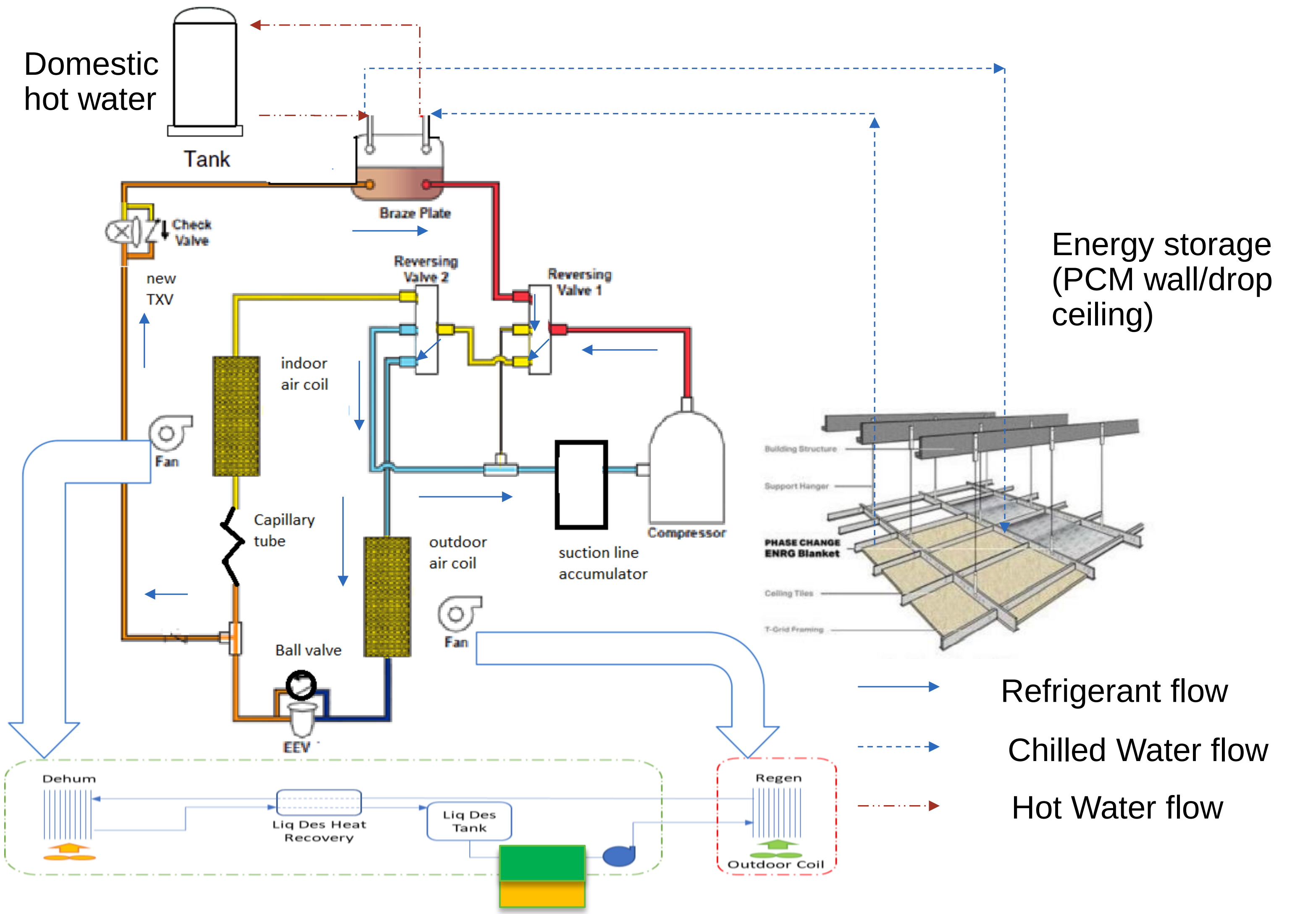
Packaged Integrated Heat Pump Coupled with a Two-Stream Liquid Desiccant System for Sensible and Latent Energy Storage in Building Envelope



Oak Ridge National Laboratory
Presenter: Lingshi Wang
PI: Bo Shen, Senior R&D Scientist
865-574-5745/shenb@ornl.gov

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Project Summary

Indoor side:

Outdoor side:

Objective and outcome

1. Develop **cost-effective multi-functional** packaged heat pump for multi-family buildings, having a IEER > 17.0; HSPF > 10.0 and annual water heating COP > 4.0, operate down to -10F.
2. **Grid-responsive sensible and latent energy storage** to maximize use of renewable energy, shift peak load > 2 hours.

