



Development and Analysis of Desiccant Enhanced Evaporative Air Conditioner Prototype

Eric Kozubal, Jason Woods, and Ron Judkoff

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5500-54755
April 2012

Contract No. DE-AC36-08GO28308

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Prepared under Task No. BEC7.1302

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Acknowledgments

We wish to acknowledge the efforts of many industry experts who provided valuable knowledge and support in developing the prototype desiccant enhanced evaporative air conditioner (DEVAP AC):

We would like to acknowledge Andrew Lowenstein from AIL Research for participating in project planning, design, and prototype development. Throughout the project, Andrew provided invaluable guidance and supporting analysis. His expertise was instrumental in the success of this project.

We would like to acknowledge Dylan Garrett, Ian Graves, and Redwood Stephens from Synapse Product Development for participating in a design and prototype development. Throughout the project, the Synapse team provided excellent guidance in manufacturing design. Their design team was instrumental to the success of this project.

We would like to acknowledge John Pellegrino from the University of Colorado at Boulder for his extensive knowledge of design and testing of membrane systems, Dave Paulson from Water Think Tank for his insight into the membrane component manufacturing industry and selection of industry vendors, and Michael Brandemuehl from the University of Colorado at Boulder for his experience with heating, ventilation, and air-conditioning systems and desiccants.

We would like to acknowledge Jay Burch for his guidance in planning and executing this project.

We would like to acknowledge Aaron Boranian for his assistance in analysis of the two-stage regenerator.

We would like to acknowledge Jordan Clark from the University of Texas for his analysis of air flow through the second-stage heat and mass exchanger using computational fluid dynamics.

We would like to thank the NREL peer review team: Bill Livingood, Michael Deru, Paul Torcellini, Dane Christiansen, and Ren Anderson.

We would like to thank Stephanie Woodward for her editorial review.

We would like to thank Alexis Abramson, Colin McCormick, and Tony Bouza from the U.S. Department of Energy for their support of the DEVAP prototype project.

Executive Summary

In FY 2010, the National Renewable Energy Laboratory (NREL) used numerical models and building energy simulations to analyze the performance of a DEVAP AC for residential and commercial buildings. For commercial buildings, the building energy simulations showed 80% and 40% source energy savings in a typical office building in Phoenix and Houston, respectively, compared to a high-efficiency vapor compression AC (Kozubal et al. 2011).

In FY 2011, NREL was tasked to design and build a prototype DEVAP AC for testing at NREL's Advanced Heating, Ventilation, and Air-Conditioning (HVAC) Systems Laboratory. The purposes of this effort were to:

1. Construct a DEVAP prototype.
2. Validate DEVAP cycle performance used to predict energy savings.
3. Validate numerical model and design tools to predict performance of future designs.
4. Improve cost, weight, and size estimates of future designs.

The design approach used the previously developed numerical model to investigate many variables and find near-optimal designs of small size (and therefore low cost) and with high energy efficiency. Two vendors (AIL Research and Synapse Product Development) were selected competitively to construct the DEVAP prototypes. They proposed changes to the near-optimal designs developed by NREL to fit their manufacturing techniques and their use of off-the-shelf components. Future work will focus on achieving smaller size and better efficiency.

Experimental Approach

The two DEVAP prototypes were delivered in two distinct heat and mass exchangers: a first-stage dehumidifier and a second-stage indirect evaporative cooler. They were assembled with a previously developed desiccant regenerator now being used in AIL Research's commercially available low-flow liquid desiccant AC. We tested the prototype system at NREL's Advanced HVAC Systems Laboratory. A number of tests, sufficient for characterizing performance, were conducted at various airflow rates, liquid desiccant concentrations and flow rates, and a range of return air and outdoor air psychrometric conditions.

Results

An effective integrated energy efficiency ratio ($IEER_{\text{effective}}$) was calculated to be 23.2 for the DEVAP AC, based on test standard 340/360 (AHRI 2007) for rating AC performance. For comparison, typical high-efficiency vapor compression AC achieves IEERs up to 15.4. DOE's goal in their high performance rooftop unit challenge (DOE 2012) is an IEER of 18, a level requiring state of the air technology. The American Society of Heating, Refrigerating and Air-Conditioning Engineers standard 90.1 2010 specifies a minimum of 11.2 for a 10-ton commercially packaged air-cooled unit (ASHRAE 2010). Energy savings are expected to be greater than indicated by the $IEER_{\text{effective}}$ measurement, because this standardized test does not fully account for the savings potential for desiccant and evaporative cooling technologies. Annual building energy simulations provide the best comparison of actual energy performance between a DEVAP and a vapor compression AC. Most test results agreed with our numerical model to within $\pm 10\%$ in cooling capacity, electricity use, thermal energy use, and water

evaporation rate. The AIL Research first-stage heat and mass exchanger had known issues that reduced its latent cooling capacity by 22%, which affects size but not efficiency.

Conclusions

The agreement in efficiency, measured by the coefficient of performance (COP), between the numerical model and the experiments (Figure ES–1) adds confidence to our previous building energy simulation results (Figure ES–2). It also empowers the model as a tool for future designs. A second-generation DEVAP AC was designed with this model, which showed significant size reductions and additional optimized design features. These features were based on a parametric analysis with the model and lessons learned from the two first-generation prototypes. The result is a smaller, lower cost second-generation prototype design. We estimate the footprint and weight to be equal to a vapor compression unit with an IEER of 14.5, except the DEVAP unit would have an $IEER_{\text{effective}}$ of 23.2. We estimate the retail cost to be 28% higher. Based on the estimated cost premium and the simulated energy savings, we estimate a simple payback of less than two years in Phoenix and less than three years in Houston.

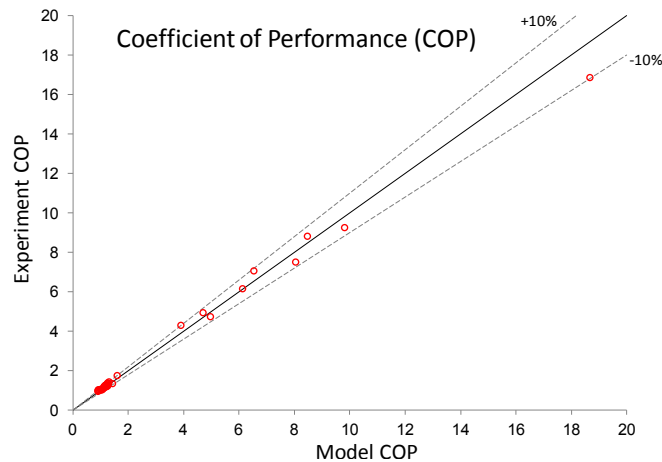


Figure ES–1 Model-experiment agreement of cooling efficiency (coefficient of performance)

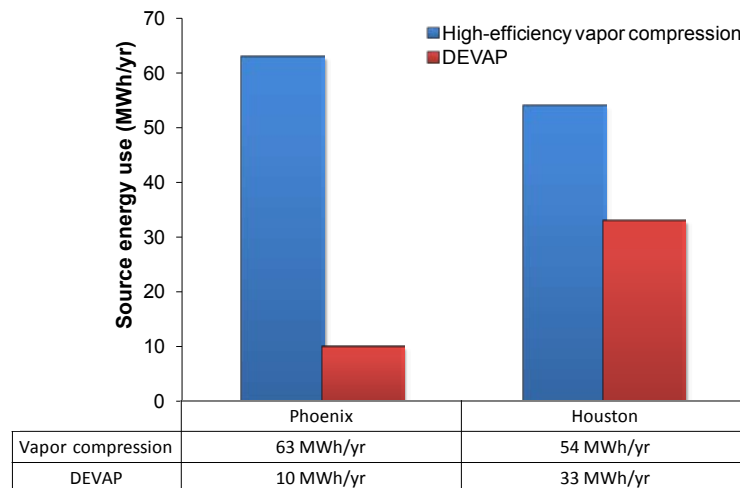


Figure ES–2 Source energy use estimate for a small office building from previous research (Kozubal et al. 2011)

Nomenclature

| | |
|----------------------------------|---|
| A | heat transfer area (ft^2/ton) |
| AHRI | Air-Conditioning, Heating, and Refrigeration Institute |
| AC | air conditioning or air conditioner |
| CAD | computer-aided design |
| C_{LD} | liquid desiccant concentration ($\text{kg}_{\text{salt}}/\text{kg}_{\text{solution}}$) |
| COP | coefficient of performance |
| $\text{COP}_{\text{latent}}$ | water removal source COP by the regenerator |
| $\text{COP}_{\text{space}}$ | total space cooling source COP |
| COP_{unit} | total cooling source COP |
| DEVAP | desiccant enhanced evaporative |
| DH | dehumidification mode |
| EA | exhaust air |
| EER | energy efficiency ratio (Btu/Wh) |
| Gen-1 | generation 1 |
| Gen-2 | generation 2 |
| gpm | gallons per minute |
| H | height |
| H_{e1} | stage 1 exhaust air channel height |
| H_{e2} | stage 2 exhaust air channel height |
| H_{s1} | stage 1 supply air channel height |
| H_{s2} | stage 2 supply air channel height |
| HMX | heat and mass exchanger |
| HVAC | heating, ventilation, and air conditioning |
| ICHX | interchange heat exchanger |
| IEC | indirect evaporative cooler or indirect evaporative cooling |
| IEER | integrated energy efficiency ratio (Btu/Wh) |
| $\text{IEER}_{\text{effective}}$ | integrated energy efficiency ratio of the DEVAP AC using the calculation method described in Section 3.3 (Btu/Wh) |
| LD | liquid desiccant |
| LDAC | liquid desiccant air conditioner |
| NREL | National Renewable Energy Laboratory |
| OA | outdoor air |
| P_{amb} | ambient pressure (psi) |
| P_{fan} | fan power (kW) |

| | |
|----------------|---|
| PP | polypropylene |
| $Q_{cooling}$ | total cooling (kW or Btu/h) |
| Q_{latent} | latent cooling (kW or Btu/h) |
| $Q_{sensible}$ | sensible cooling (kW or Btu/h) |
| Q_{th} | thermal power (kW) |
| RA | return air |
| SA | supply air |
| S1 | airstream state 1 – inlet mixed airstream to conditioner |
| S1.5 | airstream state 1.5 – airstream at the state between the first- and second-stage conditioner sections |
| S2 | airstream state 2 – supply airstream from conditioner |
| S3 | airstream state 3 – purge air inlet to first-stage conditioner |
| S4 | airstream state 4 – exhaust air outlet from first-stage conditioner |
| S5 | airstream state 5 – exhaust air outlet from second-stage conditioner |
| SCFM | standard cubic feet per minute |
| T_{db} | dry bulb temperature (°F) |
| $T_{db,in}$ | inlet dry bulb temperature (°F) |
| T_{dp} | dew point temperature (°F) |
| T_{OA} | outdoor air dry bulb temperature (°F) |
| $T_{OA,wb}$ | outdoor air wet bulb temperature (°F) |
| T_{SA} | supply air dry bulb temperature (°F) |
| T_{wb} | wet bulb temperature (°F) |
| $T_{wb,in}$ | inlet wet bulb temperature (°F) |

