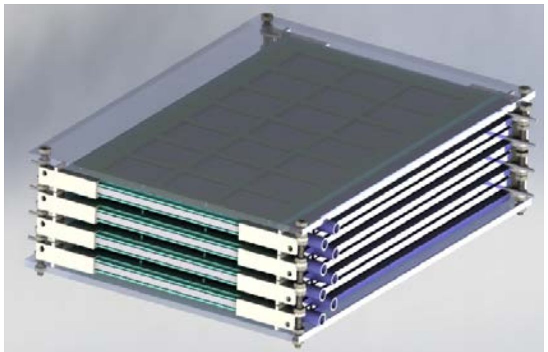
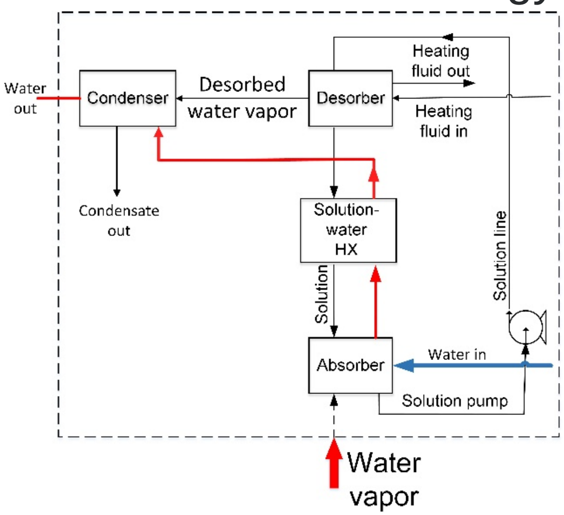
A Combined Water Heater Dehumidifier and Cooler (WHDC)

2016 Building Technologies Office Peer Review



Membrane Technology



Novel Cycle Architectures

No desiccant entrainment

High air velocity

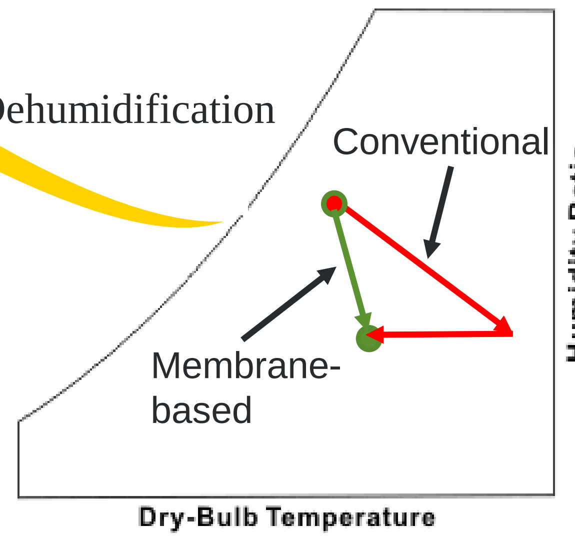
Four UF inventions

Compact size

Green fluids

No crystallization

Dehumidification



Dehumidification

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Project Summary

Timeline:

Start date: 10/01/2014

Planned end date: 11/30/2016

Key Milestones

Proof-of-concept

COP=1.6 to support EF > 1; 9/30/2015

Budget:

Total Project $ to Date:

- DOE: $999,993
- Cost Share: $111,111

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- DOE: $999,993
- Cost Share: $111,111

Key Partners:

ORNL
Stony Brook University

Project Outcome:

- Develop a low-cost gas-fired water heat pump to meet the DOE MYPP 2020 target
    - Enabled by 4 inventions
- Double the energy factor (EF) from current 0.62 to 1.3
    - Major savings in water heating energy consumption in-line with the DOE 2030 goal of reducing building energy consumption by 50%
- Additional dehumidification benefits; relevant to >50% of installations (inside house and basement)

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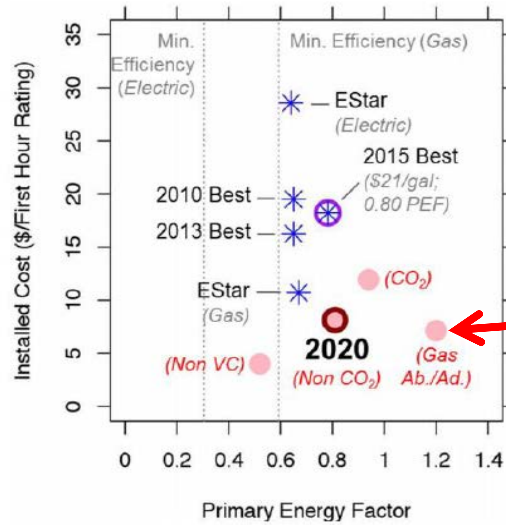
Purpose and Objectives

Problem Statement: >50% of water heaters shipped are gas-fired (~4 Millions/year)

- ➢ There is NO gas-fired water heat pump in the market

Target Market and Audience: A regional solution applicable to 3/5 of US climate zones: the mixed-humid, hot-humid and marine zones accounting for 54% of the US housing market

- ➢ Added dehumidification benefit for >50% of installations



2020 R&D targets are shown for:

Electric

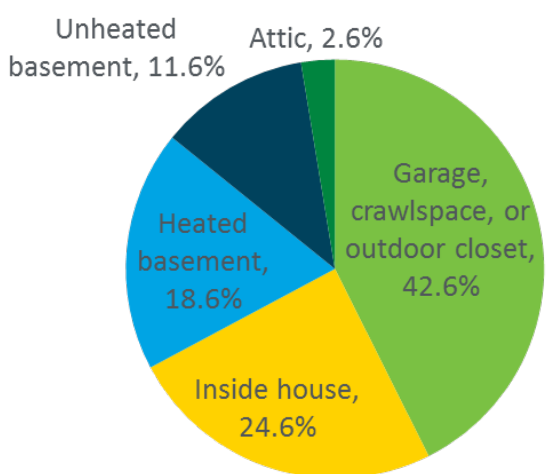
- Non-CO_2 vapor compression
- CO_2 vapor compression
- Non vapor compression

