Performance and Characterization of Membrane Liquid Desiccant Air Conditioning Systems

Cooperative Research and Development Final Report

CRADA Number: CRD-13-00512

NREL Technical Contact: Eric Kozubal

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5500-87527
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Cooperative Research and Development Final Report

Report Date: September 14, 2023

In accordance with the requirements set forth in the terms of the CRADA agreement, this document is the CRADA Final Report, and includes a list of subject inventions to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: 7AC Technologies, Inc. (now Emerson)

CRADA Number: CRD-13-00512

CRADA Title: Performance and Characterization of Membrane Liquid Desiccant Air Conditioning Systems

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Building Technologies Office (BTO)

Joint Work Statement Funding Table showing DOE commitment:

No NREL Shared Resources

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Entire CRADA duration	$0.00
TOTALS	$0.00

Executive Summary of CRADA Work:

This document is intended to describe the work objectives and tasks for several projects between the National Renewable Energy Laboratory (NREL) and 7AC Technologies, with indirect support from 3M. The projects all revolve around the performance and characterization of membrane liquid desiccant air conditioning systems. Projects are listed in order of preference to 7AC's technical and business goals.

<u>CRADA benefit to DOE, Participant, and US Taxpayer</u>:

The United States uses almost half of its primary energy for the heating and cooling of buildings. Liquid desiccant HVAC systems have the potential to significantly reduce that number, but current liquid desiccant systems are not easily retrofittable or cost efficient. First cost is always a significant consideration in HVAC purchasing decisions. The benefit to the US is the development of easy-to-deploy HVAC systems that are retrofittable to existing buildings and can reduce energy costs immediately with rapid payback periods. The benefit to the U.S. Department of Energy is to create a commercialization path for a technology that has been under development at the National Renewable Energy Laboratory (NREL). The benefit to 7AC is to develop, with the support of our partner, 3M, an optimized membrane module system for commercial launch into the market. 7AC is currently licensing desiccant-enhanced evaporative air conditioning (DEVAP a/c) technology from NREL with the intent to commercialize the technology. 7AC's partnership with NREL to develop products will allow DOE to leverage private sector funding in the commercialization of DEVAP technology which will accelerate adoption.

<u>Summary of Research Results</u>:

Purpose

The purpose of this CRADA is to develop and model a highly optimized membrane module and simulation software for the use in liquid desiccant air conditioners including DEVAP air conditioning technology. The membranes currently in use are general purpose membranes and have not been optimized for use in air conditioning systems. Efficient membrane modules with a long service life are required to successfully enter the HVAC market. A fundamental understanding is needed to optimize components in relationship to each other, such as, the sizing of conditioners, regenerators, pumps, fans, and heat exchangers that optimize system designs for various building applications. NREL will be transferring knowledge to 7AC Technologies in the design of liquid desiccant systems necessary to ensure successful market adoption.

Statement of Work, Task Descriptions and Estimated Completion Dates

Original Agreement (Mod 0):

Task 1. Prototype Air Conditioning Simulation Software

a. *UDD HMX Modeling:* Build EES software models that correctly describes 7AC's liquid desiccant membrane plate blocks:
    i. *Block Model:* Counterflow, 3-way liquid flows (**Up Down Down** and UDU configurations Water/Des/Air).
        1. Should support variable air/desiccant/water flows/temps, different desiccants, etc.
        2. Should be able to calculate all output conditions, including pressure drop in block.
    ii. *System model:* compare outputs of the model to equipment conditions.
        1. Add ancillary equipment (e.g. fans and pumps) to estimate electricity consumption and operating costs.

        2. Allow a variety of annual air conditions to serve as input for the model in a location.
        3. Build a more complete EES model that consists of all major MELDAC components: Conditioner and Regenerator, Desiccant Heat Exchanger and Compressor/Liquid Heat Exchangers.
    iii. *Optimize System:* Parametrics
        1. Optimize the ratio between conditioner and regenerator blocks.
        2. Determine optimum block dimensions for performance and cost.
b. *GEO HMX Modeling:* Transfer knowledge from task 1a to 7AC staff and co-develop models for the GEO system.
c. *Aqua (Non-integrated) HMX Modeling:* Develop models for the external Aqua system (with separate evaporator block).
d. *Aqua (270°) HMX Modeling:* Develop models for the integral Aqua system (with 270deg air flow).

Task 1 Work Description:

Component model-based design tools: NREL assisted with development of model-based design tools for the development of the 7AC dedicated outdoor air system (DOAS) product. Included were the following original component models written in engineering equation solver (EES):

1. Liquid desiccant heat exchanger (LDHX) models
2. Air-to-water coil heat exchanger models based on off-the-shelf components
3. Water-to-water heat exchanger models based on off-the-shelf components
4. Water-to-water refrigeration circuit component models based on off-the-shelf components
5. Fan models based on off-the-shelf components
6. Specialized desiccant-to-desiccant heat exchanger

The 2-D finite difference LDHX models predict the heat and mass transport within the LDHXs as a function of geometry of water, air, and desiccant flow. The models account for a plastic plate separator that maintains water containment, a microporous membrane that maintains desiccant and air separation.

Conditioner and regenerator LDHX models that had various fluid flow orientations:

1. Air flow upwards, water flow and desiccant flow downwards (UDD)
2. Air flow horizontal, water flow horizontal and counter-flow to air, desiccant flow downwards (XXD)

Figure 1 below shows the stack-up of plastic plates, micro-porous membranes, and headers, that make up the UDU LDHX design. The air flowing through the LDHXs' flow-through parallel plates that have a liquid desiccant flowing on them. The Micro-porous membrane is used to maintain air and desiccant separation. In this design, lithium chloride was used as the desiccant. Water flow internal to the plate. In the case of the conditioner, cooling water, concentrated desiccant, and humidity air enter the LDHX. Cool and dehumidified air is the product output. Diluted desiccant is then directed to the regenerator LDHX, whereby hot water, diluted desiccant, and outdoor air enter the LDHX. The chiller's heat is rejected,, and the desiccant is re-concentrated.

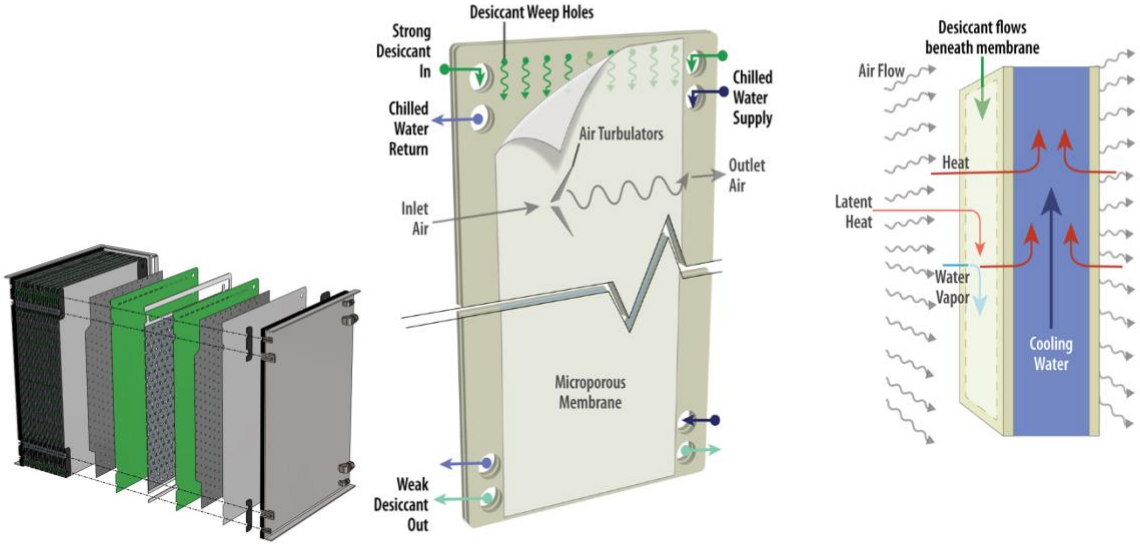


Figure 1. Left: rendering of LDHX plate and membrane stack-up. Middle: view of a single LDHX plate showing water, desiccant, air distribution through the plate. Right: zoomed view showing the heat and mass transport due to the air, desiccant, and water contact within the LDHXs.