Greek symbols

| | |
|-----------------|---|
| ϵ_{wb} | wet bulb effectiveness: $\epsilon_{wb} = \frac{T_{db,in} - T_{SA}}{T_{db,in} - T_{wb,in}}$ |
| Δh | change in enthalpy (Btu/lb _m) |
| ΔP | change in pressure (in H ₂ O) |
| ΔT | change in temperature (°F) |
| ω | humidity ratio (lb _m /lb _m) |
| $\Delta \omega$ | change in humidity ratio (lb _m /lb _m) |

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1.0 Introduction

This report documents the design of a desiccant enhanced evaporative air conditioner (DEVAP AC) prototype and the testing to prove its performance. Previous numerical modeling and building energy simulations indicate a DEVAP AC can save significant energy compared to a conventional vapor compression AC (Kozubal et al. 2011). The purposes of this research were to build DEVAP prototypes, test them to validate the numerical model, and identify potential commercialization barriers.

The prototypes were built with two vendors: AIL Research and Synapse Product Development (Synapse). An iterative process consisting of collaborative design, numerical modeling, and component testing transformed the conceptual design criteria into two working prototypes. Pursuing two independent design approaches provided us the opportunity to incorporate the best features of both into a second-generation (Gen-2) prototype.

The prototypes were tested at the National Renewable Energy Laboratory's (NREL) Advanced Heating, Ventilation, and Air-Conditioning (HVAC) Systems Laboratory (NREL 2005) over a range of operating conditions and inlet air temperatures and humidities. A key barrier to commercializing a DEVAP AC is that the cost and performance tradeoffs associated with changes in product designs cannot be accurately predicted. Prototype testing validated the numerical model making it a design tool that can rapidly—and quite accurately—predict these tradeoffs. This design tool, along with the experience from prototype construction, is used to estimate the cost, weight, and size of a Gen-2 packaged design.

1.1 DEVAP AC Design Innovations

Figure 1–1 shows a schematic of the DEVAP AC and its airflows. A top view of the airflow channels and the thermodynamics of the process are shown in Figure 1–2 and Figure 1–3. Air states are numbered in each graph. We refer to airstreams as moving from one state to the next. For example, airstream 1-1.5 is the stream of air moving from air state 1 (S1) to air state 1.5 (S1.5). The prototypes were designed in two distinct stages: a first-stage dehumidifier and a second-stage indirect evaporative cooler (IEC).

The first-stage dehumidifier is a cross-flow heat and mass exchanger (HMX) between two airstreams (airstreams 1-1.5 and 3-4). Desiccant and water flow vertically and are gravity driven. The desiccant is contained by a polypropylene (PP) microporous membrane (Z-series from Celgard LLC). AIL Research used nozzles to spray a high water flow rate that created a two-phase flow of water and outdoor air (OA) in airstream 3-4. The Synapse design used a low water flow rate that was spread by wicked surfaces in contact with airstream 3-4. Membranes were not used for water containment in either prototype. A waterside membrane was too risky for proper operation and demonstration at this early development phase. However, it may be used in the future for controlling biological growth, because it creates a barrier that prevents organisms from implanting onto wet surfaces.

The second stage is an NREL-designed counterflow IEC with wet bulb effectiveness (ϵ_{wb}) measured at 120%–128% at the design mass flow rate. For both designs, a low flow rate of water was distributed across the heat transfer surfaces by a wicking material.

Splitting DEVAP into two distinct stages gives HVAC designers many options for placing the two functions in different areas of a building. This strategy thus led to the creation of three potential products:

- Dehumidifier for OA pretreatment (first-stage HMX)
- Evaporative AC only (second-stage HMX)
- DEVAP AC system (combined first- and second-stage HMXs).

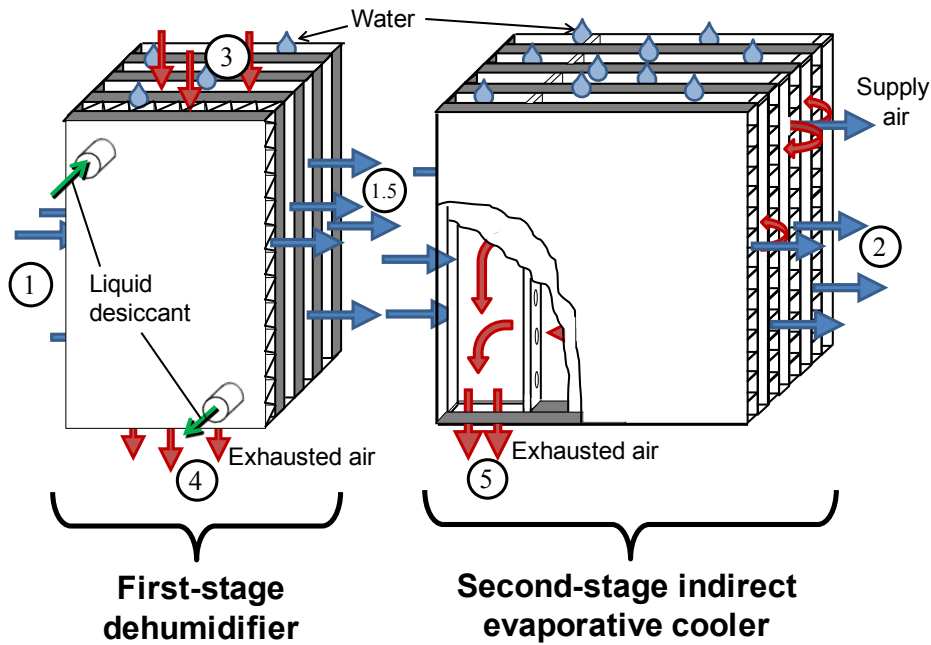


Figure 1-1 Schematic of two-stage DEVAP AC
 Illustration by Eric Kozubal and Jason Woods, NREL

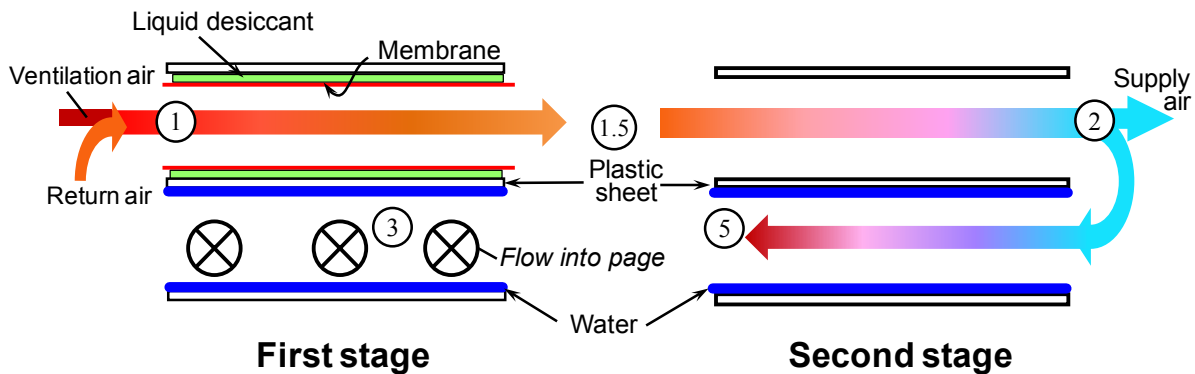


Figure 1-2 Top view of internal air passages in a single channel pair
 Illustration by Eric Kozubal and Jason Woods, NREL

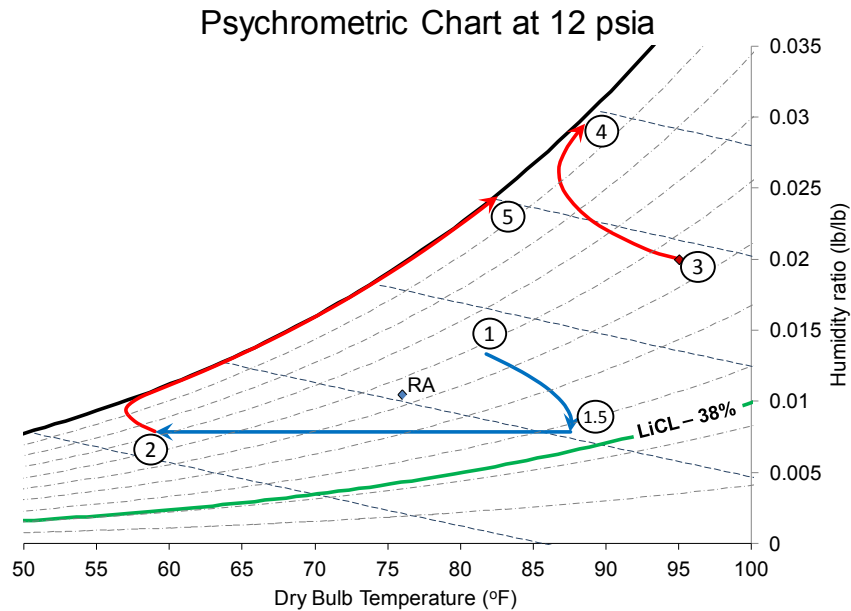


Figure 1-3 Air states shown on a psychrometric chart (RA = return air)

The first-generation (Gen-1) prototypes were built for proof of performance. The project timeline and funding required the following considerations:

- Success depended on the HMXs achieving the predicted performance.
- The design space for a DEVAP AC is large, with many variables and complex interactions that require investigation.
- Independent variables include:
 - Form factor (height, width, length)
 - Airflow channel sizes (height, width)
 - Airflow rate and resulting airflow regime (laminar versus turbulent)
 - Desiccant flow rate
 - Desiccant concentration (salt fraction by weight in solution)
 - Specific cooling rate (enthalpy change of the air)
 - Manufacturing method
 - Material selection, including membrane type and performance.
- Dependent variables include:
 - Size and weight
 - Pressure drop and electrical energy use
 - Cooling efficiency (coefficient of performance or COP)
 - Cost.