Team and Partners

- Oak Ridge National Laboratory (ORNL)
- Emerson Climate Technologies

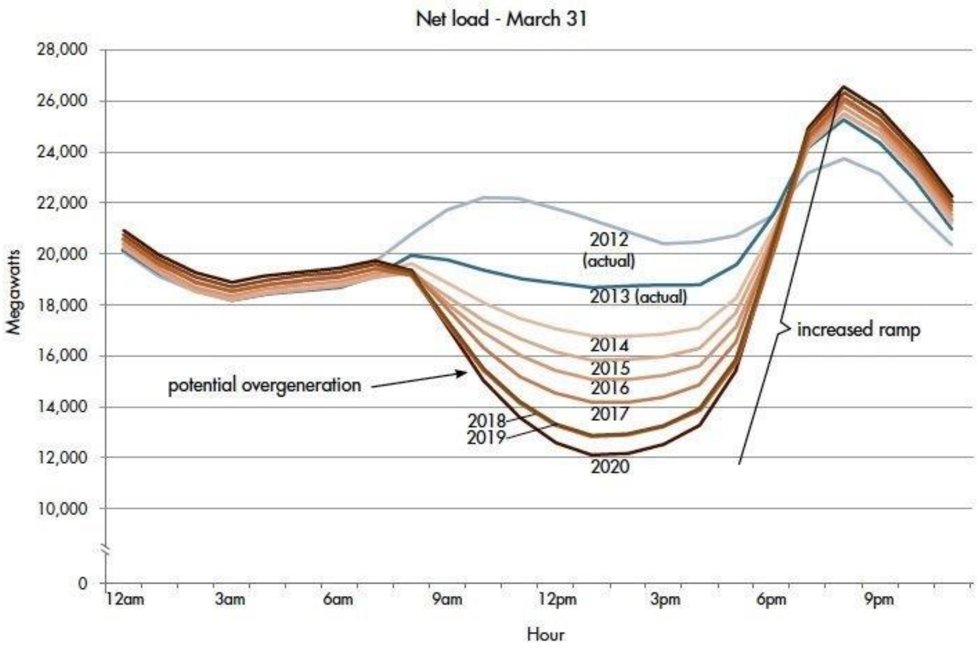
Stats

Start date: 04/01/2022
Planned end date: 09/30/2023

Key milestones

1. Complete prototype of multifunctional heat pump– 05/2022
2. Evaluate stand-alone liquid desiccant loop to verify moisture removal effect – 12/2022
3. System integration and performance tests– 05/2023
4. Install field test unit – 07/2023

Problems



- Maximize use of renewable energy: renewable energy production is not uniform.
- Grid-response: all-electrification needs energy storage to shift peak load and mitigate the size of power grids.
- Latent energy storge storage and moisture removal is a missing piece of current energy storage portfolio. Operations with reduced compressor speed and sensible energy storage lead to inadequate moisture removal.
- Multi-family building sector is a cost competitive market. A single-set of components provide all the home comforts, leading to good cost effectiveness.

Alignment and Impact

- Greenhouse gas emissions reductions: Develop high efficiency, cost-effective packaged heat pump: Achieve IEER > 17.0 (versus 14.0 mainstream products) and HSPF > 10.0, and integrated water heating annual efficiency > 4.0, to save annual energy up to 40% than a baseline suite of equipment.
- Power system decarbonization: Multifunctional unit is the charging station for grid-responsive control and active PCM sensible energy and liquid desiccant latent storage, strives to carbon free buildings.
- Energy justice: packaged multifunctional unit serves multi-family buildings and satisfies all home comfort needs.