A core functionality is the use of microporous membranes in the LDHXs (Figure 2) that separate desiccant and air, ensuring that no desiccant escapes the LDHX in aerosol form. The physics of this heat and mass transfer mechanisms were novel to this project and the generation of the theory and measurements of performance were the objective of this and future tasks.

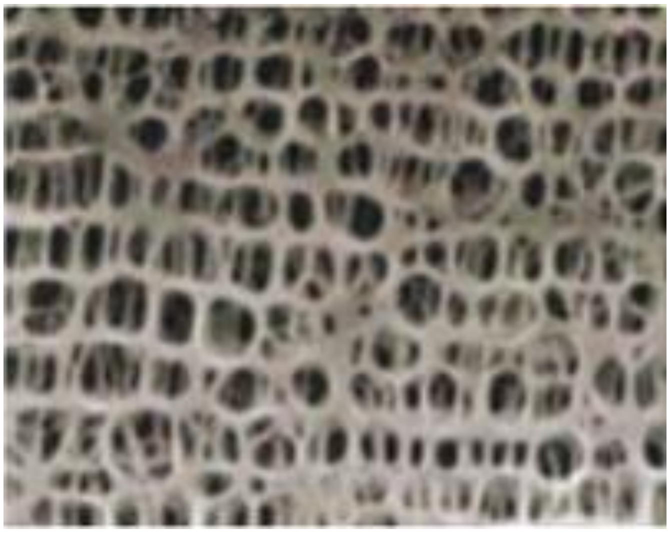
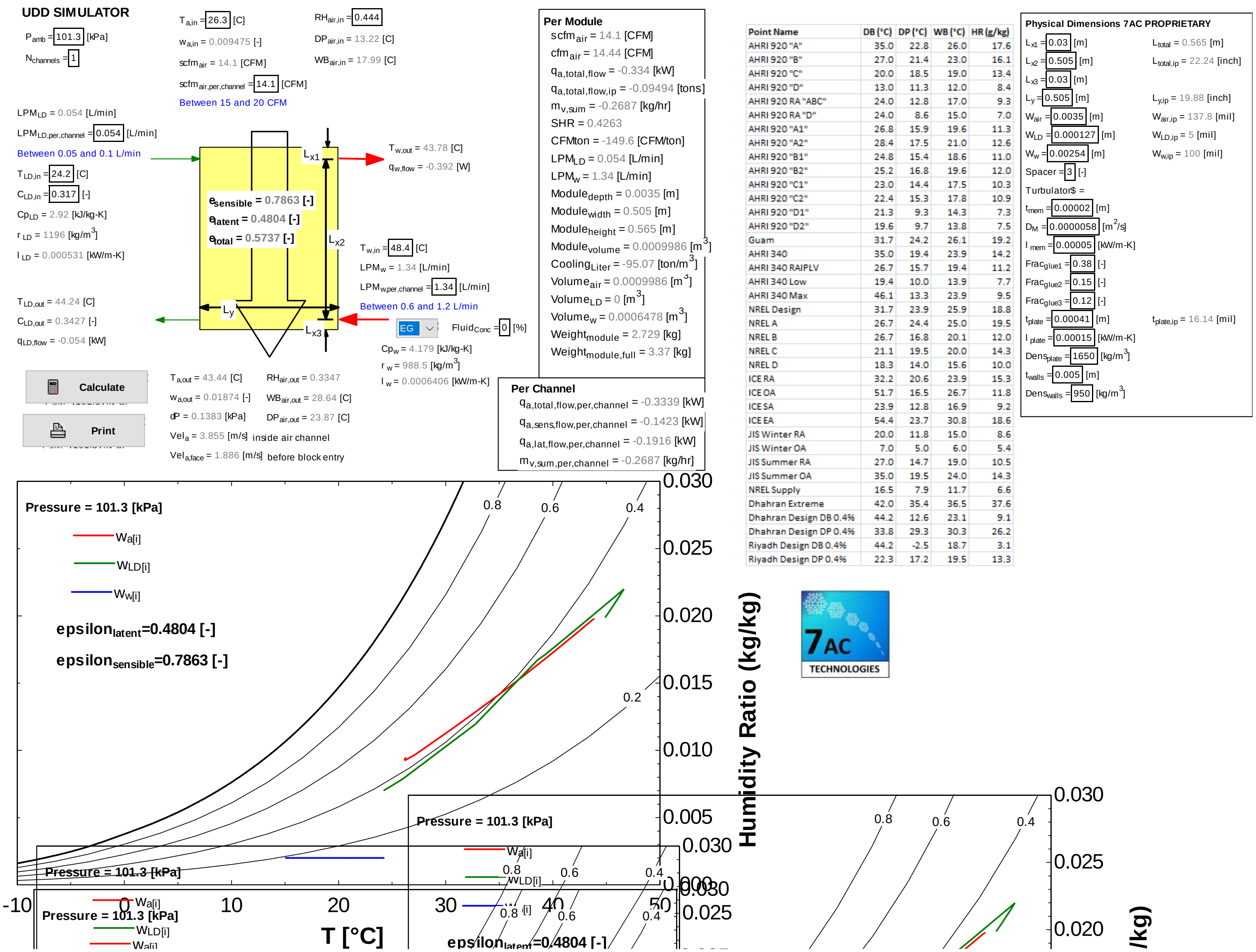


Figure 2. A scanning electron microscope image (SEM) of microporous membrane showing 70% open area. Credit: Celgard, LLC

The LDHX models developed were continuously improved throughout the entirety of the CRADA until 2020 to include up-to-date design changes, improvements, heat and mass transfer correlations, and updated theory for mass transport through micro-porous membranes. Figure 3 shows the graphical user interface (GUI) for one such model.