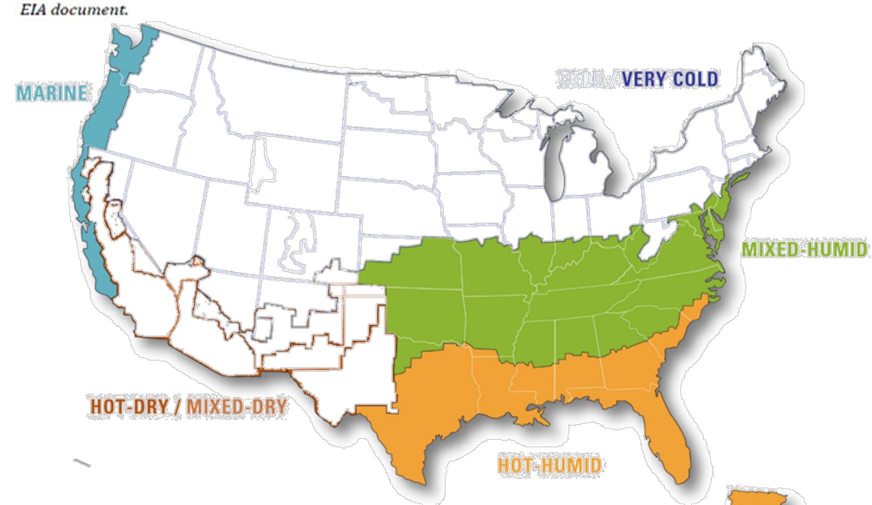
Gas-Fired

- Absorption/Adsorption

† *Installed costs are generally taken from EIA, "Updated Buildings Sector Appliance and Equipment Costs and Efficiencies," April 2015 (available at https://www.eia.gov/analysis/studies/buildings/equipcosts/). Exceptions are made for equipment not described by this EIA document, or where more accurate recent market data are available.*

* *Baseline is assumed to be the 2013 Best in Market residential electric resistance water heater from the above EIA document.*





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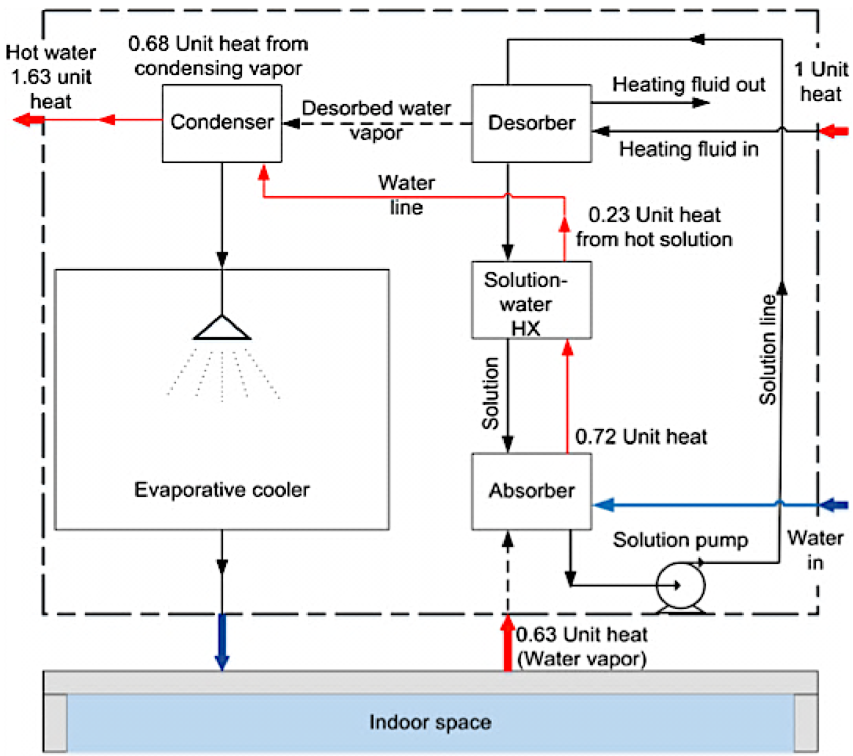
Approach: Novel Cycle

New Paradigm: latent vs. sensible heat communication with ambient

An open cycle substantially reduces the system cost

- Low-cost material (plastics), fab. process (injection molding), and equipment



Water heater, dehumidifier, and cooling (WHDC) system

Cycle performance at different operating conditions			
Environment	Conditions	Water Heating Capacity (kW)	Thermal COP
Conditioned Space	23°C, 50%	3.22	1.63
Cold Basement	6°C, 80%	3.28	1.54
Humid Outdoor	35°C, 70%	3.78	1.72

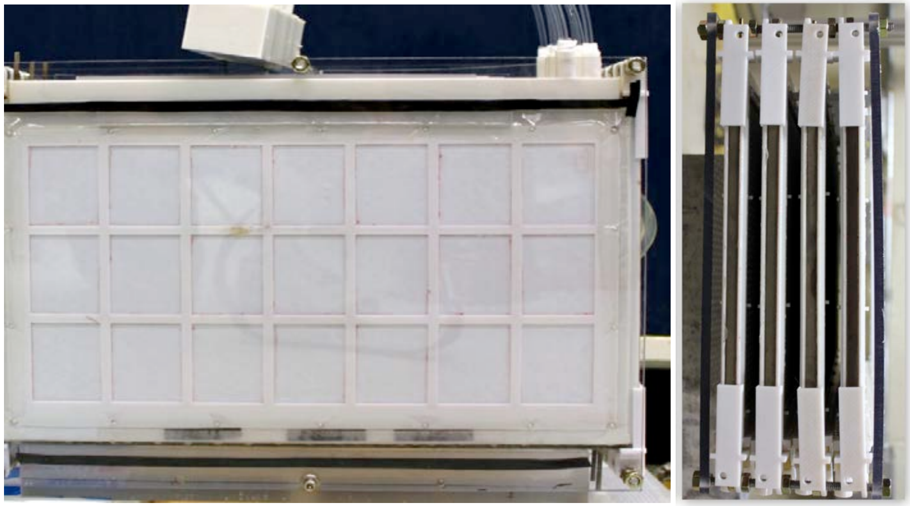
Key Issues:

- Packed-bed liquid desiccant absorbers can NOT be used due to liquid entrainment and coupling of heat and mass transfer
- Crystallization of existing salts limits operation range and requires control equipment that increase cost
- Existing salts are corrosive

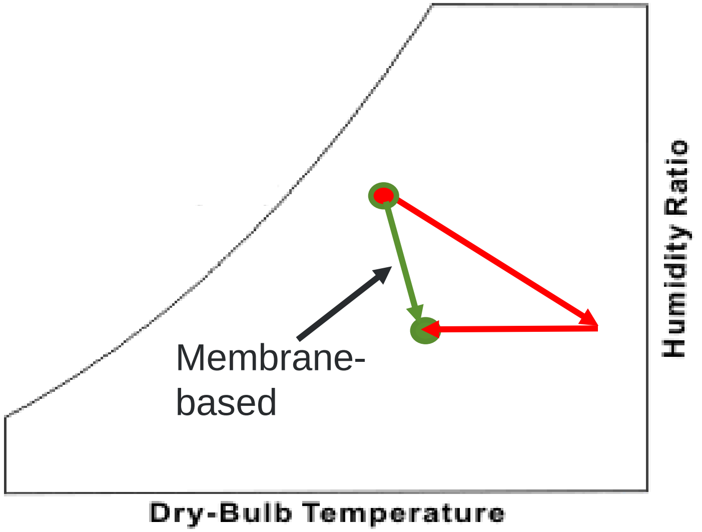
Approach: Enabling Absorber Technology

Membrane-based absorption technology:

- No liquid entrainment (we run air at 1000-2000 fpm)
- Enhances mass transfer from air but reduces heat transfer to air
- Half of the absorber is currently 3D printed and future absorbers can be mostly plastic
- Enables a compact system for installation on the existing tanks
- Liquid is fully contained within the system; enhances robustness



Fabricated absorber



Approach: Enabling Liquids

Ionic liquids (salts that remain liquid at room temperature):

Crystallization issue is addressed

- ➢ Allows to increase temperature lift
- ➢ Eliminates need for control equipment and associated costs

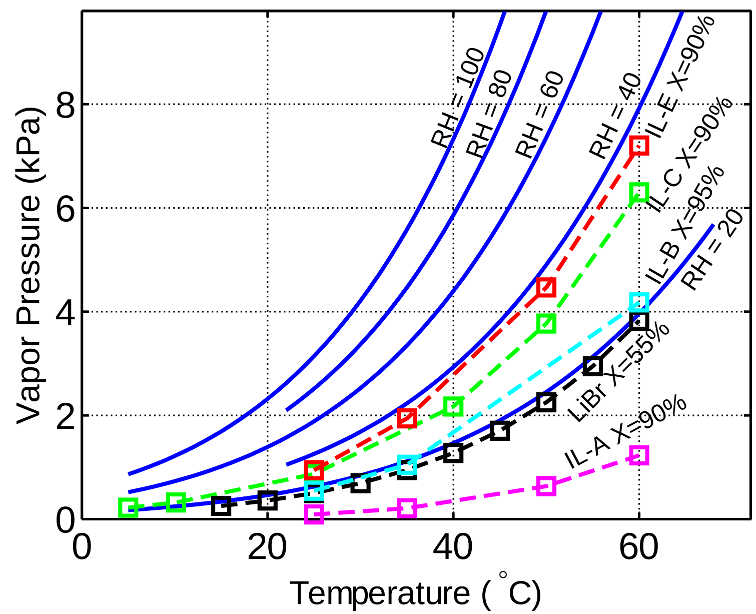
Properties can be tuned to enable different working conditions

- ➢ This will revolutionize the absorption cycles and enables operation under conditions previously not possible

Low corrosion rate

Environment friendly (green liquids!)

