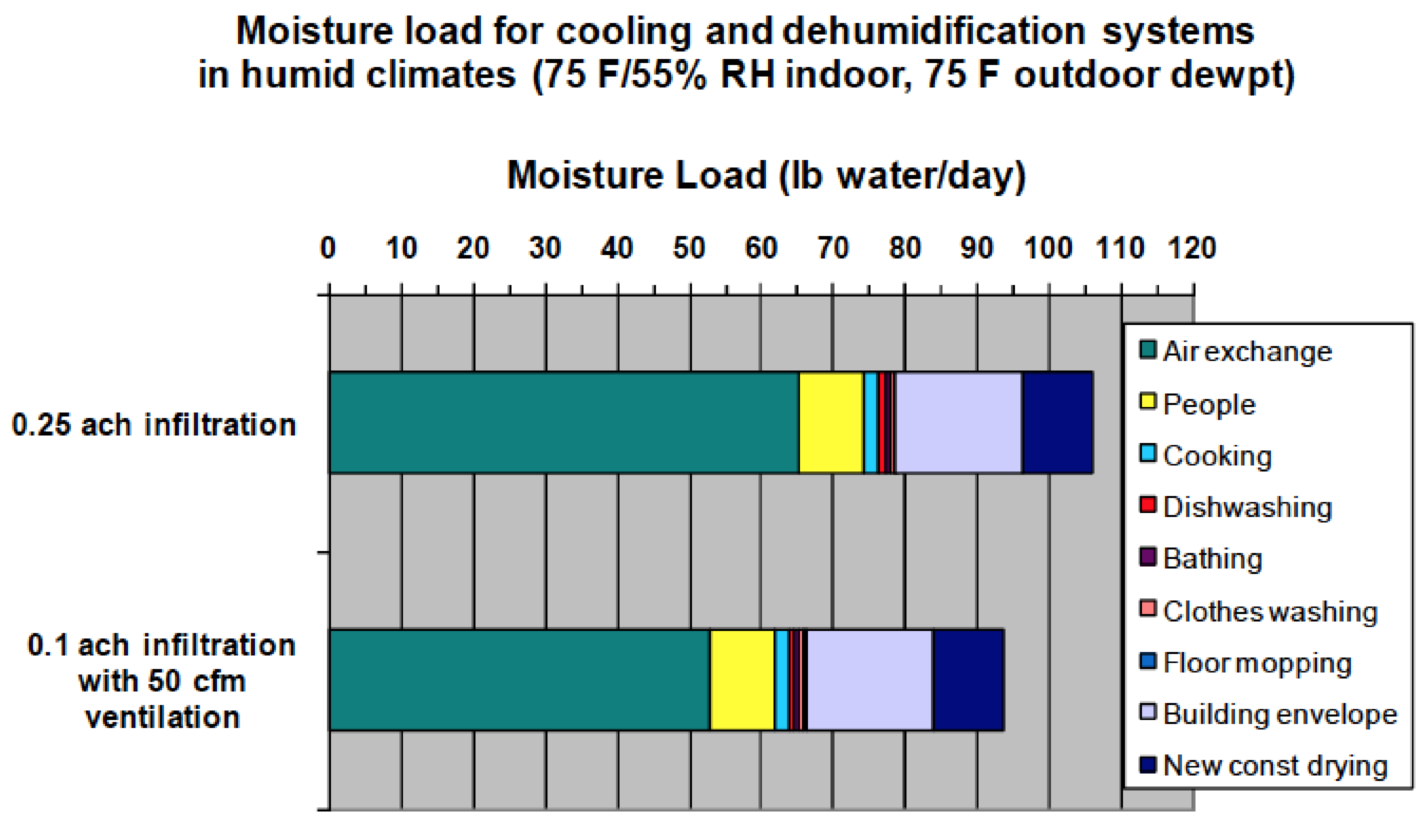
Previous duct design



Improved air distribution

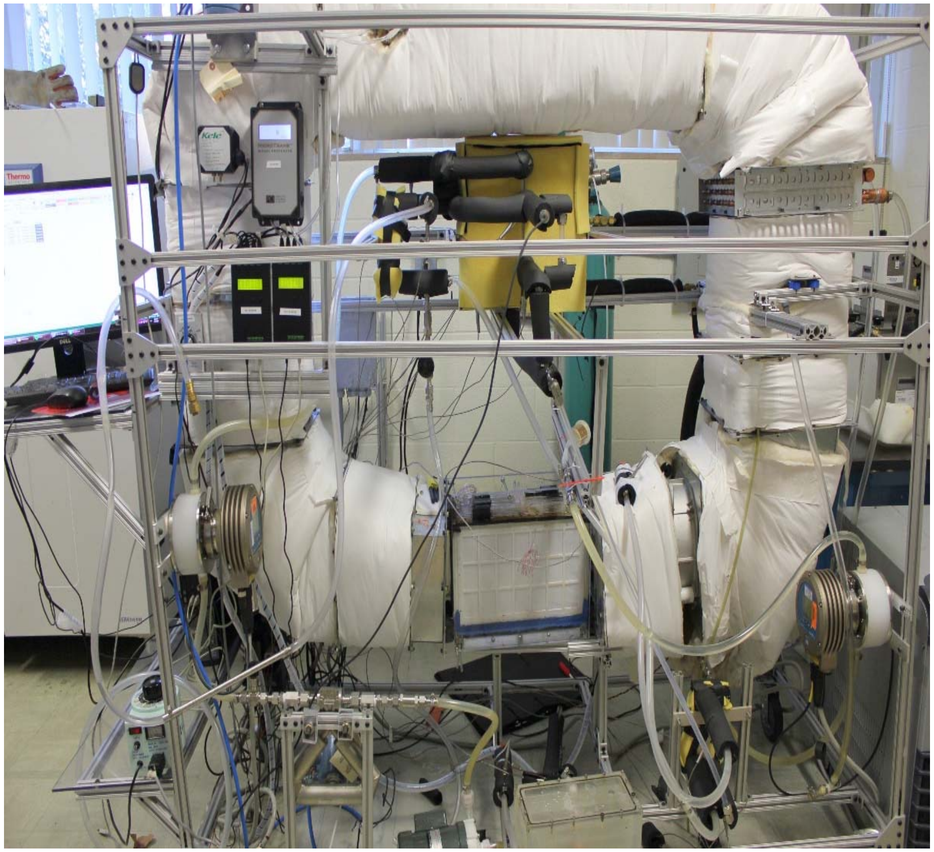


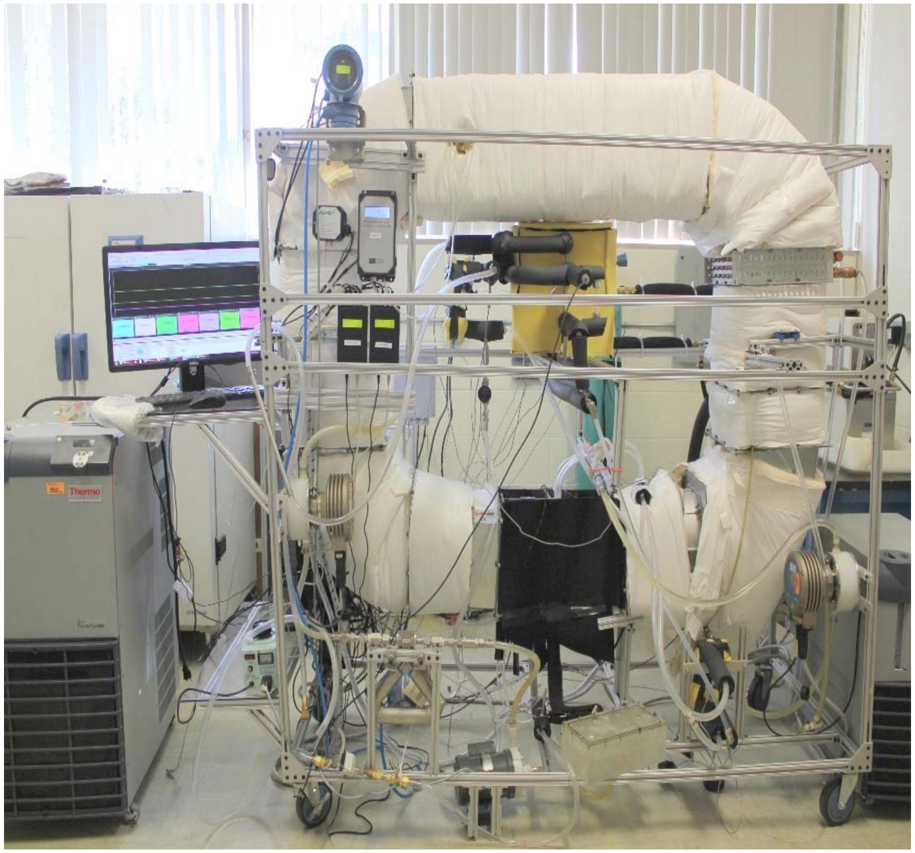
Humidity Control Challenges in Residential Buildings (cont.)



From: Armin Rudd, Residential Humidity Control Strategies, Residential Energy Efficiency Stakeholder Meeting, Austin TX, February 2012

Experimental Loop





Water Heater Configuration