- The desiccant was regenerated using a single-effect scavenging air regenerator already being commercialized by AIL Research in its low-flow liquid desiccant air conditioner (LDAC) product (see Section 2.3). Energy performance was estimated using a two-stage regenerator model that was validated for a sample of points (see Section 3.0).
- The system would be configured without packaging that would normally be required in a product.
 - Fans were not included. Fan power was estimated using laboratory pressure loss data and nominal efficiency.
 - Pumping power was not indicative of an actual product because of the prototype's small size and added liquid sensors. Thus, this power was also calculated using head pressure and nominal pump efficiency.

Having two vendors enabled us to develop two design strategies, manufacturing methods, and material choices. Given the many variables and time constraints, some aspects of both designs had to use off-the-shelf components, which meant these first prototypes would not be optimized for performance, size, weight, and cost. Instead, the project focused on validating the numerical model, which could then be used to create future designs, including a Gen-2 design that incorporates the best features of the AIL Research and Synapse prototypes.

2.0 Design Optimization

At the start of the project, we developed design criteria from a parametric analysis with our thermodynamics-based numerical model. These criteria set the geometric parameters, materials, and manufacturing methods. With this basic blueprint, we sought expert manufacturing vendors to develop a prototype. We contracted with Dave Paulson from Water Think Tank and John Pellegrino from the University of Colorado, Boulder to create selection criteria and identify candidate companies. We identified eight companies and ultimately chose AIL Research (www.ailr.com) and Synapse Product Development (www.synapse.com).

AIL Research previously developed the low-flow LDAC with NREL and has expertise in the manufacture of prototype desiccant systems. Its founder, Andrew Lowenstein, is widely regarded as a top expert in the field of liquid desiccant (LD) cooling. Synapse designs products for other entities that do not have the necessary staff and prototyping capabilities. Synapse uses many manufacturing partnerships for rapid prototype development. Its engineering staff has designed plate-and-frame membrane systems with similar requirements to a DEVAP prototype.

Figure 2–1 outlines the method used to develop the two prototypes. NREL and the two vendors used an iterative process to design the Gen-1 prototype. This process involved numerical modeling, component testing, experience from NREL about desired design features, and experience from the vendors about manufacturing methods.

The iterative process starts with the numerical modeling. The design goal was to optimize the conditioner to provide efficient space cooling, which was calculated from return air (RA) to supply air (SA). The system uses 0%–30% OA to provide the necessary airflow for the second-stage HMX, and by doing so creates a 0%–30% guaranteed ventilation rate. However, to properly converge on efficient space cooling performance, the cooling required to bring the OA to room neutral conditions was not included. This ensures that the process converges on a design that provides efficient space cooling, and not one that only provides efficient ventilation. We used the following peak design conditions:

- OA at a 95°F, humidity ratio (ω) = 0.020 lb/lb
- RA at 76°F, ω = 0.010 lb/lb
- SA flow rate = 380 SCFM/space cooling ton
- First-stage exhaust air (EA) ratio = 0%–50%
- Second-stage EA ratio = 0%–40%
- Design OA fraction = 30%
- SA change relative to RA: enthalpy change = 7 Btu/lb, sensible heat ratio = 0.6 (SA = 59°F, ω = 0.0077 lb/lb)
- Desiccant inlet and outlet concentration = 38% and 36% by weight of lithium chloride resulting in a flow rate = 0.34 gpm/space cooling ton.

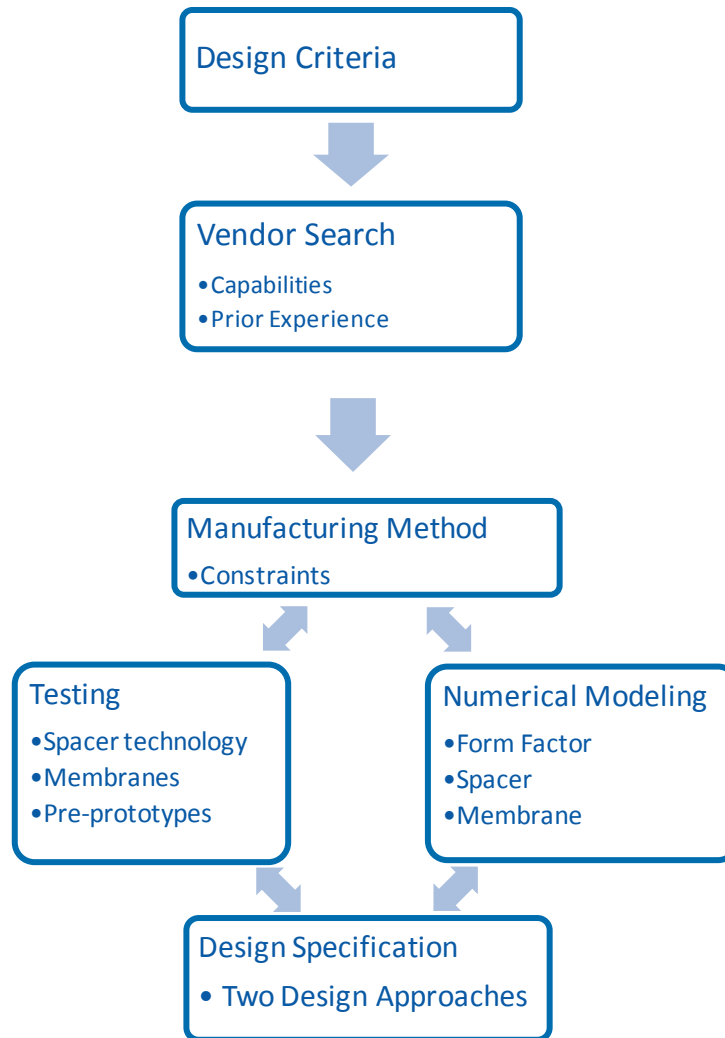


Figure 2–1 Design approach flow diagram

The numerical modeling determined the performance based on a range of independent variable combinations. We developed routines to determine near-optimal designs that balance source energy space cooling COP (COP_{space}), size, and material costs given the constraints on manufacturing methods and available off-the-shelf parts. Figure 2–2 and Figure 2–3 show how the process was used to explore the sensitivity and interaction between channel heights (H): stage 1 SA (H_{s1}), stage 2 SA (H_{s2}), stage 1 EA (H_{e1}), and stage 2 EA (H_{e2}). In these two charts, our method seeks a design in the upper left corner. This results in high efficiency with minimal heat transfer area, a surrogate for size, weight, and cost. Cost was not used explicitly because this surrogate is sufficient for this stage of development.

We started with a design at the intersection of all the sensitivity lines (diamond point). We used the sensitivity shown in Figure 2–2 to find the path that maximizes COP_{space} at a reduced area. This leads to the next iterative point in Figure 2–3. This process defines the “knee” in the curve where smaller heat transfer area results in significantly reduced COP_{space} . We then used our engineering judgment to choose a near-optimal design with heat transfer area and COP_{space} near this “knee”. We discuss only the interactions of channel heights in this report; however, in

practice we accounted for the interactions of all factors listed. Section 4.0 discusses COP_{space} versus heat transfer area for each prototype and a proposed Gen-2 design.

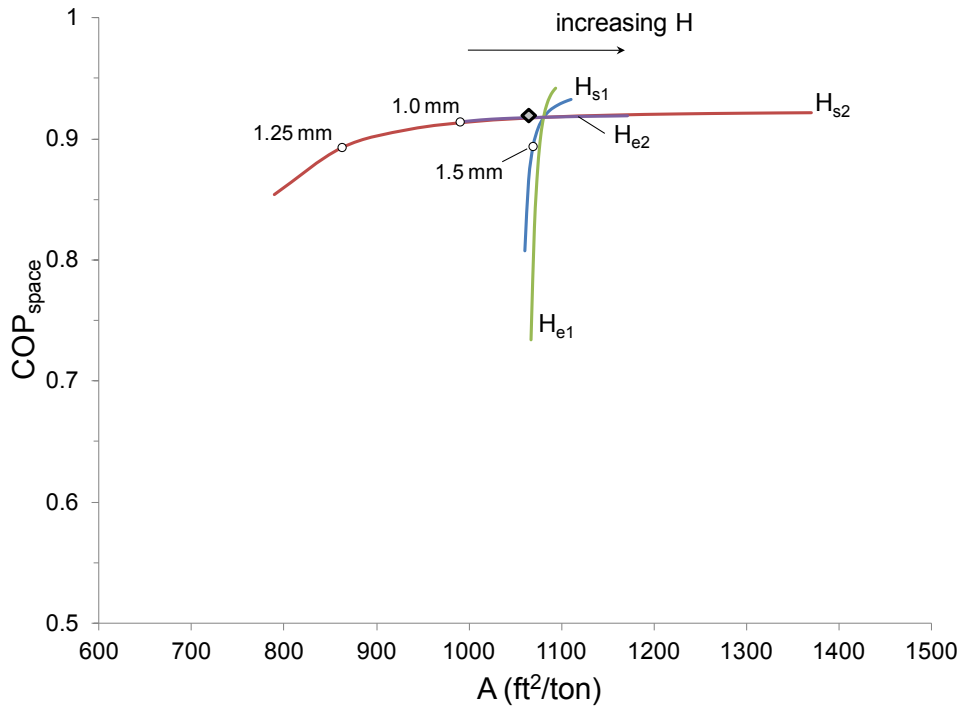


Figure 2–2 Example of interaction between channel heights, heat transfer area, and COP_{space}