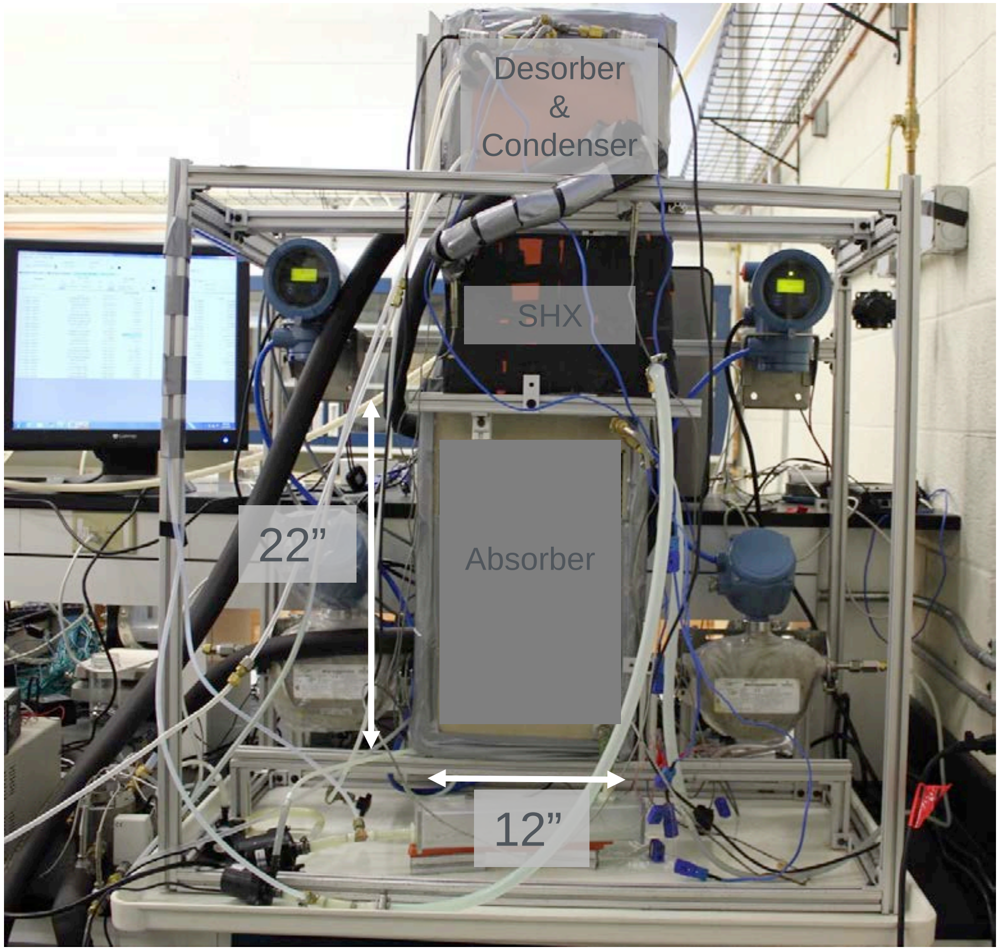
- ➢ We dispose the liquid in lab sink

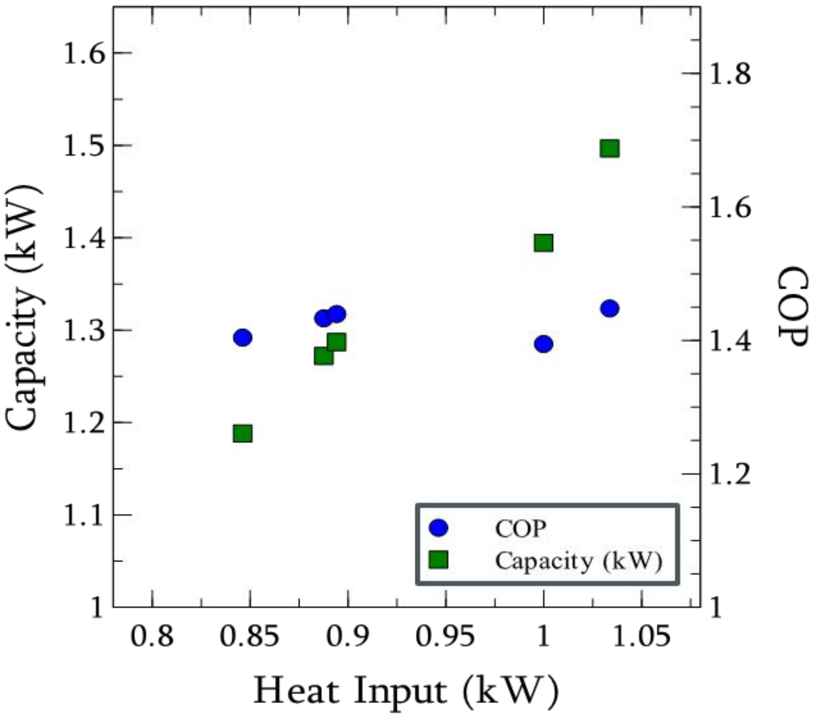


Progress and Accomplishments: 1st Gen. System

A demonstration unit was fabricated with LiBr solution (operated with hot oil)

- ➢ Required careful control to avoid crystallization
- ➢ Corrosion was a major issue, as expected





Performance of a LiBr system at 20-22 ° C and ~60% RH

Progress and Accomplishments: Energy Factor

This low cost technology can achieve the MYPP primary energy factor target.

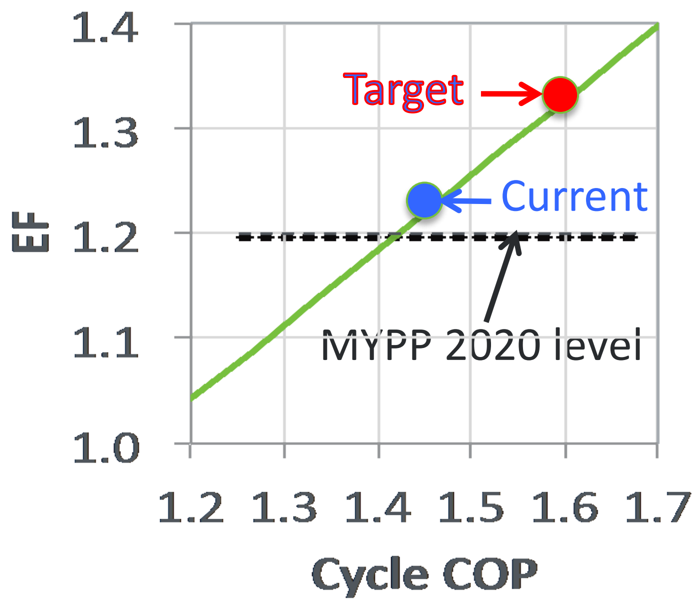
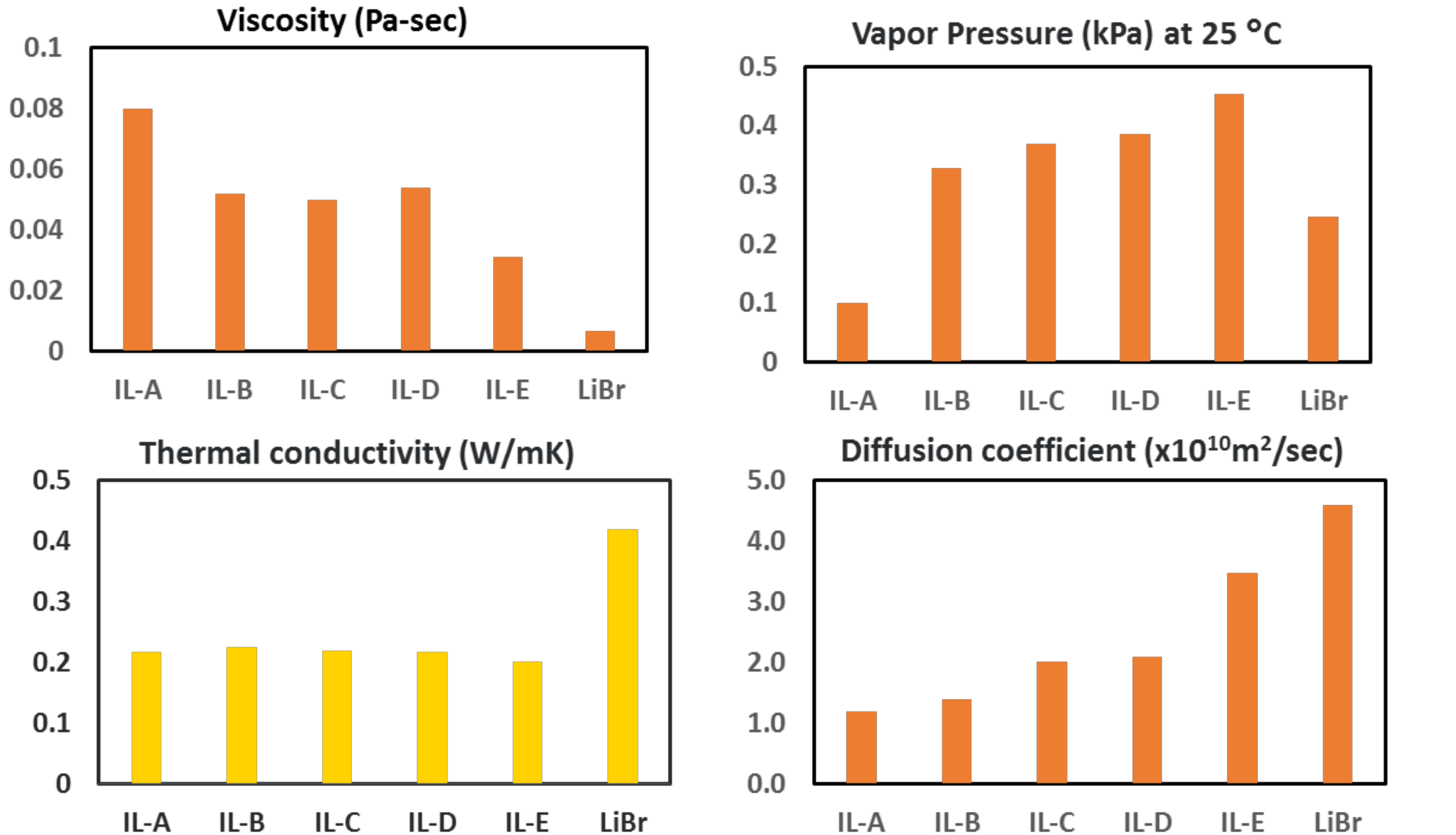