Greenhouse gas emissions reductions

50-52% reduction by 2030 vs. 2005 levels

Net-zero emissions economy by 2050

Power system decarbonization

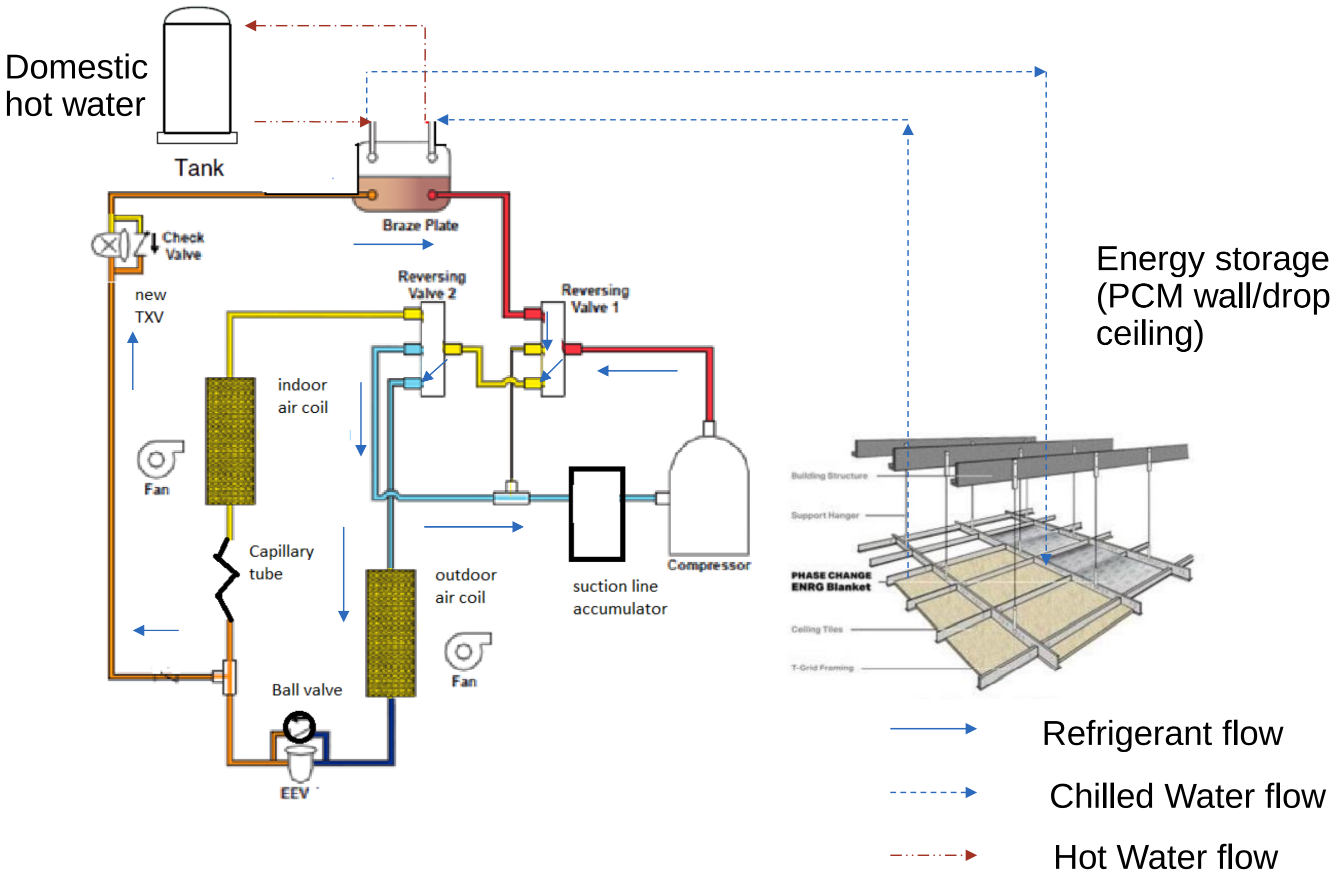
100% carbon pollution-free electricity by 2035

Energy justice

40% of benefits from federal climate and clean energy investments flow to disadvantaged communities

Approach – Built upon a Previous Development of Packaged Multi-functional Heat Pump with Grid-responsive Sensible Energy Storage

An innovative wall embedded air-source integrated heat pump (WAS-IHP) solution capable of space cooling, space heating, water heating (WH). Coupled with enhanced thermal storage elements—a water tank and phase change material (PCM) panels—the unit will respond to grid signals to shift peak load, for weather-forecast transactive control.



Six Working Modes:

- Space cooling
- Space heating
- Cooling energy storage
- Heating energy storage
- Water heating with outdoor air source
- <u>Water heating with indoor air source (combined space cooling and water heating)</u>