UDD SIMULATOR

P_{amb} = 101.3 [kPa]
$N_{channels}$ = 1

$T_{a,in}$ = 26.3 [C]
$w_{a,in}$ = 0.009475 [-]
$scfm_{air}$ = 14.1 [CFM]
$scfm_{air,per,channel}$ = 14.1 [CFM]
Between 15 and 20 CFM

$RH_{air,in}$ = 0.444
$DP_{air,in}$ = 13.22 [C]
$WB_{air,in}$ = 17.99 [C]

LPM_{LD} = 0.054 [L/min]
$LPM_{LD,per,channel}$ = 0.054 [L/min]
Between 0.05 and 0.1 L/min
$T_{LD,in}$ = 24.2 [C]
$C_{LD,in}$ = 0.317 [-]
Cp_{LD} = 2.92 [kJ/kg-K]
r_{LD} = 1196 [kg/m^3]
l_{LD} = 0.000531 [kW/m-K]

$T_{LD,out}$ = 44.24 [C]
$C_{LD,out}$ = 0.3427 [-]
$q_{LD,flow}$ = -0.054 [kW]

$e_{sensible}$ = 0.7863 [-]
e_{latent} = 0.4804 [-]
e_{total} = 0.5737 [-]

$T_{w,out}$ = 43.78 [C]
$q_{w,flow}$ = -0.392 [W]

$T_{w,in}$ = 48.4 [C]
LPM_w = 1.34 [L/min]
$LPM_{w,per,channel}$ = 1.34 [L/min]
Between 0.6 and 1.2 L/min
EG
$Fluid_{Conc}$ = 0 [%]
Cp_w = 4.179 [kJ/kg-K]
r_w = 988.5 [kg/m^3]
l_w = 0.0006406 [kW/m-K]

$T_{a,out}$ = 43.44 [C]
$w_{a,out}$ = 0.01874 [-]
dP = 0.1383 [kPa]
Vel_a = 3.855 [m/s] inside air channel
$Vel_{a,face}$ = 1.886 [m/s] before block entry

$RH_{air,out}$ = 0.3347
$WB_{air,out}$ = 28.64 [C]
$DP_{air,out}$ = 23.87 [C]

Per Module
$scfm_{air}$ = 14.1 [CFM]
cfm_{air} = 14.44 [CFM]
$q_{a,total,flow}$ = -0.334 [kW]
$q_{a,total,flow,ip}$ = -0.09494 [tons]
$m_{v,sum}$ = -0.2687 [kg/hr]
SHR = 0.4263
CFMton = -149.6 [CFM/ton]
LPM_{LD} = 0.054 [L/min]
LPM_w = 1.34 [L/min]
$Module_{depth}$ = 0.0035 [m]
$Module_{width}$ = 0.505 [m]
$Module_{height}$ = 0.565 [m]
$Module_{volume}$ = 0.0009986 [m^3]
$Cooling_{Liter}$ = -95.07 [ton/m^3]
$Volume_{air}$ = 0.0009986 [m^3]
$Volume_{LD}$ = 0 [m^3]
$Volume_w$ = 0.0006478 [m^3]
$Weight_{module}$ = 2.729 [kg]
$Weight_{module,full}$ = 3.37 [kg]

Per Channel
$q_{a,total,flow,per,channel}$ = -0.3339 [kW]
$q_{a,sens,flow,per,channel}$ = -0.1423 [kW]
$q_{a,lat,flow,per,channel}$ = -0.1916 [kW]
$m_{v,sum,per,channel}$ = -0.2687 [kg/hr]

Point Name	DB (°C)	DP (°C)	WB (°C)	HR (g/kg)
AHRI 920 "A"	35.0	22.8	26.0	17.6
AHRI 920 "B"	27.0	21.4	23.0	16.1
AHRI 920 "C"	20.0	18.5	19.0	13.4
AHRI 920 "D"	13.0	11.3	12.0	8.4
AHRI 920 RA "ABC"	24.0	12.8	17.0	9.3
AHRI 920 RA "D"	24.0	8.6	15.0	7.0
AHRI 920 "A1"	26.8	15.9	19.6	11.3
AHRI 920 "A2"	28.4	17.5	21.0	12.6
AHRI 920 "B1"	24.8	15.4	18.6	11.0
AHRI 920 "B2"	25.2	16.8	19.6	12.0
AHRI 920 "C1"	23.0	14.4	17.5	10.3
AHRI 920 "C2"	22.4	15.3	17.8	10.9
AHRI 920 "D1"	21.3	9.3	14.3	7.3
AHRI 920 "D2"	19.6	9.7	13.8	7.5
Guam	31.7	24.2	26.1	19.2
AHRI 340	35.0	19.4	23.9	14.2
AHRI 340 RAIPLV	26.7	15.7	19.4	11.2
AHRI 340 Low	19.4	10.0	13.9	7.7
AHRI 340 Max	46.1	13.3	23.9	9.5
NREL Design	31.7	23.9	25.9	18.8
NREL A	26.7	24.4	25.0	19.5
NREL B	26.7	16.8	20.1	12.0
NREL C	21.1	19.5	20.0	14.3
NREL D	18.3	14.0	15.6	10.0
ICE RA	32.2	20.6	23.9	15.3
ICE OA	51.7	16.5	26.7	11.8
ICE SA	23.9	12.8	16.9	9.2
ICE EA	54.4	23.7	30.8	18.6
JIS Winter RA	20.0	11.8	15.0	8.6
JIS Winter OA	7.0	5.0	6.0	5.4
JIS Summer RA	27.0	14.7	19.0	10.5
JIS Summer OA	35.0	19.5	24.0	14.3
NREL Supply	16.5	7.9	11.7	6.6
Dhahran Extreme	42.0	35.4	36.5	37.6
Dhahran Design DB 0.4%	44.2	12.6	23.1	9.1
Dhahran Design DP 0.4%	33.8	29.3	30.3	26.2
Riyadh Design DB 0.4%	44.2	-2.5	18.7	3.1
Riyadh Design DP 0.4%	22.3	17.2	19.5	13.3

Physical Dimensions 7AC PROPRIETARY
L_{x1} = 0.03 [m]
L_{x2} = 0.505 [m]
L_{x3} = 0.03 [m]
L_y = 0.505 [m]
W_{air} = 0.0035 [m]
W_{LD} = 0.000127 [m]
W_w = 0.00254 [m]
Spacer = 3 [-]
Turbulator$ =
t_{mem} = 0.00002 [m]
D_M = 0.0000058 [m^2/s]
l_{mem} = 0.00005 [kW/m-K]
$Frac_{glue1}$ = 0.38 [-]
$Frac_{glue2}$ = 0.15 [-]
$Frac_{glue3}$ = 0.12 [-]
t_{plate} = 0.00041 [m]
l_{plate} = 0.00015 [kW/m-K]
$Dens_{plate}$ = 1650 [kg/m^3]
t_{walls} = 0.005 [m]
$Dens_{walls}$ = 950 [kg/m^3]

L_{total} = 0.565 [m]
$L_{total,ip}$ = 22.24 [inch]
$L_{y,ip}$ = 19.88 [inch]
$W_{air,ip}$ = 137.8 [mil]
$W_{LD,ip}$ = 5 [mil]
$W_{w,ip}$ = 100 [mil]
$t_{plate,ip}$ = 16.14 [mil]

Figure 3. Example graphical user interface for a developed LDHX model for the UDD configuration

System model-based design tools: The component models above were integrated into a system-level design tool that predicts the performance of air conditioning systems that use LDHXs. Figure 4 shows the general design of an air conditioner using LDHXs. The conditioner LDHX in the system received chilled water from the chiller, humid process air and a strong (concentrated) liquid desiccant. The conditioner then processes the air down to a cool and dehumidified condition. The regenerator LDHXs receive the hot water from the chiller, diluted desiccant from the conditioner, and an ambient air stream. The regenerator rejects the chiller heat and humidity obtained from the dehumidification step, and re-concentrates the desiccant, thus completing the cycle. The desiccant heat exchanger is used for energy conservation, ensuring warm desiccant does not enter the conditioner LDHX, and imposing a parasitic thermal load.