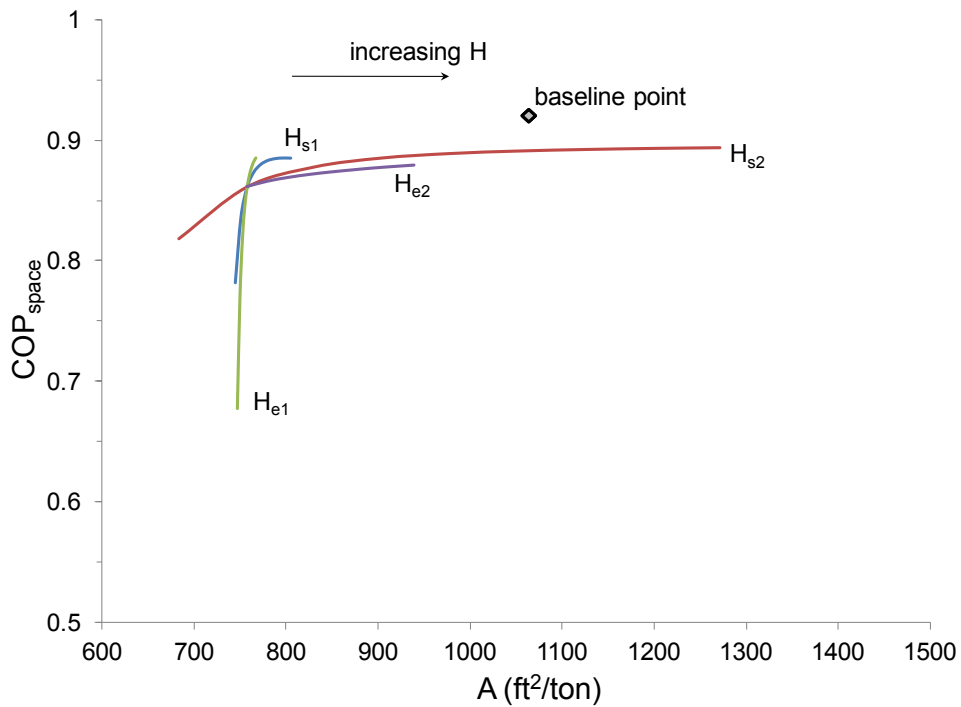


Figure 2–3 Example of interaction between channel heights, heat transfer area, and COP_{space} showing next iterative point

The optimization process was used at the start of the project to determine an initial conceptual design. With this in mind, we began an independent collaborative design process with each vendor in which ideas about manufacturing methods and their effects on performance were exchanged. The vendors focused on construction methods. NREL focused on achieving higher heat and mass transfer and uniform air flow. This led us to focus on the development of two critical features: a support spacer for the air gaps, and a membrane for desiccant containment.

The spacer performs two functions: (1) it maintains airflow gap geometry; and (2) it enhances heat and mass transfer without excessive friction loss (pressure drop).

To find suitable spacers, we tested off-the-shelf and newly constructed components. We then developed evaluation techniques. This involved the construction of an air channel test apparatus for air to liquid flow evaluation. Heat and mass transfer in this the DEVAP geometry is not well developed in industry, and literature searches turned up little information. Our work on characterizing the pressure drop and heat transfer performance of these spacers was submitted to the journal *Applied Thermal Engineering* (Woods and Kozubal 2012b).

We identified the microporous PP membrane from Celgard LLC as a good candidate for use in DEVAP. This membrane came with the option of a nonwoven PP adhered backing, which improves tear resistance, but reduces the diffusion coefficient. We used data from the manufacturer and from nitrogen gas permeation tests to estimate the water vapor diffusion coefficient for the unbacked and backed versions, then used these estimates in the numerical model to calculate vapor transport through the membrane.

The DEVAP design evolved with these new performance data for the spacers and the membrane and with input from the vendors. We adjusted the design as constraints and data on manufacturing methods, materials, geometry, and membrane and spacer performance became apparent. Two 1/10-scale pre-prototypes were then created, built, and delivered for testing at NREL's Advanced HVAC Systems Laboratory. After testing, we conducted a redesign review with each firm to determine areas for improvement. We then collaborated on two full-scale prototypes with nominal capacity of 1 ton at Air-Conditioning, Heating, and Refrigeration Institute (AHRI) standard conditions.

2.1 AIL Research Prototype Description

The construction of the AIL Research prototype revolved around extruded PP plastic made by Coroplast (Figure 2–4). A computer-aided design (CAD) rendering of the first- and second-stage DEVAP HMXs is shown in Figure 2–5. Numbers in the figure indicate airstreams in and out of the device as described in Figure 1–1. A photo of the assembled first-stage HMX is shown in Figure 2–6.

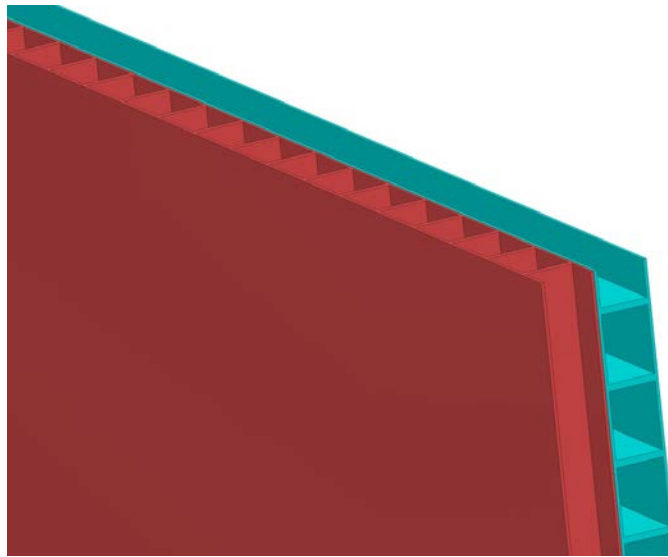


Figure 2-4 Example of extruded PP sheets

Illustration by Andrew Lowenstein, AIL Research, used by permission

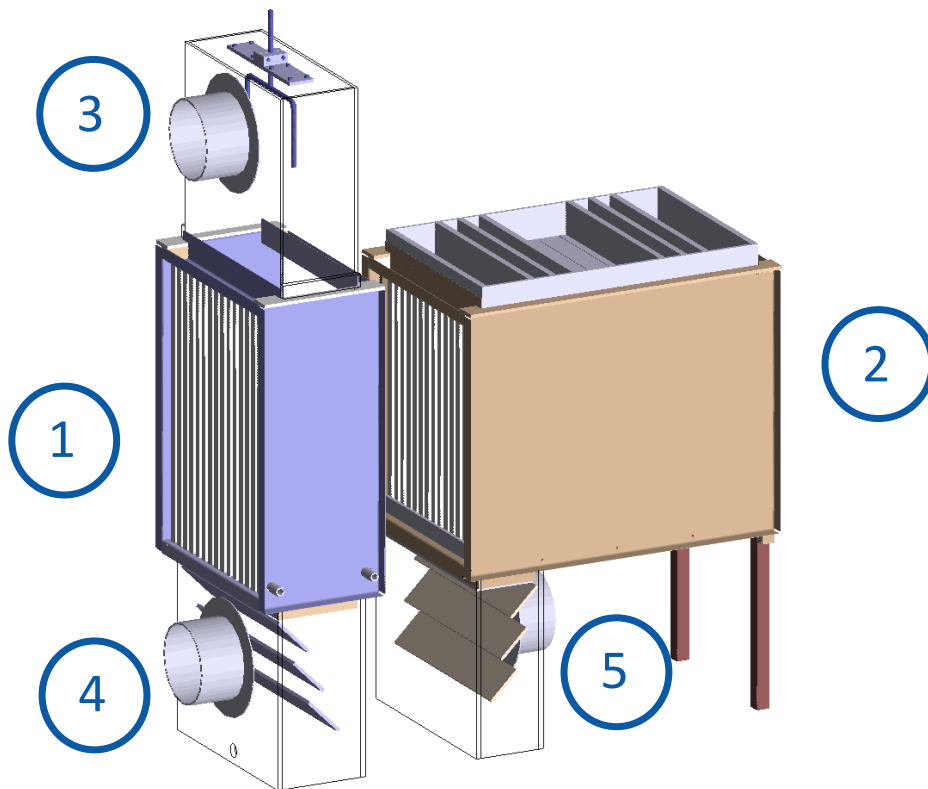


Figure 2-5 CAD rendering of the AIL Research DEVAP AC showing first- and second-stage HMXs in the enclosure. Airstream numbers are also shown.

Illustration by Andrew Lowenstein, AIL Research, used by permission

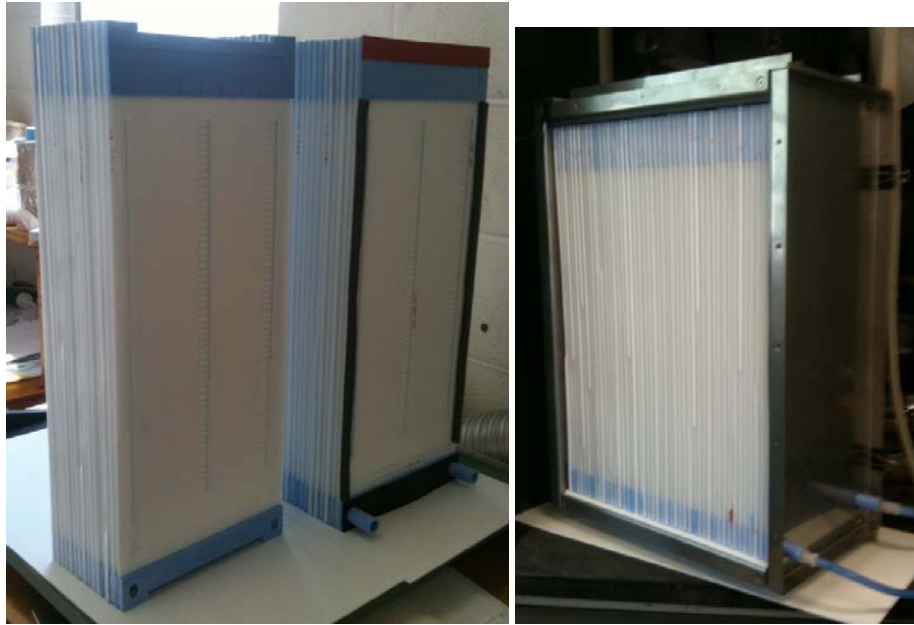


Figure 2-6 Subassembly and fully assembled view of AIL Research first-stage conditioner
Photo from Andrew Lowenstein, AIL Research, used by permission

In the first-stage, AIL Research used the flutes created by the Coroplast extrusion to form the coolant airstream 3-4. Water was distributed via flow nozzles at the top of the HMXs (shown in the airstream 3 plenum) and mixed with airstream 3-4, which ran vertically downward. Some water evaporated as it traveled through the HMX, but most was collected at the bottom of the airstream 4 plenum. Louvers shown in this plenum were used to separate the water droplets from the airstream. Because this design did not have a method to hold up the water internal to the flutes (e.g., wicked surfaces), this configuration requires a water flow rate that is significantly higher than the water evaporation rate. Thus, a water reservoir and pump are required to return the water from the collection sump to the top flow nozzles.