Progress: Laboratory Prototype

Hot water storage tank

Air-source integrated heat pump

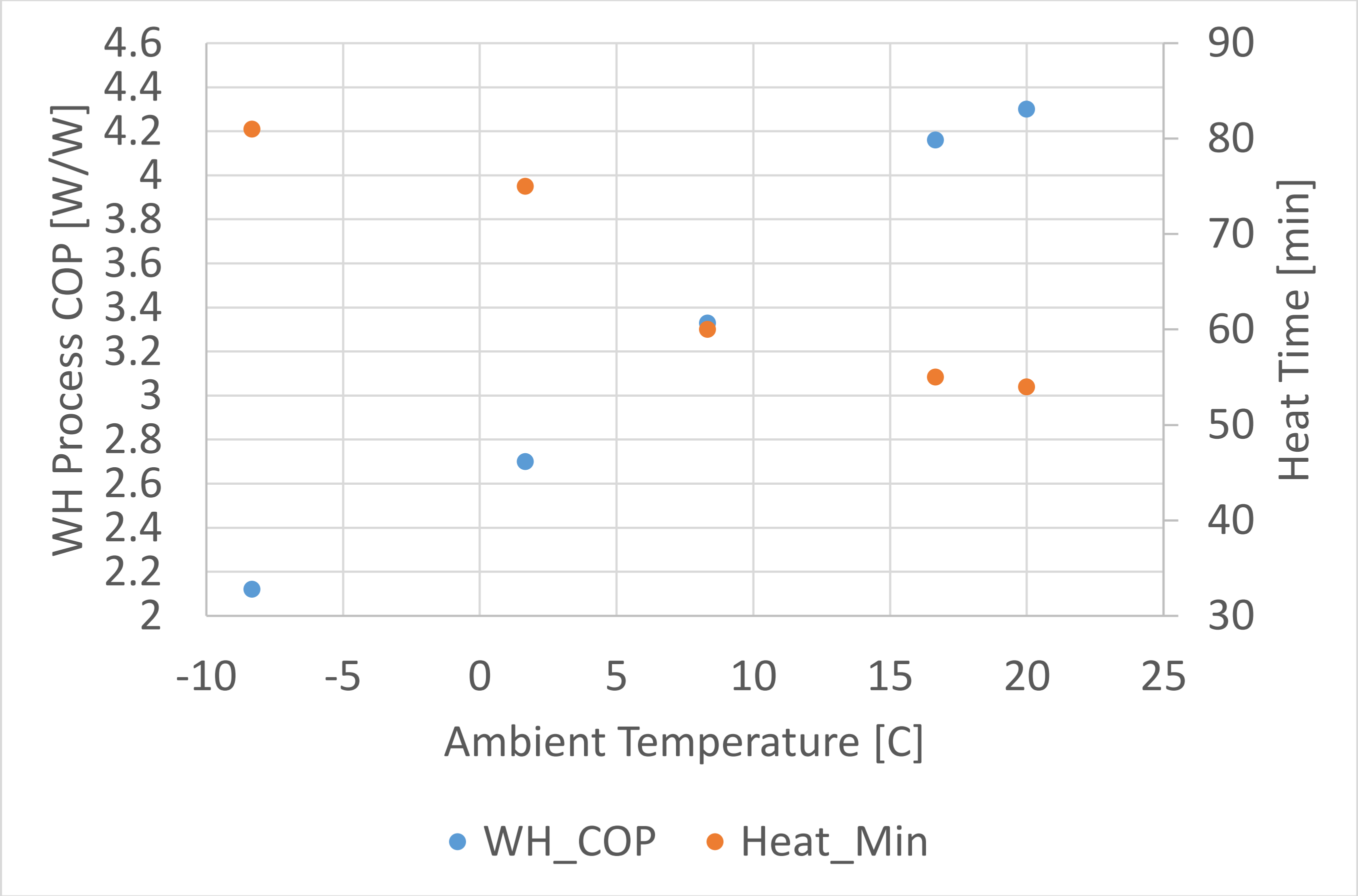
1st Two-Layer PCM HX

Heated/ cooled by IHP

BioPCM blankets

- ❑ PCM melting temp = 24C

Progress: Water Heating Energy Storage

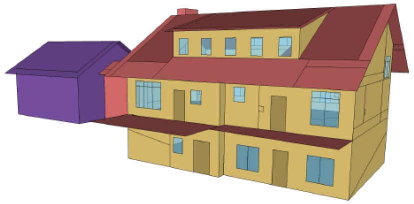


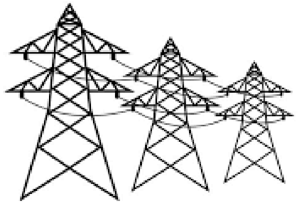
- Speedy heat-up of a 40-gallon water tank from 14˚C to 51.7˚C
- Efficient WH down to -8.3 ˚C
- Most efficient combined space cooling and water heating – integrated COP >8.5
- Extensive water heating capability and storage, which can be used to regenerate liquid desiccant

Progress: Development Platform of Model-predictive Control and Building Energy Simulation

Building Energy Simulation results:

	Baseline	PCM sensible energy storage
Average Relative Humidity (%)	57.9	70.1





Grid signals

Weather forecast

PCM model:
- Multi-node enthalpy method
- Piece-wise linear map between enthalpy and temperature
- Natural convection for room-to-PCM HX
- Effectiveness-NTU method for ASIHP charging rate calculation