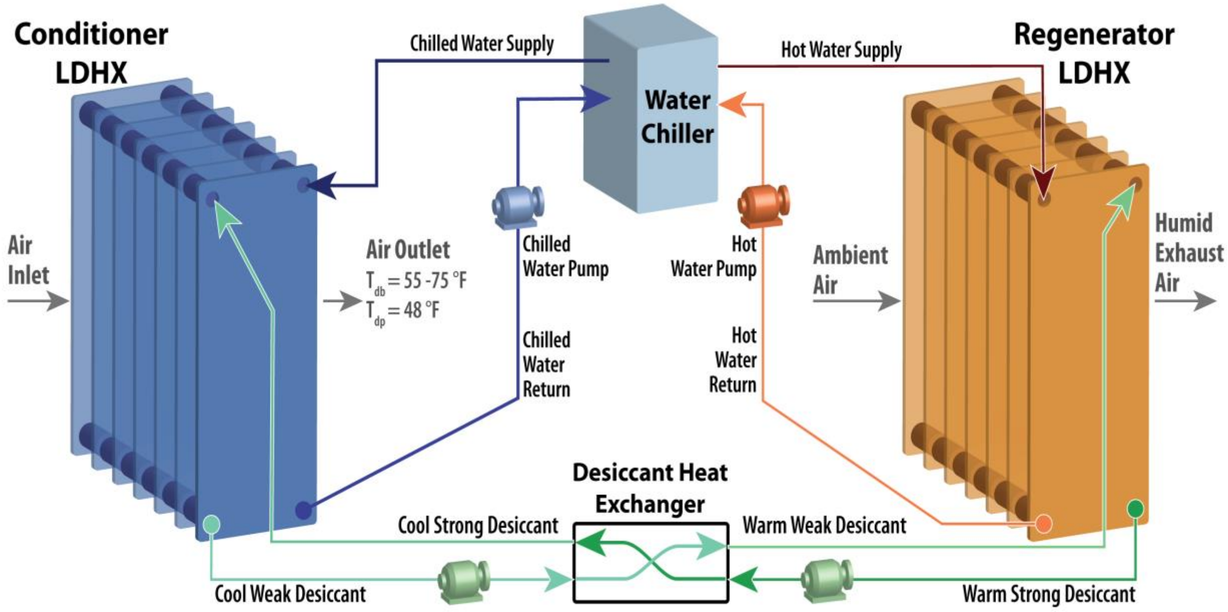


Figure 4. Air conditioning design concept using LDHXs

Figure 5 shows the process diagram and GUI for a general DOAS product design, which includes a more detailed accounting of components in this particular design. Each component on the graphic is described in an EES model with physical parameters (e.g., heat exchanger area and transfer values) that affect the performance of the system. Many standard components (e.g., liquid-to-refrigerant heat exchangers) were off-the-shelf and performance was of these were adjusted to match manufacturer’s data when possible. The LDHXs specifications were continually updated as new prototype designs were generated through collaboration with 7AC staff.

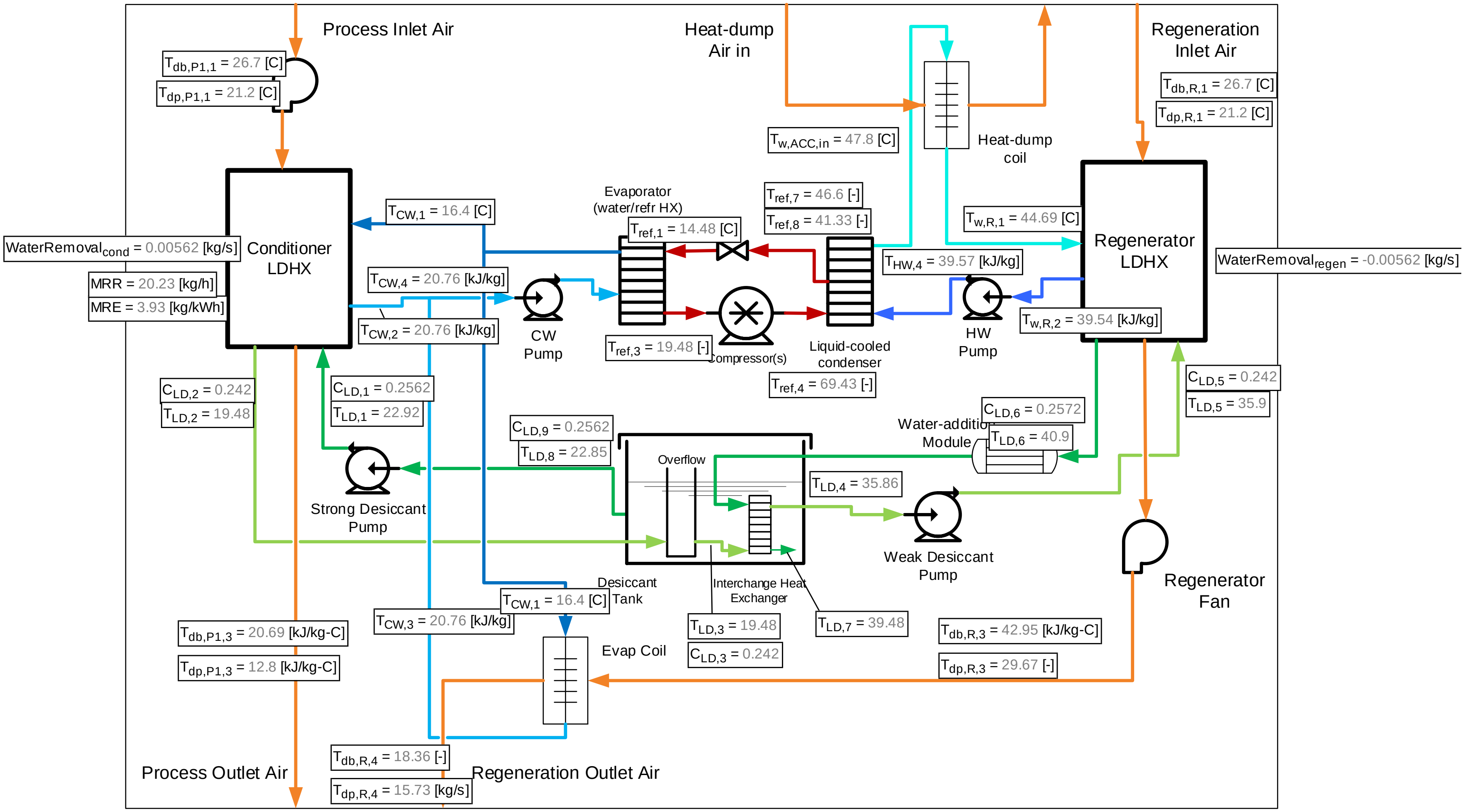


Figure 5. Example of graphical user interface of 7AC Chill system model.

Pareto optimization: The air conditioner design space was explored using pareto techniques to understand the tradeoff of a LDHX heat exchanger size (a proxy for cost) versus total cooling efficiency. The ambient conditions simulated were for a design dehumidification condition in Houston, TX. Figure 6 shows the pareto plot for 80 different design parameters. The pareto scheme developed attempts to find the pareto front (boundary) whereby COP is maximized versus a given conditioner plus regenerator heat exchange area. The problem uses LDHX design parameters such length, width, height, material thickness and type, air-gap spacing, water-gap spacing, inclusion of air-side air and water turbulators (between plate mixers). The pareto plot also inputs process parameters such as water, desiccant, and air flow rates. The design is constrained using a fixed balance of system component design (e.g., chiller design) as well as manufacturing constraints for the LDHXs (e.g., air and water gap dimensions, material thicknesses). The scheme, using the LDHX and system models generate a myriad of design choices for 7AC to consider in designing DOAS's. The red point in the figure shows the design originally chosen by 7AC independent of the CRADA. The work in the CRADA showed a path to a reduction of heat transfer area by 20% (maintaining a constant efficiency).