Figure assumes:

- 82% burner efficiency (fuel to desorber)
- 98% total combustion efficiency
- Electrical COP of 30
- Tank loss penalty factor of 94%

Progress and Accomplishments: Most Comprehensive Analysis of Ionic Liquids for Absorption Cycles

Developed extensive capabilities to measure P-T-X, thermal conductivity and capacity, heat of absorption, density, viscosity, mass diffusion coefficient (using PFG-NMR), and corrosion rate

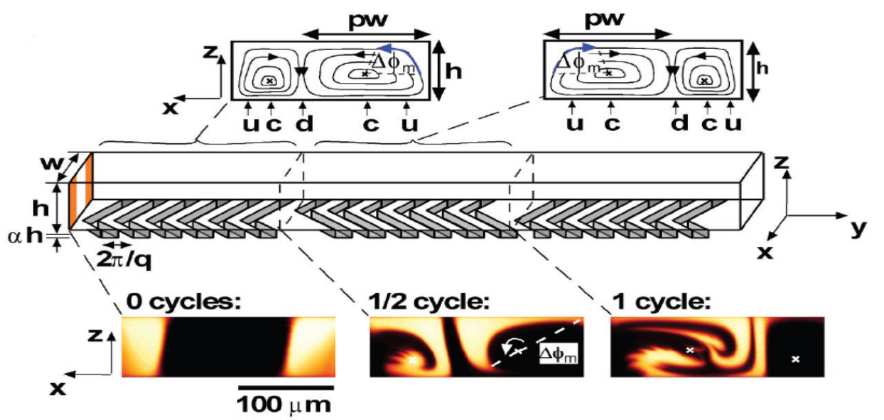


Progress and Accomplishments: Overcome Absorption Limitation of Ionic Liquids

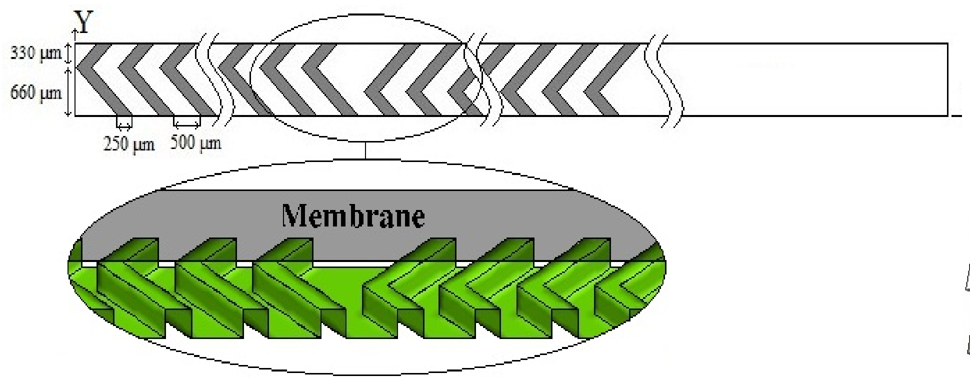
Low mass diffusion coefficient of ionic liquids lowers the absorption rate

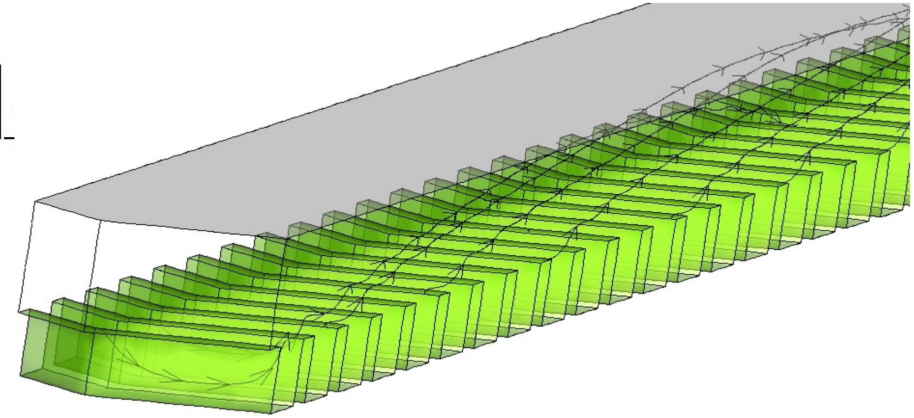
Chaotic mixing of the solution flow can help to overcome diffusion limitations