Building Envelope + ASIHP

FMU Export of EnergyPlus

binaries
resources
.xml
.fmu

EnergyPlus fmu

Zone temperature + ASIHP operation status

PyFMI

Predictive Controller + PCM ceiling

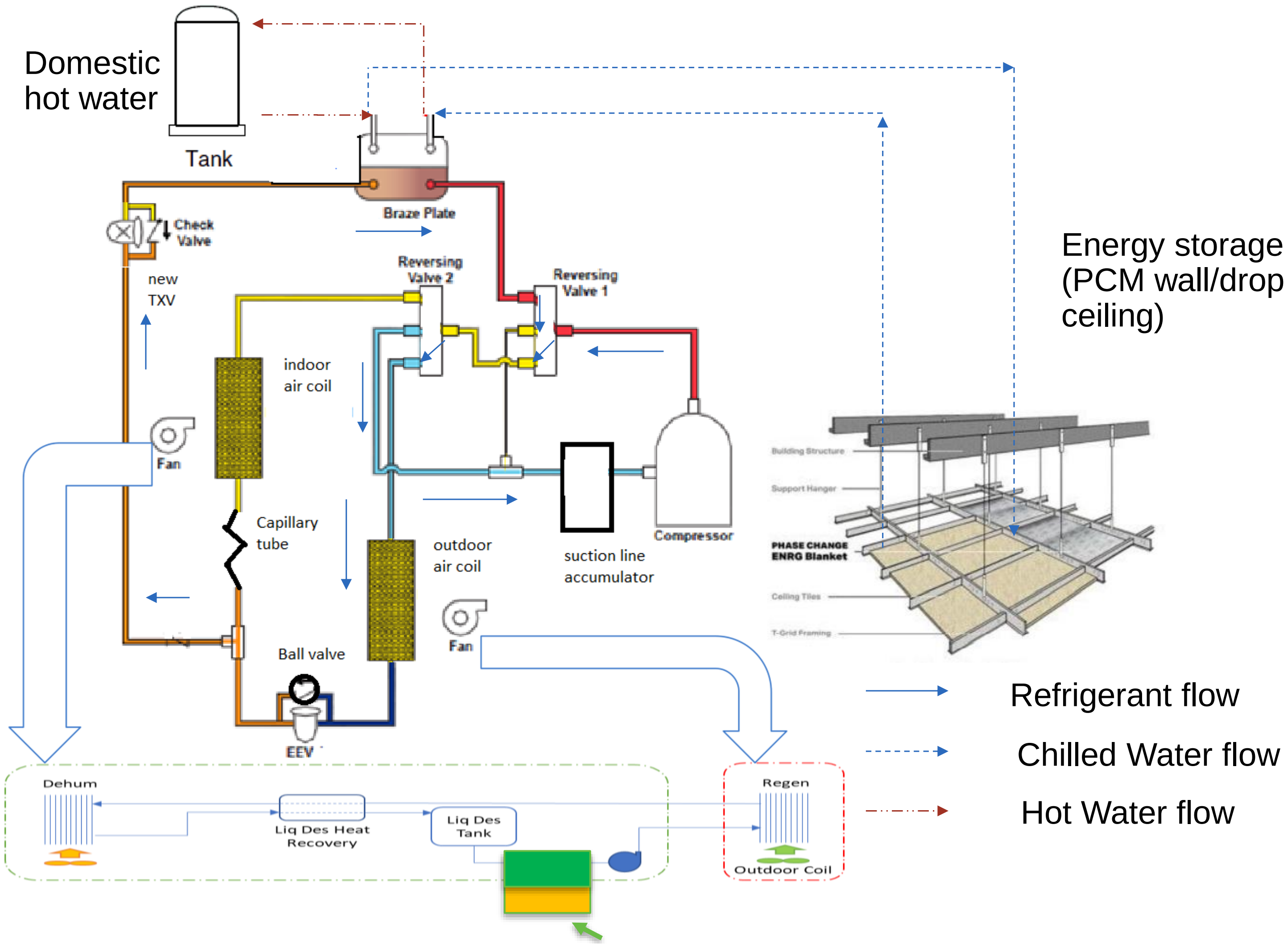
PCM-to-room HX rate + control commands

Functional Mock-up Interface

Controller design
- Mixed-integer convex programming algorithms for control optimization
- Data-driven control models for ASIHP, PCM and building loads

PCM sensible energy storage will lead to a new challenge – no enough humidity removal !!!