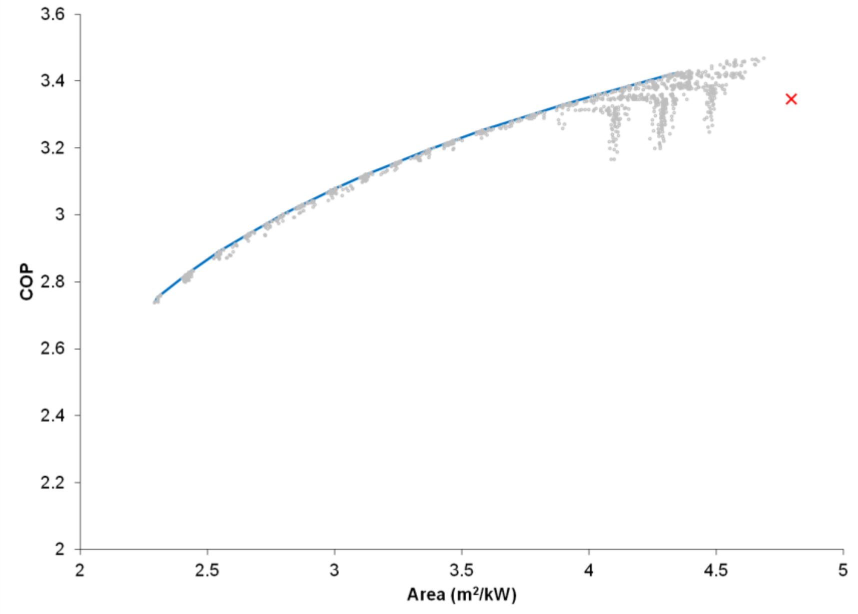


Figure 6. Pareto plot of over 80 design specification on a plot of total conditioner + regenerator heat transfer area versus coefficient of performance (COP)

Task 2. Add building layer to EES modeling

a. Work with 7AC staff to integrate the models from task 1 into a building level load simulation tool such that annual power and energy consumption can be estimated.

Task 2 Work Description:

This task was not started due to direction of 7AC.

Task 3. Characterize heat and mass transfer of membranes and turbulators.

a. NREL will use existing experimental capability to determine the heat and mass transfer of several turbulator designs, including the 7AC Mesh and 5 other designs.
   i. Characterize turbulators for heat and mass transfer, and pressure drop at multiple air flow rates
   ii. Normalize results such that experimental results are sufficient for predicting performance of heat exchanger designs with different form factors and dimension.
   iii. Create data set that can be integrated into EES modeling.
b. Determine vapor permeability of membranes
   i. Characterize membranes through bench scale testing to determine performance of membrane component.
   ii. Create data set that can be integrated into EES modeling.

Task 3 Work Description:

<u>Turbulator evaluation</u>: 7AC provided NREL with parallel plate air-turbulators (Figure 7) that fit into their parallel plate LDHX models. The designs of the turbulators were generated by 7AC staff and the performance measurement of several designs were evaluated by NREL. Turbulators reduce the cost of LDHX design by increasing heat and mass transfer rates, thus reducing heat transfer area, which directly relates to size and cost of LDHXs.

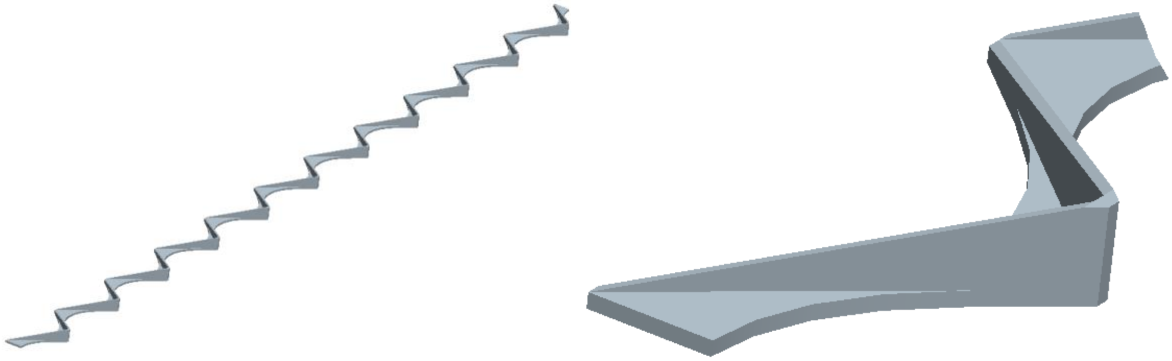


Figure 7. Multi-vortex generating features that tabulate air in a parallel plate configuration

Figure 8 and Figure 9 show example measurements of heat transfer and pressure drop performance of five candidate designs. The performance of these turbulator designs were incorporated into the model-based design framework described above. The Colburn j factor plotted is a dimensionless parameter that shows relative heat and mass transfer the designs. The (Darcy) friction factor, f, is a dimensionless parameter that shows the difference in static pressure loss of the designs. Each plot is versus the Reynold's number, a dimensionless parameter of air mass flux in the test apparatus. These correlations can then be scaled appropriately to different channel gaps and lengths accordingly to predict performance with the model framework.

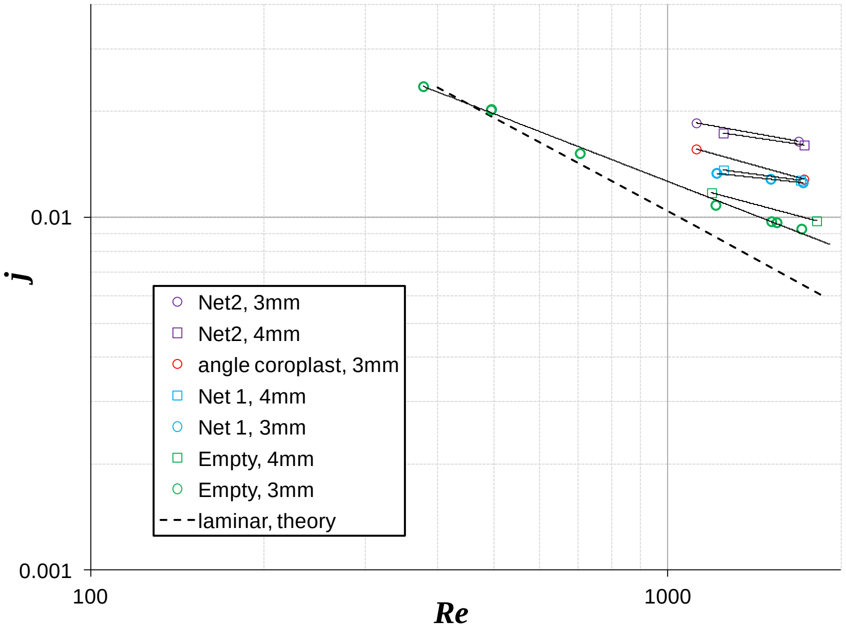


Figure 8. Colburn j factors for an empty channel, each spacer, and for laminar theory.