Used surface microstructures to generate vortices

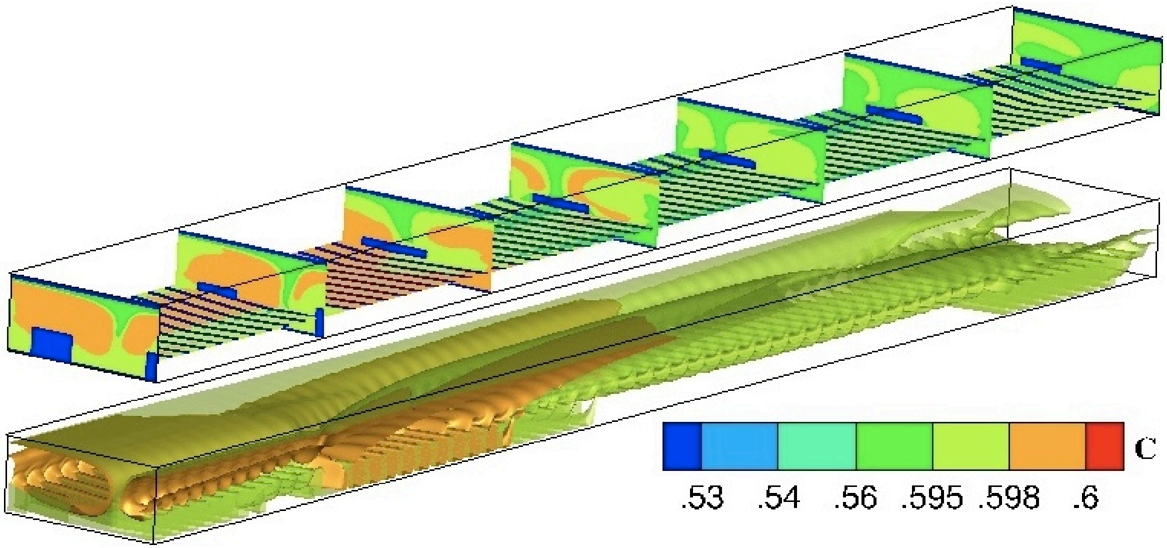


A. D. Stroock et al., Science, 2002

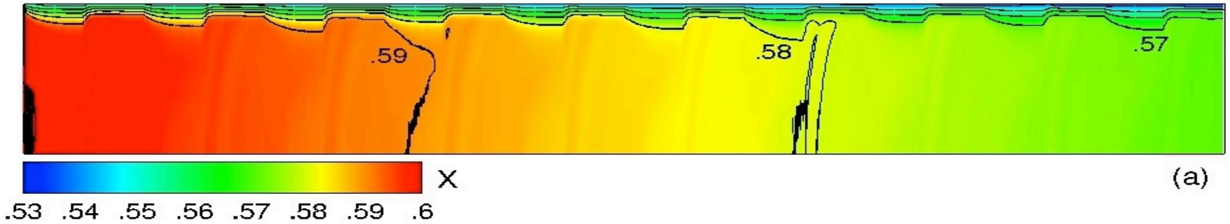




Progress and Accomplishments: Overcome Absorption Limitation of Ionic Liquids

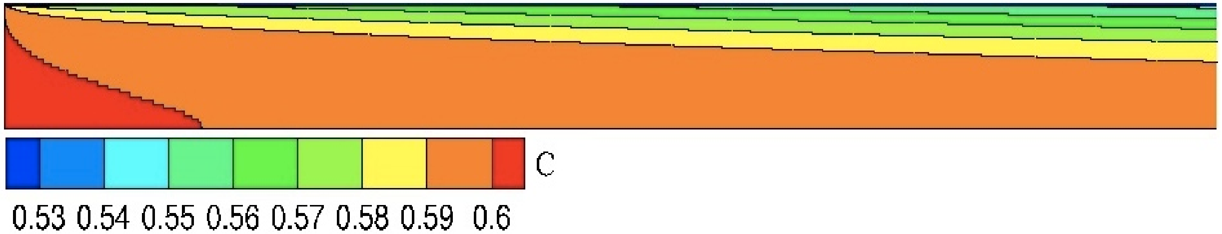


With mixing



Scaled by a factor of 100 in the x-direction

Without mixing



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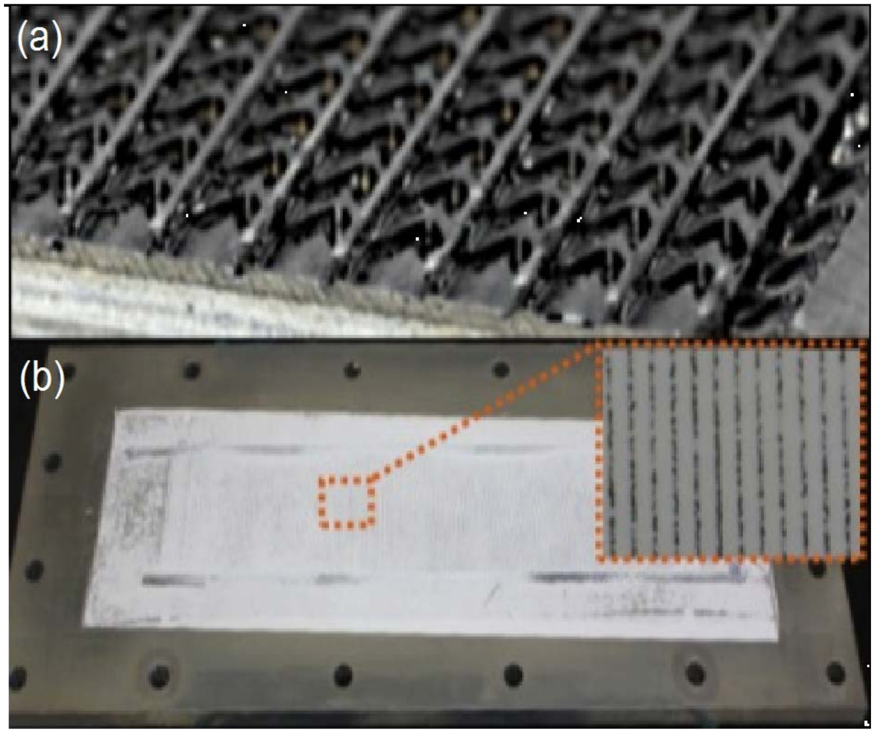
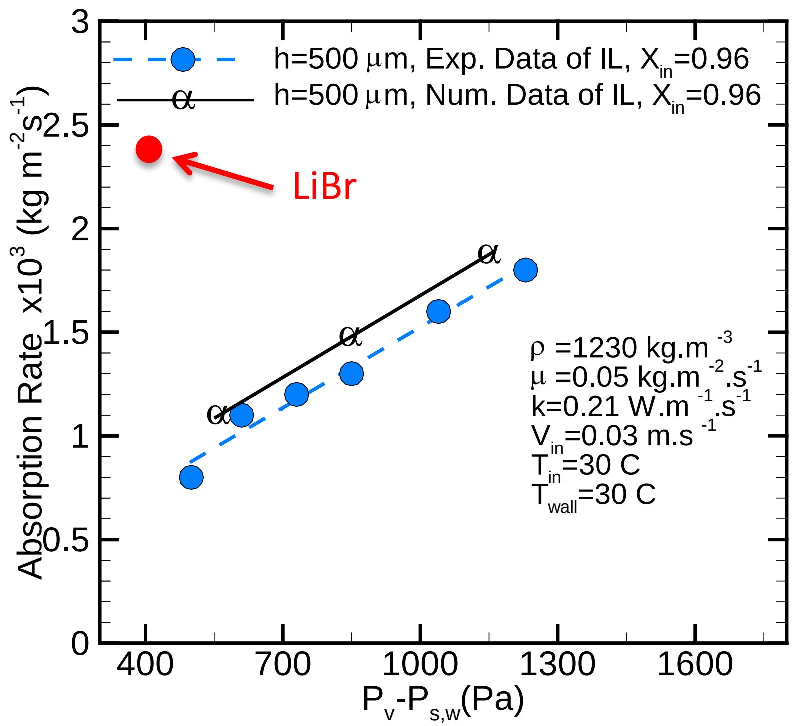
Progress and Accomplishments: Measured Absorption Rate of Ionic Liquids in a Closed System





Momentum, Energy and Concentration:

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

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

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

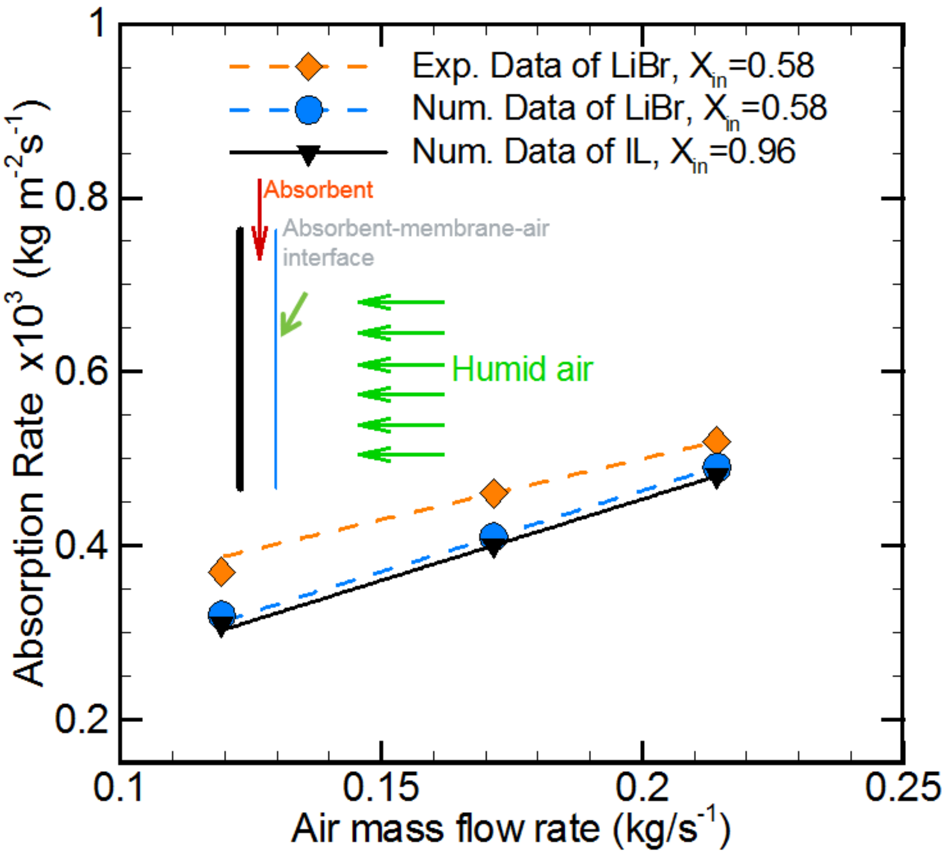
Dusty-Gas model to calculate the vapor flow rate through the membrane pores:

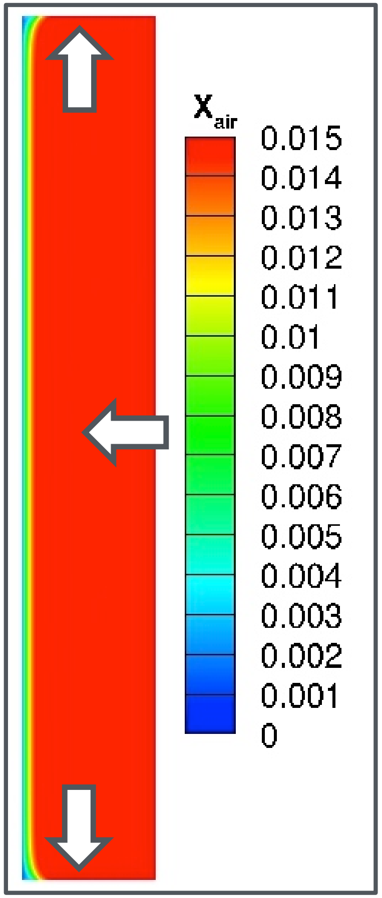
$$J = k_m \left(P_v - P_{s,w}\right)$$

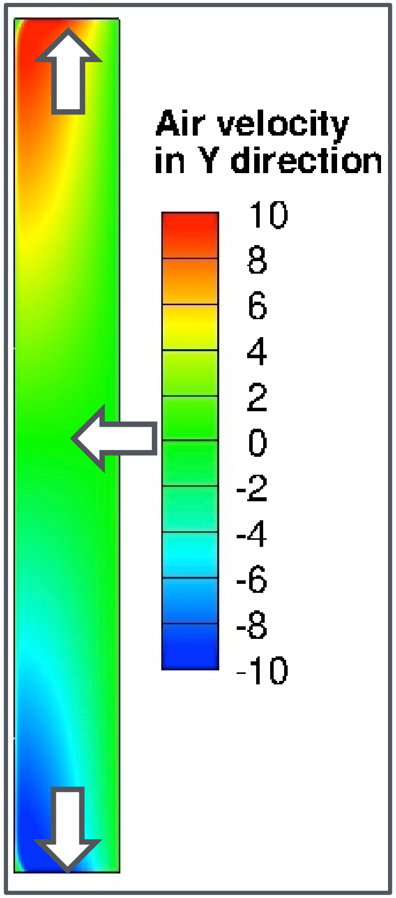
$$k_m = -\left(M / \delta_m\right)\left[D_e^k / (RT) + PB_0 / (RT\mu)\right]$$

Progress and Accomplishments: Full Numerical Model of Air, Solution and Cooling Medium

Absorption in air with ionic liquids is more limited by water molecules slow diffusion in air than in the solution