Approach: Cascading Liquid Desiccant Loop for Moisture Removal and Latent Energy Storage



Hot water heat exchanger to control liquid desiccant temperature and elevate the driving potential for regeneration

Table 1. Modes that enable efficient comfort improvement in all psychrometric operating states using liquid desiccant

	Heating	No Sensible	Cooling
Dehumidification	Not Needed due to Absolute Humidity at Heating Condition Water Vapor Saturation	• Dehumidification by Stored Desiccant • Mechanical Cooling with Liquid Desiccant Dehumidification	• Mechanical Cooling with Liquid Desiccant Dehumidification • Mechanical Cooling
No Latent	Mechanical Heating	System Idle	• Mechanical Cooling • Indirect Evaporative Cooling
Humidification	Mechanical Heating and Direct Evaporative Cooling	Mechanical Heating and Direct Evaporative Cooling	• Direct Evaporative Cooling • Mechanical Cooling and Direct Evaporative Cooling

Progress: Fabrication of Membrane, Plastic Heat Exchangers and System Assembly

Indoor side

Membrane

Outdoor side

Plastic recovery heat exchanger

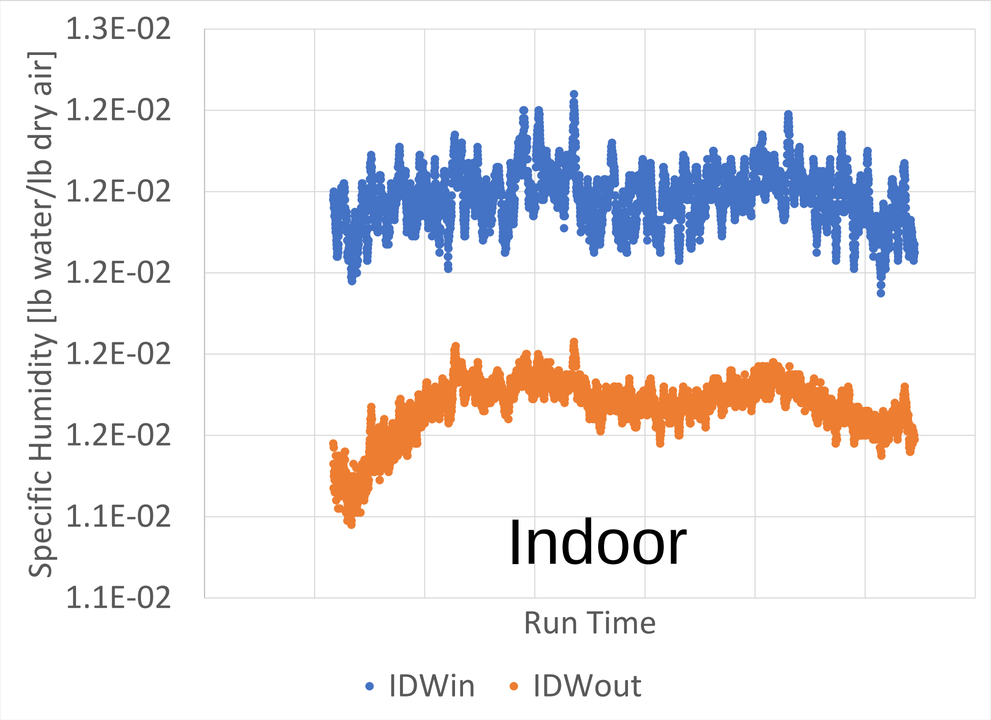
Progress -Verify Moisture Transfer Through Liquid Desiccant Circulation

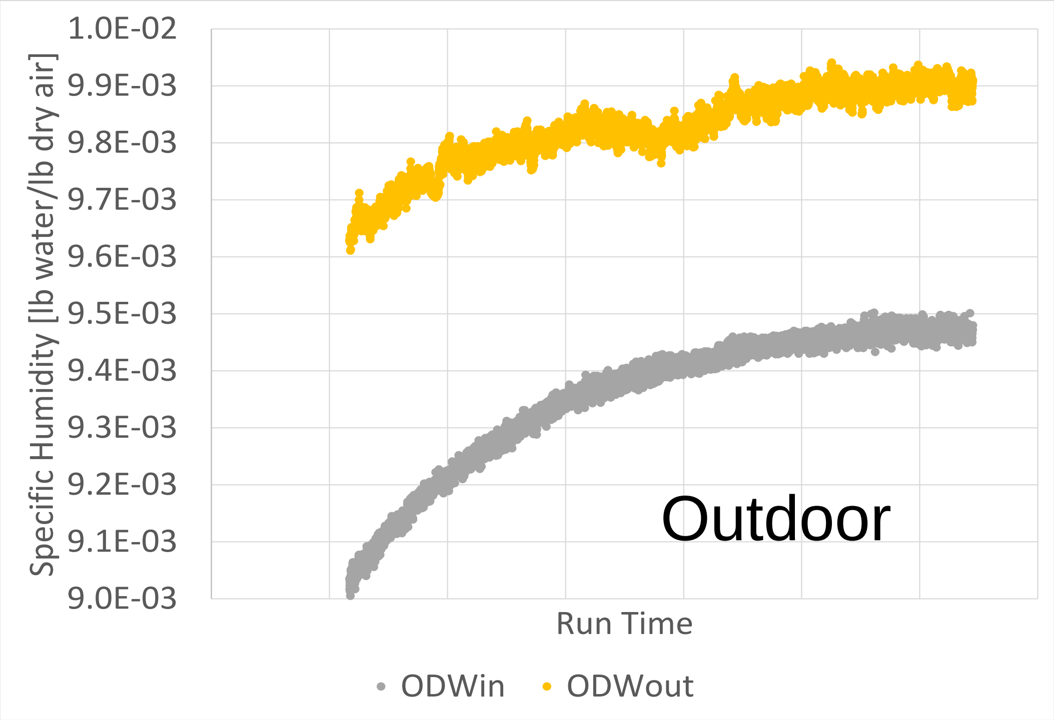
Test conditions:

	Temperature (°F)	Relative humidity (%)	Flow rate (CFM)
Indoor air	65	80-85	150
Outdoor air	85, 95, 110	20	Driven by the single-speed condenser fan
Desiccant solution	32 wt% $CaCl_2$ in the loop		

Test results:

- Indoor air was dehumidified
- Desiccant solution discharged moisture to the outdoor air





Progress -Improve Membrane Exchangers to Eliminate Leaks

Previous design had noticeable leakage through edges and pores

New design

- Improve the mass transfer effectiveness
- Minimize liquid desiccant leakages

Dissemination

FY23 Journal Publications:

- Hlanze, P., Z. Jiang, J. Cai, B. Shen. Model-based predictive control of multi-stage air-source heat pumps integrated with phase change material-embedded ceilings. **Applied Energy**, (2023), DOI: 10.1016/j.apenergy.2023.120796

FY23 Conference Publications:

- Shen, B., K. Gluesenkamp, Z. Li. Cold Climate Integrated Heat Pump with Energy Storage for Grid-Responsive Control. **ASHRAE and SCANVAC HVAC Cold Climate Conference 2023,** Anchorage, Alaska, March 6-8, 2023.

Stakeholder Engagement – Close Collaboration with Emerson

- Emerson developed a liquid-desiccant based latent energy storage technology, and fabricated all the membrane heat & mass exchangers, and plastic heat exchangers
- Emerson provided a multi-stage compressor sample for the multi-functional heat pump.

Future Work

(1) Improve the membrane exchangers to be leak free and higher effectiveness

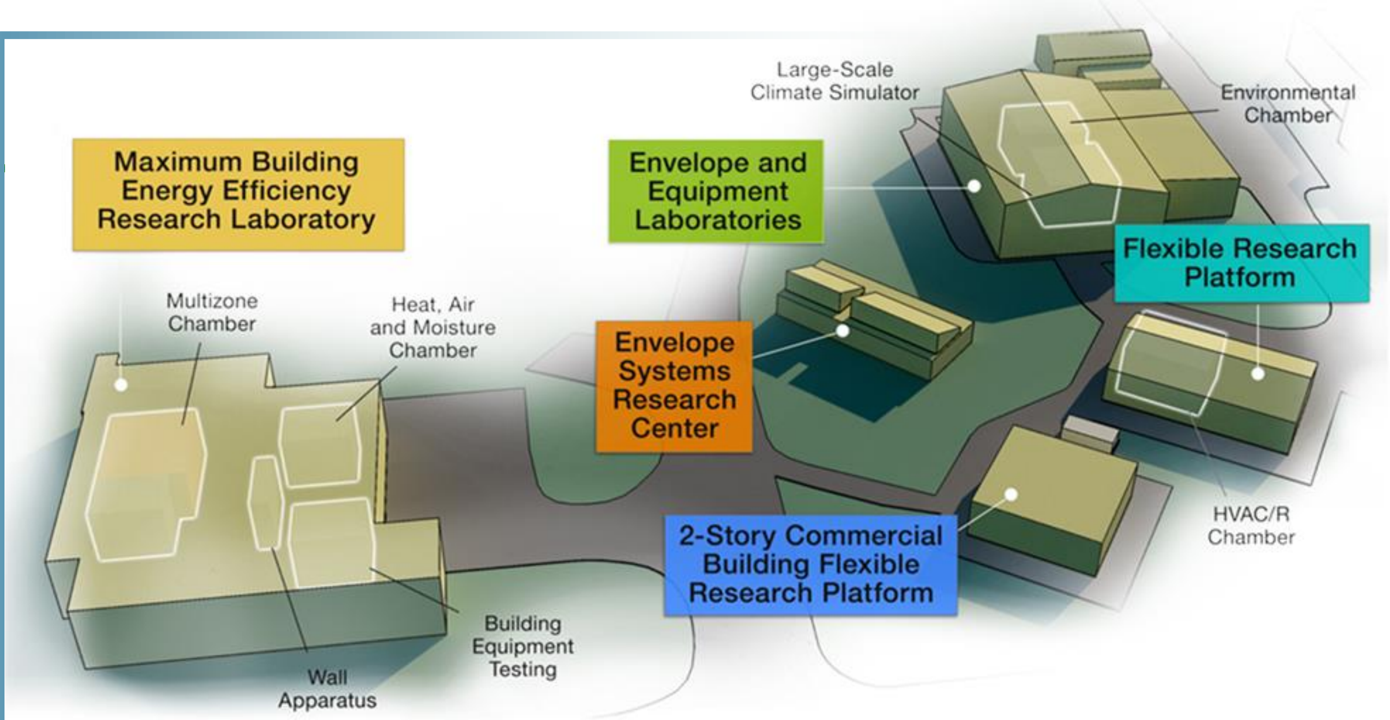
- The new generation of membrane exchangers will be tested to verify their stand-alone dehumidification performance.
- Latent energy storage performance of the liquid desiccant loop will be evaluated.