The unbacked Celgard PP membrane was welded to the Coroplast extrusions using techniques developed by AIL Research. A liquid manifold design (proprietary to AIL Research) distributed desiccant to the space between the membrane and Coroplast. Air gaps on airstream 1-1.5 were maintained by strips of Coroplast spacers with the extruded flutes oriented parallel to the airflow. The design also incorporated proprietary AIL Research spacers that mix the airstream to enhance heat and mass transfer.

A photo of the assembled second-stage HMX is shown in Figure 2-7. AIL Research used the Coroplast flutes to form the SA channels (airstream 1.5-2). A nylon wick was applied to the outer walls of the PP. These subassemblies were then stacked with spacers between each to form the EA channels (airstream 2-5). A low flow of water was distributed into the second-stage EA channels from the top. The nylon wick had sufficient water upkeep to allow this flow rate to be marginally above the water evaporation rate. Thus, a solenoid valve controlling domestic cold water is the only mechanism required to distribute water. Purge water was collected at the bottom of the EA plenum (airstream 5), at which point it was directed to a drain.



Figure 2–7 Fully assembled view of ALL Research second-stage conditioner (outlet airstream 2 shown)

Photo by Eric Kozubal, NREL

Wicked surfaces provide the following advantages for IECs:

- The wicking ensures that the walls are fully wetted and there is no lost evaporation area.
- The water feed rate can be held to a factor of 1.25-2 times that of the evaporation rate. This technique allows for “once-through” water use. The water that drains off the HMX is concentrated with minerals and can then be drained away. A sump and pumping system are no longer required, which improves energy performance and eliminates sump-borne biological growth.
- A simple controller in the AC can periodically use fresh (low concentration) water to rinse the HMX and clear any built-up minerals.

Airstreams 1.5-2 and 2-5 are in counterflow in the second-stage HMX. A sensitivity analysis showed that the cooling effectiveness could be reduced by as much as 20% if proper counterflow was not achieved. Airstream 1.5-2 flowed straight, through extruded flutes, but airstream 2-5 required a 90-degree turn before exiting the HMX. NREL used computational fluid dynamics software to design an air restrictor to ensure proper counterflow of airstream 2-5. Figure 2–8 shows the resulting stream lines of the EA stream with this air restrictor. Both vendors incorporated this technique in their final designs.

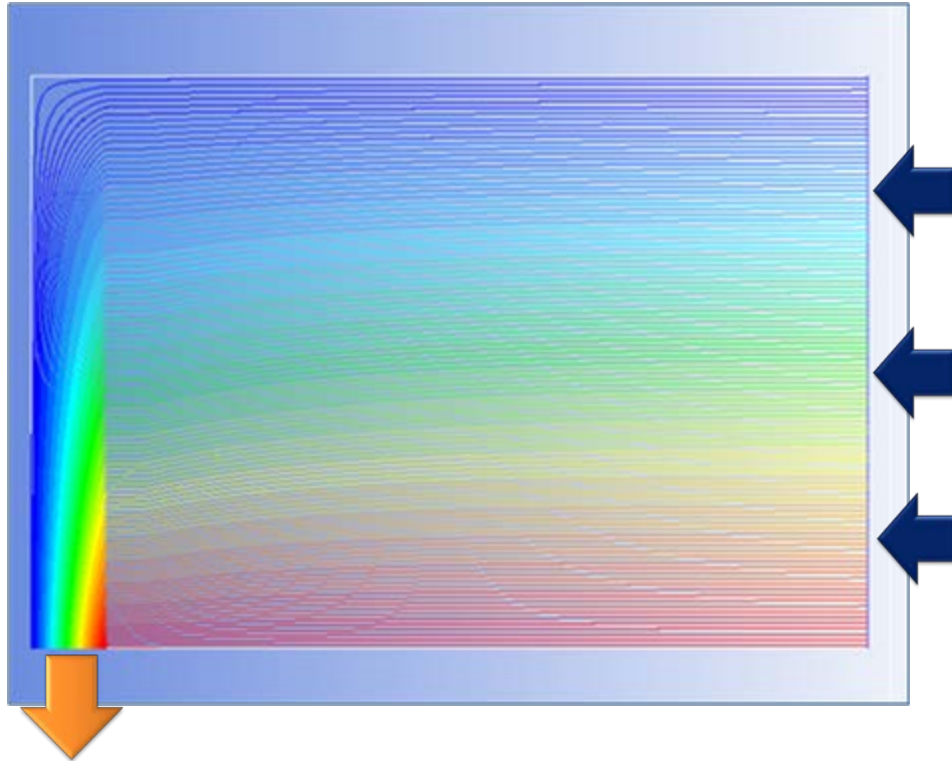


Figure 2–8 Stream lines from computational fluid dynamics software showing the airflow pattern in airstream 2-5. The color map represents the stream function values. Areas with sharp color transitions indicate higher velocity flow.

2.2 Synapse Prototype Description

The construction of the Synapse prototype revolved around laminated layers of polyethylene terephthalate (PET) plastic that were adhered with layers of acrylic pressure-sensitive adhesive (see Figure 2–9). Although this assembly method cannot easily be scaled to high-volume manufacturing, the achievable geometries are nearly ideal and therefore appropriate for prototypes. This enabled us to create a prototype with parallel plate geometry and to include airside turbulators to enhance heat and mass transfer on airstreams 1-1.5 and 3-4.

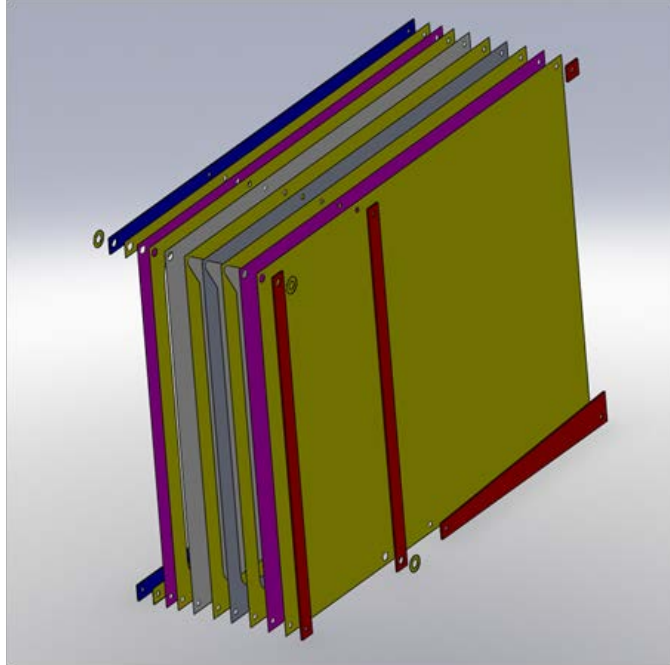


Figure 2–9 Example CAD rendering of laminated design approach showing layers of polyethylene terephthalate plastic, membrane, and pressure-sensitive adhesive

Illustration by Ian Graves, Synapse, used by permission

For the first-stage, the laminated layers enabled us to use wicked surfaces in the airstream 3-4 channels. For the spacer, we adapted an off-the-shelf expanded aluminum grating made by Permatron, because an optimized solution was not feasible in the project schedule. The spacer created airflow channels that were larger than optimum and would not be used in a future product design. This spacer was used in airstream 1-1.5 and airstream 3-4.

The Synapse design used the same expanded PP hydrophobic membrane from Celgard, but was backed with a nonwoven PP fabric to add strength. The backing reduces vapor diffusion through the membrane, but increases tear resistance. Synapse oriented the backing to the airside gap, where tears can originate from abrasion by foreign objects or the aluminum spacer.

Synapse developed a desiccant manifold that used laminated layers of plastic and adhesive to effectively and evenly distribute LD behind the membrane. Distribution was verified using dyed water flowing through a sample assembly as a method of flow visualization.

The Synapse second stage used laminated construction, but with minimal spacers to create laminar flow, parallel plate air channels. The design used Coroplast strips as airflow spacers and wicked surfaces on the wet side of the HMX.