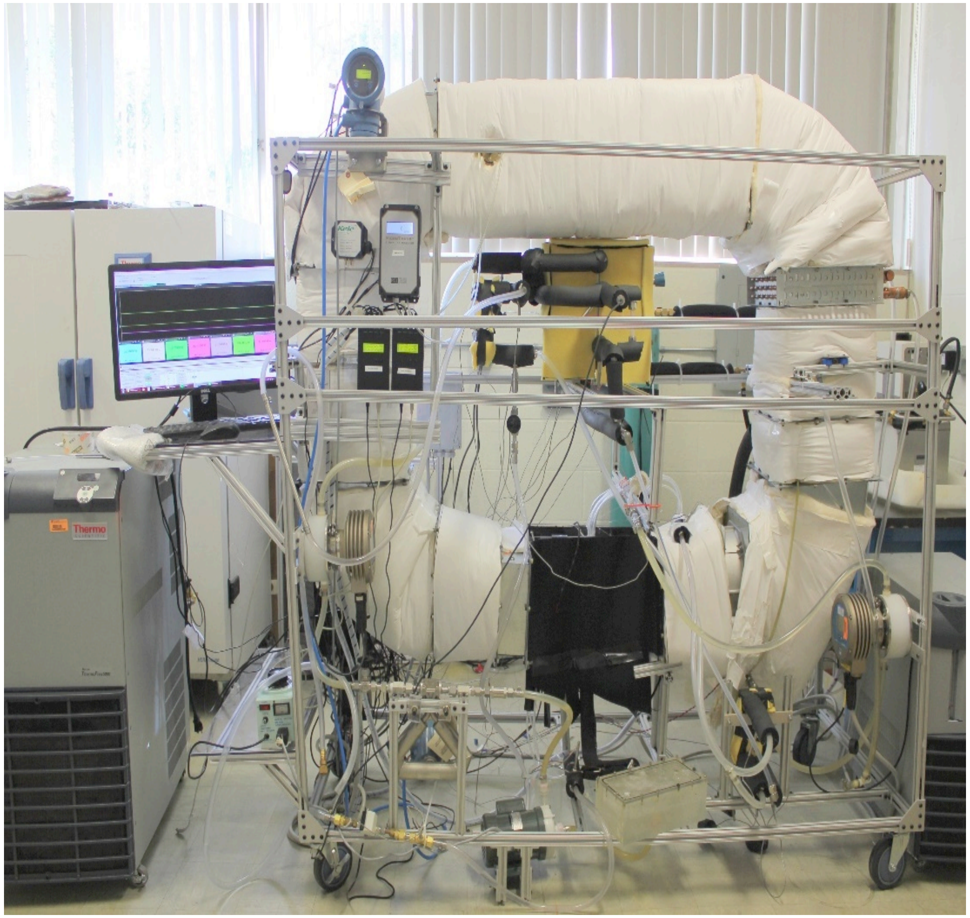


Progress and Accomplishments: Experimental Loop for Comprehensive Testing of the System

The system is equipped with

- Humidifier section to control air humidity
- Heat exchanger section to adjust air temperature (cooling and heating)
- Two concentration meters (after absorber and desorber)
- Air flow metering section and 3 liquid flow meters
- 12 temperature and humidity measurements before and after absorber

The evaporative cooler section has been tested



Progress and Accomplishments: Analysis of System Energy Saving Potential and Combustion System (Stony Brook University & ORNL)

During year one a model was developed to evaluate the potential of the proposed technology versus other competing technologies. The model involves analysis of system performance for representative cities (Miami, Atlanta, Houston, Los Angeles, etc.)

Hourly weather data, city water temperature, conditions at installation location (garage, indoor, and attic), stratified storage tank and draw pattern are parameters used in the analysis

- Final fine tuning of the results is being conducted

Commercial applications have been identified and are being analyzed

Applications with substantial latent load and water heating needs are suitable

- Swimming pools: dehumidification to control space humidity and add the energy back into the pool water
- Ice rinks: dehumidification for fog control and space heating
- Hospitals, hotels, and restaurants

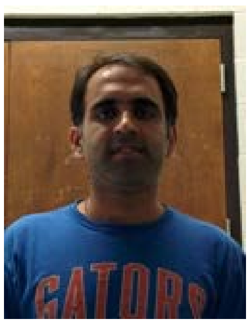
A combustion system with 85% efficiency has been fabricated/tested in ORNL

Project Integration and Collaboration

Project Integration: we communicate with other experts in the field and manufacturers on a continual basis

Partners, Subcontractors, and Collaborators:

University of Florida PhD students:



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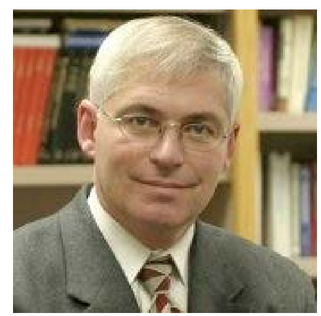

Communications:

ACEEE Hot Water Forum, Portland OR, 2016

ACEEE Hot Water Forum, Nashville TN, 2015

ASME ICNMM, San Francisco CA, 2015

Next Steps and Future Plans

System Performance: continue experimental (and analytical/numerical) study of the system performance under different working conditions (humidity and temperature)

Ionic Liquids: continue fine tuning the ionic liquids design; improve their properties and absorption and desorption characteristics

Prototype: first prototype is currently being fabricated, preliminary performance tests will be conducted at UF and the system will be shipped to ORNL for EF studies in an environmental chamber

Commercialization: upon successful demonstration of the system performance the following steps towards commercialization will be taken

a. Near term (1yr after completion): modify design based on lessons learned, address failure issues, and fabricate 2nd generation prototype and test
b. Intermediate (1-3yr after completion): field testing and partnership with other domain experts and manufacturers
c. Long-term (3yr.+ after completion): lunch the first product in 2020

References

Publications

- R. Nasr Isfahani, S. Bigham, M. Mortazavi, X. Wei, and S. Moghaddam, "Impact of Micromixing on Performance of a Membrane-Based Absorber," Energy, vol. 90, pp. 997-1004, 2015.
- M. Mortazavi, R. Nasr Isfahani, S. Bigham, and S. Moghaddam, "Absorption Characteristics of Falling Film LiBr (lithium bromide) Solution Over a Finned Structure," Energy, vol. 87, pp. 270-278, 2015.
- 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, M. Mortazavi, S. Bigham, Compact and Efficient Plate and Frame Absorber, UF-15794, 2015
- 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, 2014.
- 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-14936, 2013

Project Budget

Project Budget: Total Budget i) Federal Share $999,993 ii) Cost Share $111,111

**see details below*

Variances: PI assumed additional effort following resignation of a Post Doc and increase in Supplies needed for fabrication of equipment

Cost to Date: $638,654

Additional Funding: Not applicable

*Budget History						
Period	10/01/2014– FY 2015 (past)		FY 2016 (current)		FY 2017 – 11/30/2016 (planned)	
Details	DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
UF	$259,139	$43,436	$379,661	$48,476	$63,270	$8,079
SUNY	$39,085	$5,560	$52,147	$4,766	$8,691	$794
ORNL	$65,571	$-	$111,219	$-	$21,210	$-
Total	$363,795	$48,996	$543,027	$53,242	$93,171	$8,873

Project Plan and Schedule

- Project original initiation date: 10/01/2014
- Project original completion date: 9/30/2016
- Project updated completion date: 11/30/2016
  - ➢ Extended for 2 months due to lengthy 2nd year contract process
- Milestones have been met and project has received "GREEN" status for the quarter ending on December 30, 2015 (report submitted on January 31, 2016)
- The cycle thermal COP of 1.45 with the 1st generation is slightly less than proposed 1.6 but an EF (ultimate objective) of 1.2 is higher than the proposed EF
  - ➢ The new goal is to achieve an EF of 1.3