(2) System integration and test

- The new membrane exchangers will be integrated with the heat pump. Fully functional tests will be conducted to evaluate system performance with enhanced dehumidification.

(3) Conduct field demonstration

Unoccupied field demonstration home



Thank you

Oak Ridge National Laboratory
Bo Shen, Senior R&D Scientist
(865)-574-5745| shenb@ornl.gov

ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 60,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results

236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Budget

Project Budget: $350K (DOE)
Variances: NONE
Cost to Date: $150K
Additional Funding: NONE

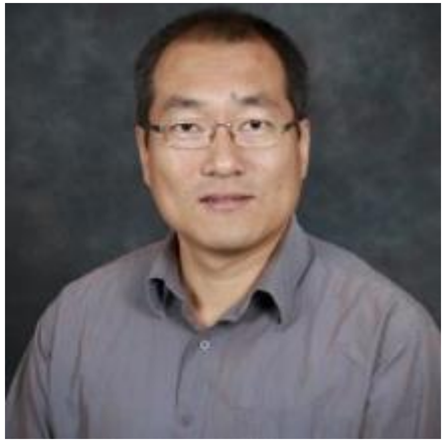
	DOE funds	Costed	Cost share
FY22	175K	50K	175K
FY23	175K	100K	175K

Project Plan and Schedule

	Task		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Year 1	1	Simulation-driven design and optimization.								
	2	Evaluate performance of liquid dessicant system in ORNL's environmental chambers								
	Milestone 1	Verify dehumdification capability of stand-alone liquid desiccant system								
	3	Develop second prototype of membrance heat & mass exchangers								
	4	System integration and control development								
	5	Evaluate integrated system performance and controllability								
	Milestone 2	Measure the integrated system performance with enhanced dehumidification								
Year 2	6	Field installation and building integration								
	Milestone 3	Install the integrated system, construct ductwork and PCM storge elements in one residential home								
	7	Monitor cooling seasonal performance and grid responsive load shifting								
	Milestone 4	Report seasonal cooling performance, dehumidification rate and utility cost reduction by load shifting								
	8	Develop a commercialization plan for the component and system technologies								
	9	Final reporting								
	Milestone 5	Submit project final report summarizing all the laboratory and field investigations								

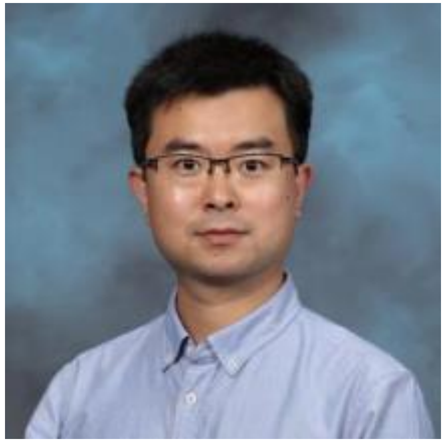
Go/No-Go

Team



Dr. Bo Shen (PI)
Senior R&D Scientist

- System design
- Building energy simulation



Dr. Lingshi Wang
R&D Associate Staff

- Laboratory investigation

Dr. Zhenning Li
R&D Associate Staff

- Building energy simulation

Drew Welch
Senior Lead HVAC Systems Engineer

- Develop 3-stage compressors for multi-family buildings
- Liquid desiccant latent storage