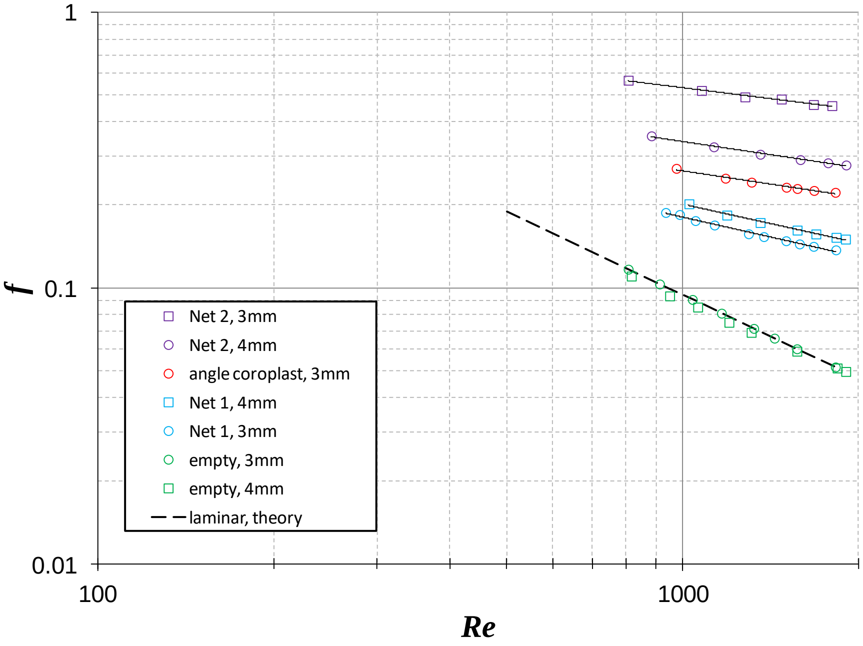


Figure 9. Friction factors for an empty channel, each spacer, and for theoretical laminar flow.

Task 4. System and Component Level Laboratory Testing (Original and Modification 1) NREL will perform the following system and component level laboratory testing as dictated by project needs:

a. Desiccant systems up to 20 tons in capacity over a full range of cooling and heating test conditions for dedicated outdoor air systems (DOAS) and recirculating (recirc systems required by OEM partners
b. Liquid desiccant heat exchangers that require balanced input of chilled and heated water
c. Advanced heat transfer enhancements to heat exchangers, reducing heat exchange area, material use, and cost.
d. Prototyping and testing of new designs for the desiccant channel, water channel, manifold, and housing designs as required
e. Auxiliary equipment such as: liquid to liquid membrane mass exchanger exchangers (e.g. desiccant dilution exchangers)
f. Examine membrane capabilities for use in LDHXs
g. Finned tube heat exchangers
h. Perform testing of components as assigned by 7AC

Task 4 Work Description:

LDHX evaluation at NREL's HVAC laboratory:

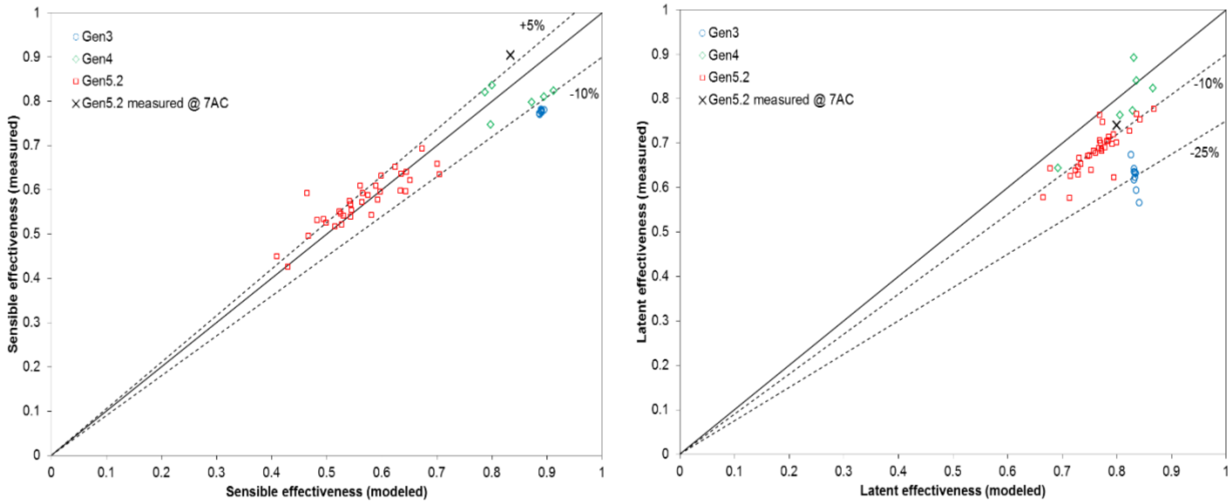


Figure 10. Conditioner LDHX sensible and latent effectiveness measurements vs model prediction for three generation of LDHX designs.

Figure 13 below shows an example test data taken from this system. The psychrometric chart process is useful in visualizing the cooling and heat rejection process and is illustrative in determining methods to improve total system design. For example, the potential points shown illustrate that there is room for more effective heat and mass exchange from both the regenerator and conditioner LDHXs.

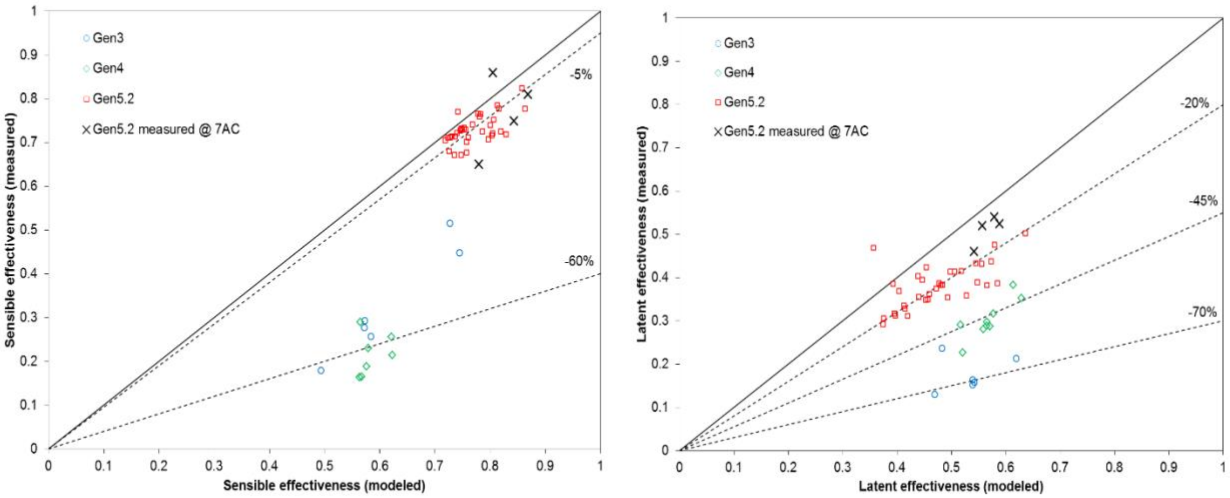


Figure 11. Regenerator LDHX sensible and latent effectiveness measurements vs model prediction for three generation of LDHX designs.

<u>System evaluation at NREL's HVAC laboratory</u>:

NREL evaluated a prototype 10-ton dedicated outdoor air conditioning system at the HVAC facility in Golden, CO. The system, shown in Figure 12, was used to evaluate liquid desiccant heat exchangers and system design. The system was delivered to NREL in several components and assembled in the laboratory and connected to two air streams from the laboratory to simulate typical operational environments.