The Synapse first- and second-stage HMXs are shown together in Figure 2–10 and Figure 2–11. Numbers in the figure indicate airstreams in and out of the device as described in Figure 1–1

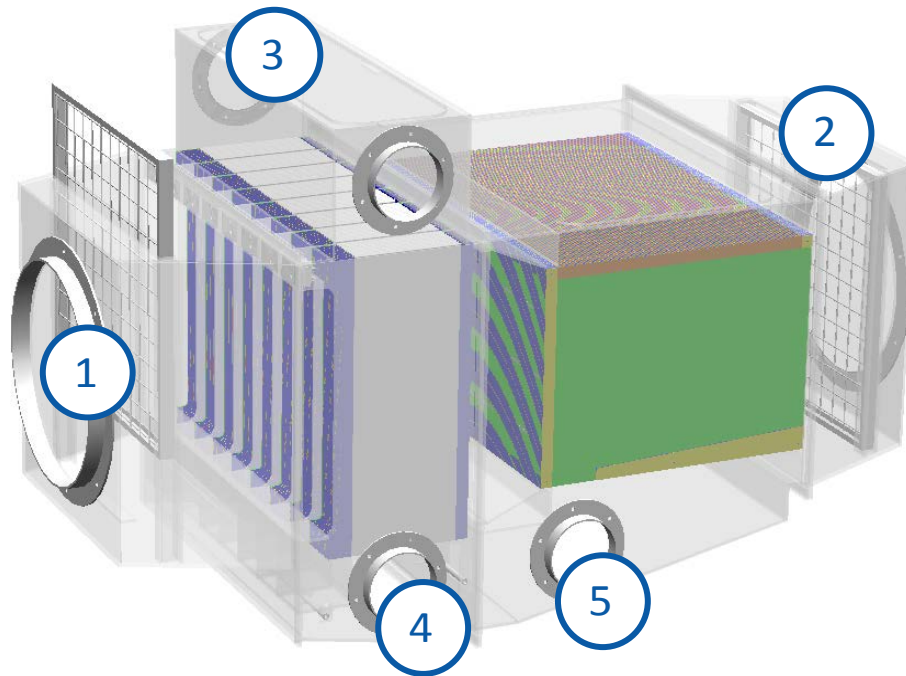


Figure 2–10 CAD rendering of the Synapse DEVAP AC showing first- and second-stage HMXs in the enclosure. Airstream numbers are also shown.

Illustration by Ian Graves, Synapse, used by permission

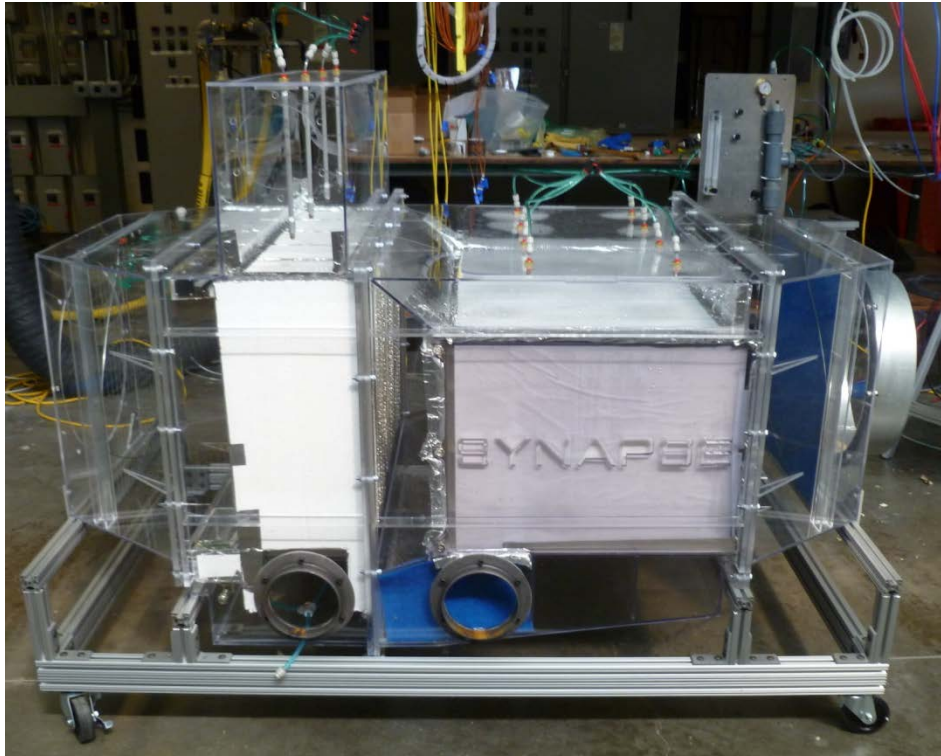


Figure 2–11 Photo showing the Synapse HMXs at the NREL HVAC laboratory

Photo by Eric Kozubal, NREL

2.3 Balance of System Description

In addition to the two prototype DEVAP conditioners, NREL assembled the balance of system in the laboratory for testing. We used a scavenging air LD regenerator developed for NREL by AIL Research (Lowenstein et al. 2006) (see Figure 2–12). This regenerator, shown in Figure 5 of Lowenstein’s report, was delivered to NREL in 2006. For this project, we sent the regenerator back to AIL Research to refurbish it for use with the DEVAP AC. The delivered unit had the following characteristics:

- Two-ton (about 24 lb/h) low-flow LD regenerator that accepts approximately 8 gpm of hot water. Hot water was supplied by the boiler system at NREL’s laboratory.
- LD storage tank, designed specifically for DEVAP desiccant concentration working range.
- Interchange heat exchanger (ICHX) to improve regeneration efficiency.
- A desiccant pump and fittings to circulate desiccant from the tank to the scavenging air regenerator component.

We connected the regenerator and conditioner with off-the-shelf components PP desiccant storage tank, Kynar tube fittings, polyvinyl chloride tubing for liquid delivery, and a magnetic drive centrifugal pump from March Pumps). Two toroidal conductivity sensors from Analytical Technology Inc. (ATI Q45CT) measured the salt concentration of the lithium chloride solution from Kathabar. These sensors were used to measure inlet and outlet concentrations from the DEVAP AC. A schematic of the system configuration is shown in Appendix A, Figure A–1.

We connected the airstreams to the HVAC laboratory to measure all inlet and outlet airflow rates, temperatures, and humidities. The laboratory control software maintained set points for the inlet airstreams and controlled the water feed rate to the systems by modulating a control valve. The software maintained inlet desiccant concentration to a typical dead band of two percentage points by modulating the desiccant regenerator on and off.

The regenerator operation is similar to the low-flow LDAC, with the following adaptations for operating with DEVAP:

- The regenerator operated at a concentration increase of 6 to 8 percentage points, up to 43% concentration.
- The desiccant was stratified to avoid mixing strong and weak desiccant by carefully returning weak desiccant to the top of the tank and strong desiccant to the correct vertical location by means of natural density stratification.
- System control is based on desiccant concentration directly rather than on SA humidity.

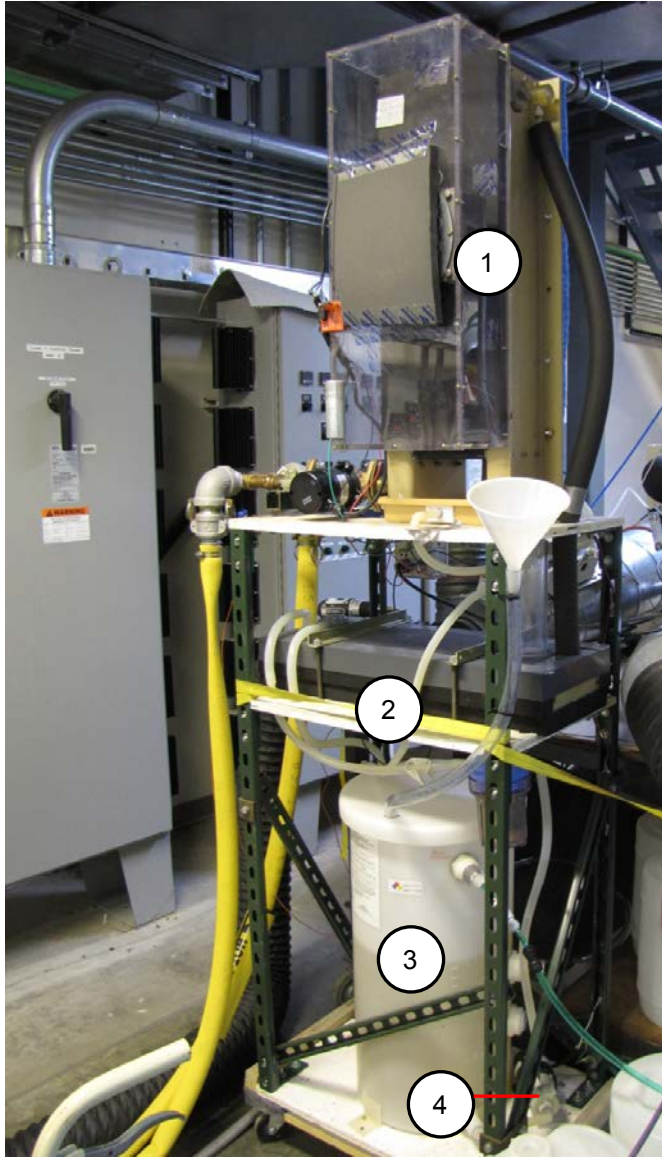


Figure 2-12 Left: (1) Scavenging air regenerator, (2) ICHX, (3) desiccant tank, and (4) desiccant pump set up at the NREL HVAC laboratory. Right: Scavenging air regenerator delivered to NREL in 2006.

Left Photo by Jason Woods, NREL; Right Photo by Andrew Lowenstein, AIL Research, used by permission

3.0 Laboratory Testing and Results

We tested the cooling and dehumidification performance of the first-stage, second-stage, and the two stages combined in NREL’s HVAC Laboratory. Table 3–1 lists the measured parameters.

Table 3–1 Measured Parameters

| | Measurement |
|-------------------------------------|--|
| Global measurements | Ambient temperature, ambient pressure in laboratory |
| Airstreams 1, 2, 3, 4, and 5 | Temperature, dew point temperature, mass flow rate, pressure |
| LD inlet and outlet streams | Temperature, electrical conductivity |
| Water flow | Nozzle flow rate, duty cycle, temperature |
| Scavenging air regenerator | Inlet water temperature, duty cycle |

The DEVAP AC numerical model comprises three smaller, integrated numerical models: the first- and second-stage HMXs, and a desiccant regenerator. Our focus was to validate the first- and second-stage HMX numerical models, based on Woods and Kozubal (2012a), with the experimental prototypes. The single- and two-stage regenerators have been under development through separate project funding. Ultimately, to determine the efficiency of the DEVAP AC with a two-stage regenerator, we must use the experimental data for the first- and second-stage HMXs and combine them with a two-stage regenerator numerical model.