Figure 12. Prototype 10-ton system evaluated at NREL's HVAC facility in Golden, CO. The prototype system, not intended to be installed in the field, was used to characterize the combined refrigeration and liquid desiccant heat exchangers together to understand performance and design trade-offs.

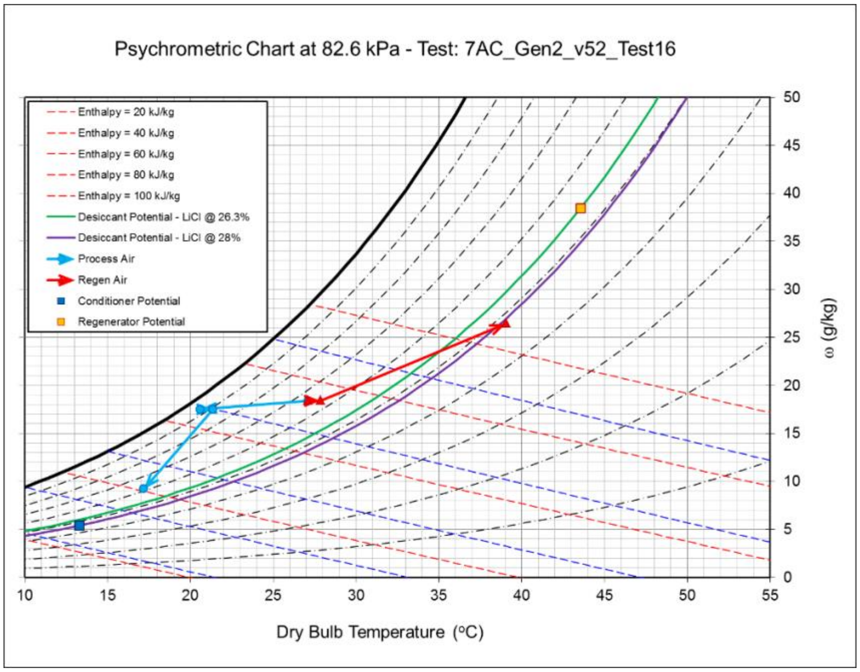


Figure 13. Example measured system performance of the generation 2 system showing the air cooling and dehumidification process along with the heat and moisture rejection. The Psychrometric chart shows the desiccant potential points with the vapor compression system that heated and cooled the water streams in the system. The LDHXs then drive the process and regeneration air streams toward these potential points.

Figure 14 shows the compressor power comparison between multiple test data points and the anticipated compressor power.

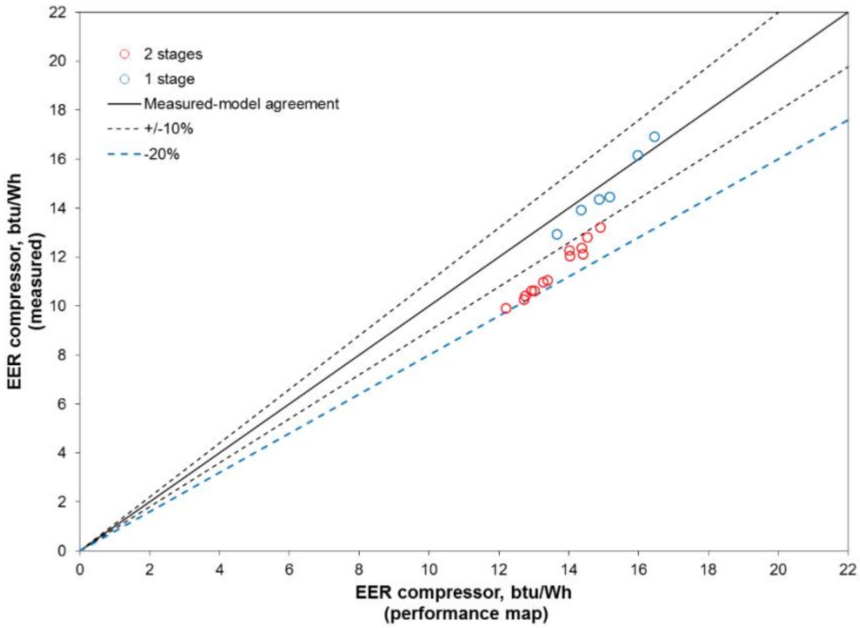


Figure 14. Measured vs anticipated compressor power shows the impact of the less-than ideal chiller performance. This data led to 7AC to endeavor upon custom chiller design rather than relying on turnkey solutions.

As a result of the work done, calibrated system models (Figure 15) were generated that were used in future activities to design new system (See Task 5).

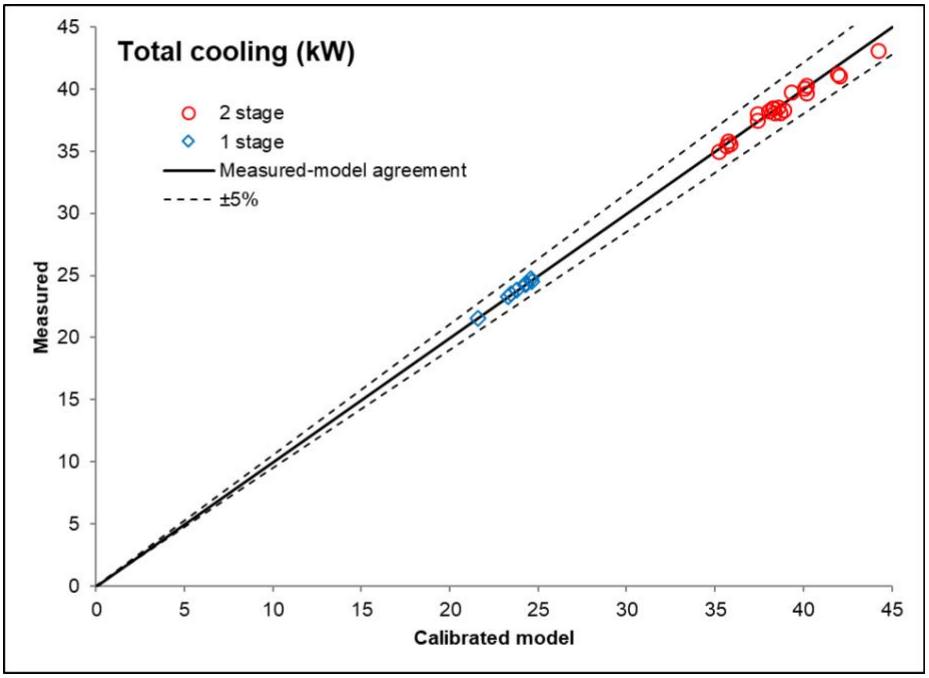


Figure 15. Calibrated system model showing the measured vs model total system capacity for the prototype system evaluated at in the HVAC laboratory. The calibration procedure stemming from adjusting both LDHX and compressor performance parameters allow for accurate prediction of performance of the prototype system. Furthermore, these calibrations allow for a platform on which to design new systems and have confidence in the predicted performance of new system designs.

Task 4. Improve model usability (Modification 2 and 3)

a. Refrigeration system performance maps
    a. NREL will model the refrigeration system for a 7AC Chill System in EES. We will use this model to create performance maps of the refrigeration system for use in a simplified 7AC system model.
b. Simplified 7AC system model
    a. NREL will build a new EES model of the 7AC Chill System that calls performance maps for both the LDHX modules and the refrigeration system. The model will include additional models for the desiccant components, fans/pumps, additional water/air HX coils, and the connections for all relevant water, desiccant, and air streams. As part of this task, NREL will set up a method for storing and accessing the required performance maps. NREL will also create documentation so others can use this model.
c. LDHX model performance maps
    a. NREL will modify an existing LDHX EES model to create performance maps for use in the new 7AC system model. This will include an input spreadsheet that takes design data and creates input tables for the EES file, as well as an output spreadsheet that takes the EES runs and creates the necessary performance maps for the system model. NREL will also create documentation on how to create performance maps.

Task 4 Work Description (Modification 2 and 3):

The numerical models developed under this CRADA ran on the engineering equation solver (EES) software. However, the complexity of these models grew to the point that the convergence stability was poor and required experienced users to navigate their use. 7AC desired to expand the use of these models and it was determined that the models needed to be more stable for broader distribution. Therefore, the system model and all its components were sub-divided into sub-systems. These sub-systems were placed into separate EES models. The sub-system models were then transformed into performance maps that were effectively a digital twin of the more detailed model. These digital twins were then re-assembled into a unified system model. Figure 16 shows this graphically as the team was determining the methodology. Figure 17 shows the comparison of the simplified and detailed models to demonstrate the change in fidelity. The data produced was for standard conditions from AHRI standard 920.

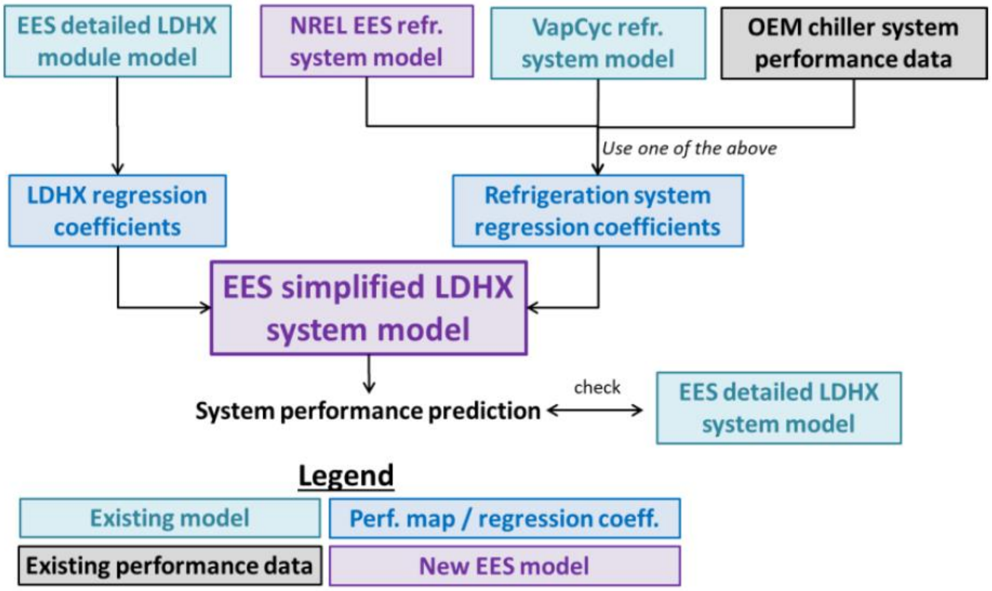


Figure 16. Show the methodology of creating the simplified model.

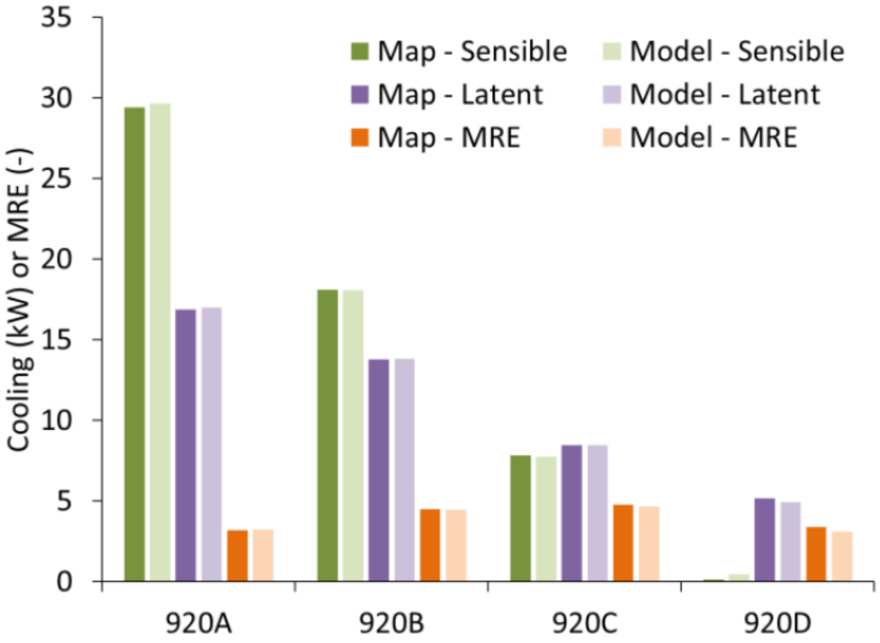


Figure 17. Comparison of the simplified system model against the detailed model.

Reporting

a. *Monthly reporting:* NREL will report on project status monthly to 7AC with key information (by the 10th day of each month):
   i. Current project status: Description of all work done on each project for the prior month with relevant data or references to data taken.
   ii. Issues: Description of issues related to technical work, project scope and schedule of work
   iii. Next steps: Description of work to be performed in the following month
   iv. Financial update: Table of financial information related to budget and cash flow.

b. *Consultation:* In connection with monthly reporting NREL will consult with 7AC and consider 7AC suggestions and input with respect to the work.

Final report: At the conclusion of the technical work, NREL will complete a final report that describes the work performed, technical results, and conclusions for all the tasks in the CRADA. The final report will also identify further research topics. NREL will provide 7AC with copies of any software, in source and object code, generated in performance of the work. It is intended that such results will be marked as Protected CRADA Information for the purposes of the CRADA.

Publications:

Several presentations and publications were output from the above tasks:

1. Vandermuelen et al (2013), "*A Liquid Membrane Air Conditioner*" Seminar 14, 2013 ASHRAE winter conference in Dallas, TX.
2. Kozubal, E. (2014), "*Liquid Desiccant Dehumidification As a Way to Enhance IAQ and Dedicated Outdoor Air System Performance.*" Seminar 30, 2014 ASHRAE Annual Conference in Seattle, WA.
3. Woods, J. (2016), "*Modeling and design of liquid desiccant heat exchangers.*" Seminar 26, 2016 ASHRAE Winter Conference in Orlando, FL.
4. Woods, J. and Kozubal E. (2018) "*On the importance of the heat and mass transfer resistances in internally-cooled liquid desiccant dehumidifiers and regenerators*." International Journal of Heat Transfer. Volume 122, July 2018, Pages 324-340.
5. Woods, J., Kozubal E., et al (2022), "*Modeling And Experiments On A Dedicated Outdoor Air System Using Liquid Desiccant Heat And Mass Exchangers*." Conference paper, 2022 Refrigeration and Air Conditioning Conference at Purdue.

Subject Inventions Listing:

Tank System For Liquid Desiccant Air Conditioning System 15-104, Vandermeulen, Peter F.; Kozubal, Eric; Allen, Mark A.; Rowe, Scott N.

ROI #:

ROI 15-104 *Tank System For Liquid Desiccant Air Conditioning System*, Kozubal, Eric; Woods, Jason; Vandermeulen, Peter F.