We did not test the DEVAP conditioner with the two-stage regenerator in the laboratory, because it could not be developed for this smaller scale testing with the allotted time and resources. However, AIL Research has developed a two-stage regenerator through separate NREL-funded projects (Lowenstein 2006). In Figure 3–1, we compare the performance of this Gen-1 regenerator to NREL’s two-stage regenerator model. The graph shows the water removal source energy efficiency (COP_{latent}) versus desiccant concentration change. Higher COPs are achieved with lower inlet concentrations and with a high change in desiccant concentration across the regenerator. High concentration change results in lower heat losses because of the lower desiccant flow rate. The DEVAP working range is shown on the graph, along with two data points from AIL Research (Lowenstein 2006). The data show that the modeled COP_{latent} is less than the measured values and is therefore conservative. More data points that cover a greater range of operating conditions would fully validate the two-stage regenerator model, but are not available until AIL Research completes the fabrication of a Gen-2 regenerator and measures its performance.

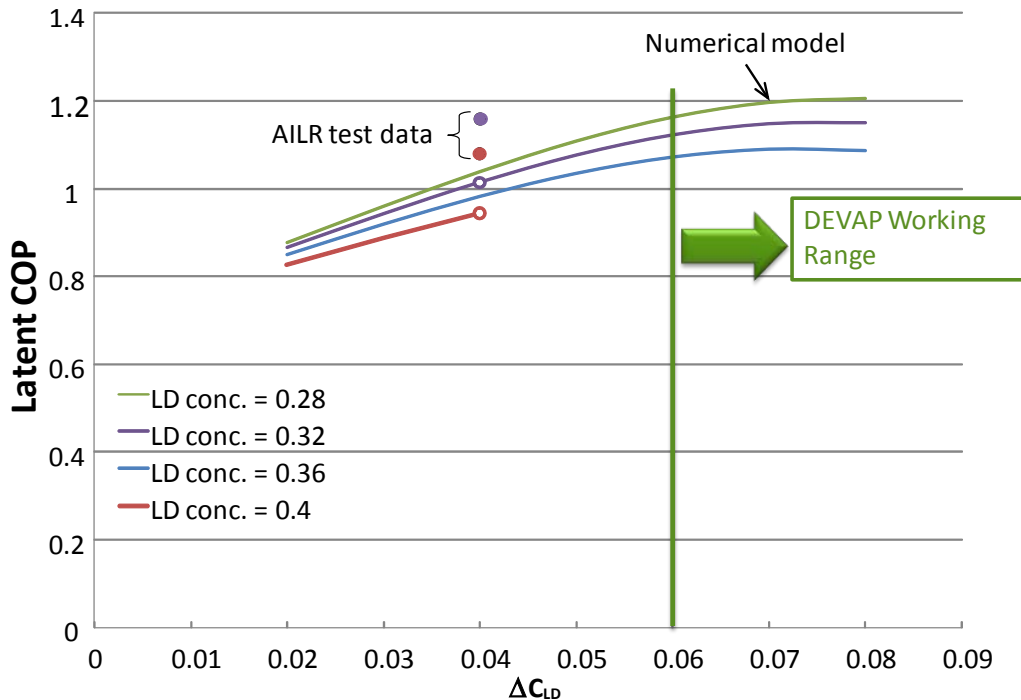


Figure 3–1 Modeled performance of two-stage regenerator with two data points plotted from data obtained by AIL Research (Lowenstein 2006)

We measured the performance of the AIL Research and Synapse first-stage designs and the AIL Research second-stage design. During our evaluation of the Synapse second-stage design, we determined that the construction technique used inadequate spacers, which led to inconsistent air channel geometry. These air channels did not have sufficient support to maintain geometrical tolerance, a problem that degraded cooling capacity by about 20%. We concluded that the short project timeline would prevent us from resolving this performance issue.

3.1 Test Interpretation

In this section, we describe key test points that illustrate the operation of the DEVAP AC. We show the test points on psychrometric charts and show the model predictions against the measured data. The full dataset can be found in Appendix B, which shows both measured and modeled data used to create the figures in this section. Details of the numerical model can be found in Woods and Kozubal (2012a), which also shows test data from the Synapse first-stage and the AIL Research second-stage HMXs. Appendix C shows similar information for the AIL Research first-stage HMX.

3.1.1 First-Stage HMX Performance (AIL and Synapse Units)

Tests were performed at AHRI standard rating conditions (AHRI 2007). Figure 3–2 shows the performance of the AIL Research and Synapse first-stage HMX using the AHRI RA and OA conditions as the inlet air states for S1 and S3, respectively. The measured outlet state (S1.5) is shown against the modeled performance. Figure 3–3 shows the measured versus predicted performance from numerical modeling for all tests on the first-stage (for test points, see Appendix B). The AIL and Synapse HMXs performed on average to about 78% and 98.4% of

the modeled latent capacity, respectively. All data for the Synapse first-stage HMX were within 10% of predicted values.

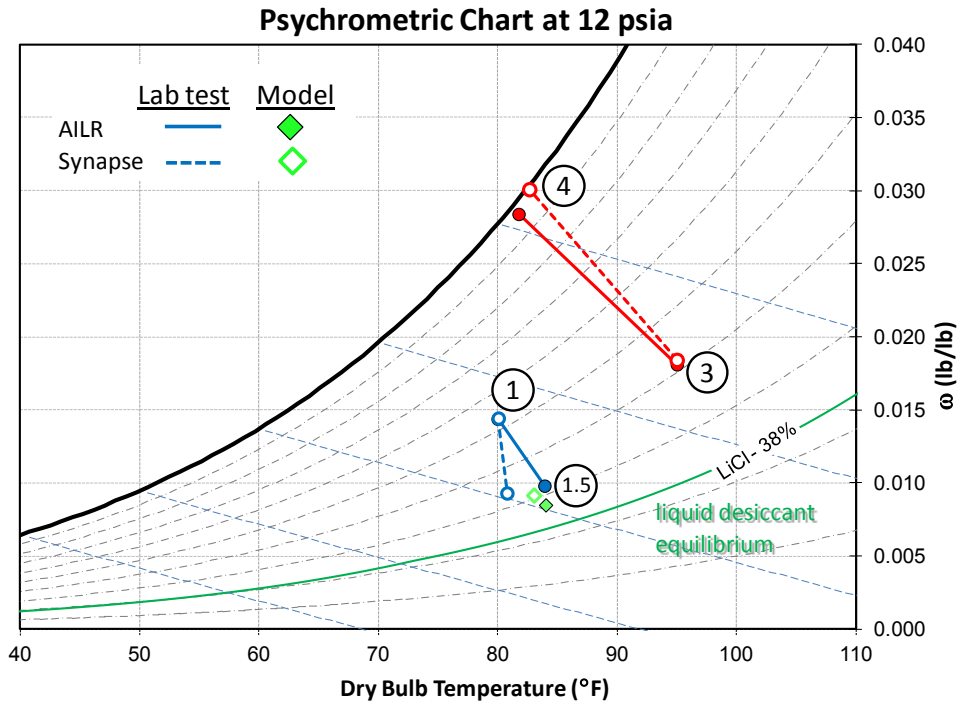


Figure 3–2 Measured performance of AIL Research and Synapse first-stage HMXs at AHRI standard conditions

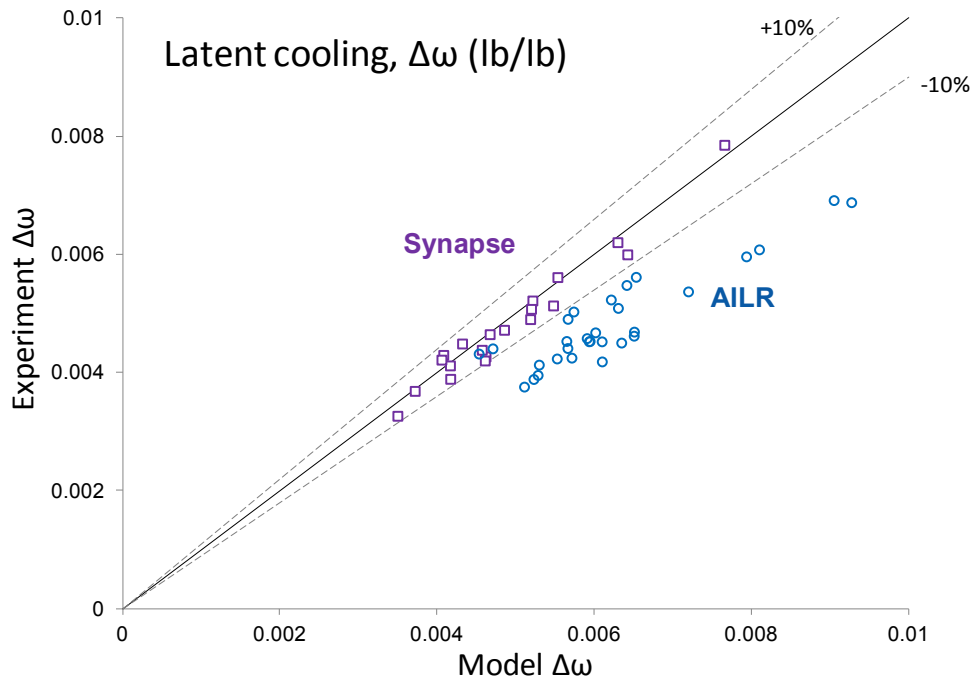


Figure 3–3 Modeled versus experimental measurement of Stage 1 latent cooling

We carefully investigated the performance of the AIL Research first-stage conditioner by using a chilled mirror, dew point hygrometer to measure the latent removal effectiveness of each S1-1.5 air channel. We discovered a large variation from channel to channel; some channels underperformed compared to model prediction. Figure 3–4 shows the latent removal effectiveness of several channels that did not meet the modeled prediction. The cause of this discrepancy was nonuniform desiccant distribution from channel to channel caused by a known manufacturing and design flaw in the desiccant manifold. The data shown are after we spent significant time diagnosing the problem and improving distribution. To help compensate for the deficient desiccant distribution, we increased the total desiccant flow rate by 30% for performance testing.

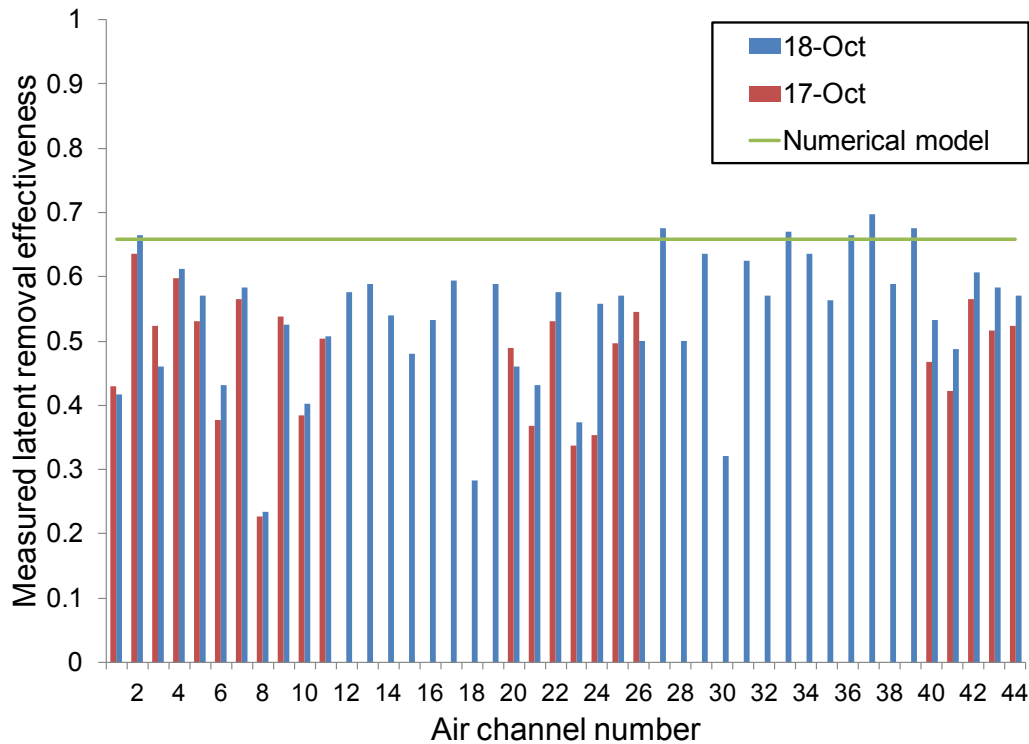


Figure 3–4 Graph of measured latent removal effectiveness per air channel of AIL Research first-stage conditioner

We also performed tests to determine the evaporative cooling performance of the first-stage AIL Research HMX, which showed that the heat transfer was less than predicted. We concluded that the lack of a wicked surface in the flutes of the Coroplast (EA side) contributed significantly to this issue. The flute surfaces were unable to hold a film of water and maintain adequate cooling.

The Synapse first-stage conditioner displayed no significant performance issues, indicating good desiccant flow distribution and good surface wetting on the EA side. The desiccant flow rate is half that of the AIL Research HMX, but achieved the same dehumidification level. We thus conclude that the Synapse method of distributing desiccant is the more reliable approach.

3.1.2 Second-Stage HMX Performance (AIL Research Unit)

Figure 3–5 shows the performance of the AIL Research second-stage HMX with inlet conditions the same as the first-stage outlet from the AHRI test shown in Figure 3–2. Figure 3–6 shows the measured performance versus the modeled prediction for 10 tests. The test points are described in Woods and Kozubal (2012a). This HMX achieved on average 99.7% of sensible capacity compared to the modeled prediction. All measured data points were within 10% of predicted capacity.

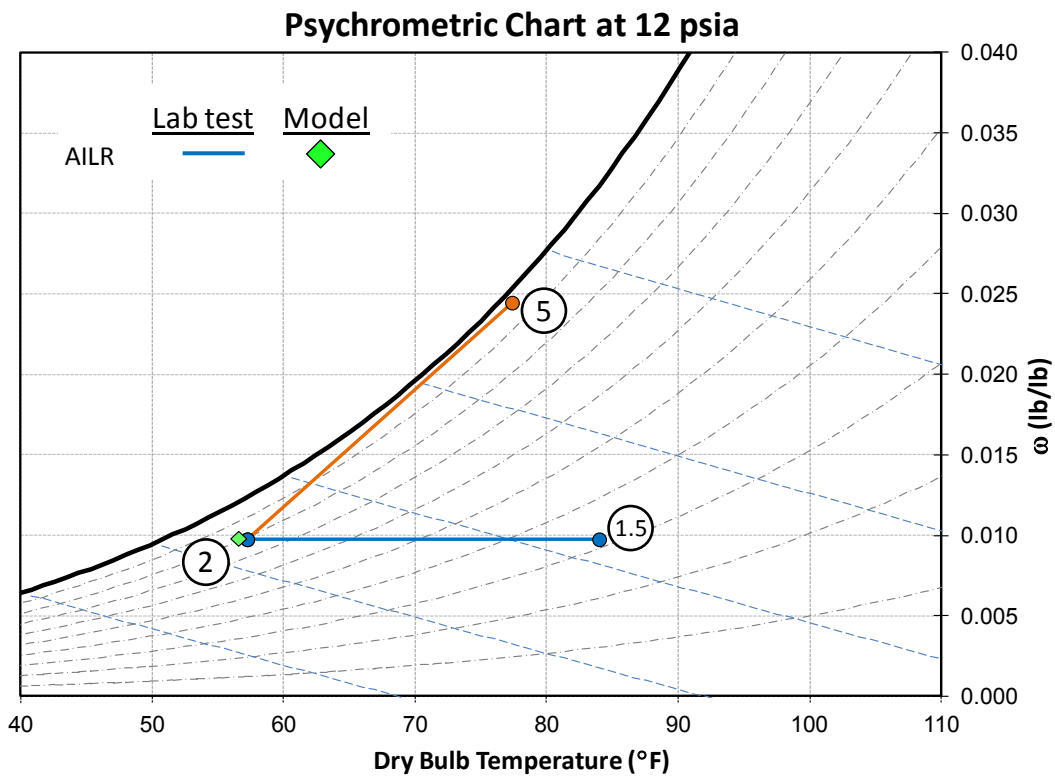


Figure 3–5 Measured performance of AIL Research second-stage HMX at outlet air conditions from the first-stage and AHRI standard conditions

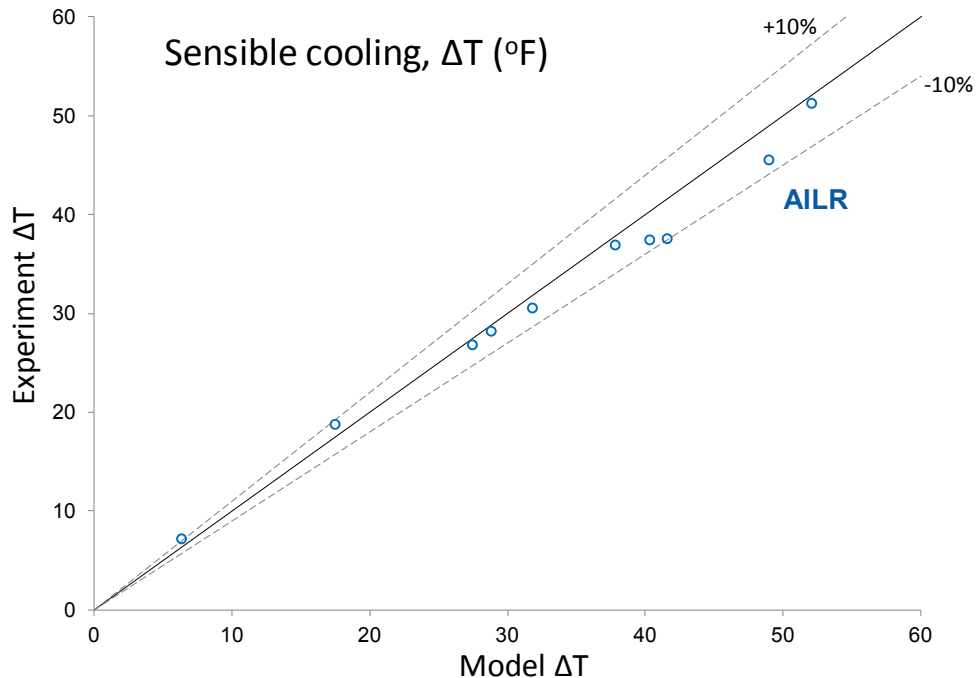


Figure 3-6 Modeled versus experimental measurement of second-stage sensible cooling

3.1.3 First- and Second-Stage HMX Performance (AIL Research Unit)

Figure 3-7 shows the combined performance of the first- and second-stage AIL HMXs at AHRI standard conditions. The difference between measured and predicted performance is due to issues with the first-stage HMX (see Section 3.1.1).

Figure 3-8 and Figure 3-9 show the performance of the first- and second-stage HMXs operating at mild/humid and hot/dry conditions, respectively. These two conditions illustrate how the DEVAP process can adapt to high sensible/low latent and low sensible/high latent conditions. During mild/humid conditions, sensible load is lower and an AC must operate in dehumidification mode (DH). The DEVAP process does this by lowering the second-stage EA flow rate, which reduces the sensible cooling and results in outlet air at a higher temperature. During hot/dry conditions, the first-stage HMX is not used because the second-stage HMX has a wet bulb effectiveness of approximately 125% and can provide air below 59°F. This temperature is low enough to provide space cooling.

As a comparison, an IEC operating in the hot/dry condition with 100% wet bulb effectiveness would provide SA at approximately 70°F, which is too warm to provide sufficient space cooling. Thus, supplemental cooling equipment is needed. As a consequence, evaporative comfort cooling is generally limited to the following applications:

- Dry climates where the ambient wet bulb temperatures are below 65°F
- Applications where backup cooling is available
- Ventilation precooling

Although not designed and optimized to be a dedicated OA system, the DEVAP prototype can supply space cooling at these conditions (Figure 3–10). Again, desiccant distribution issues kept the conditioner from achieving the predicted SA condition. Solving these issues would result in 58°F supply conditions. Creating a higher effective first-stage unit by adding heat exchange area would result in a dedicated outdoor air system that supplies dryer and colder air. This could also reduce the required desiccant concentration, which would improve efficiency.

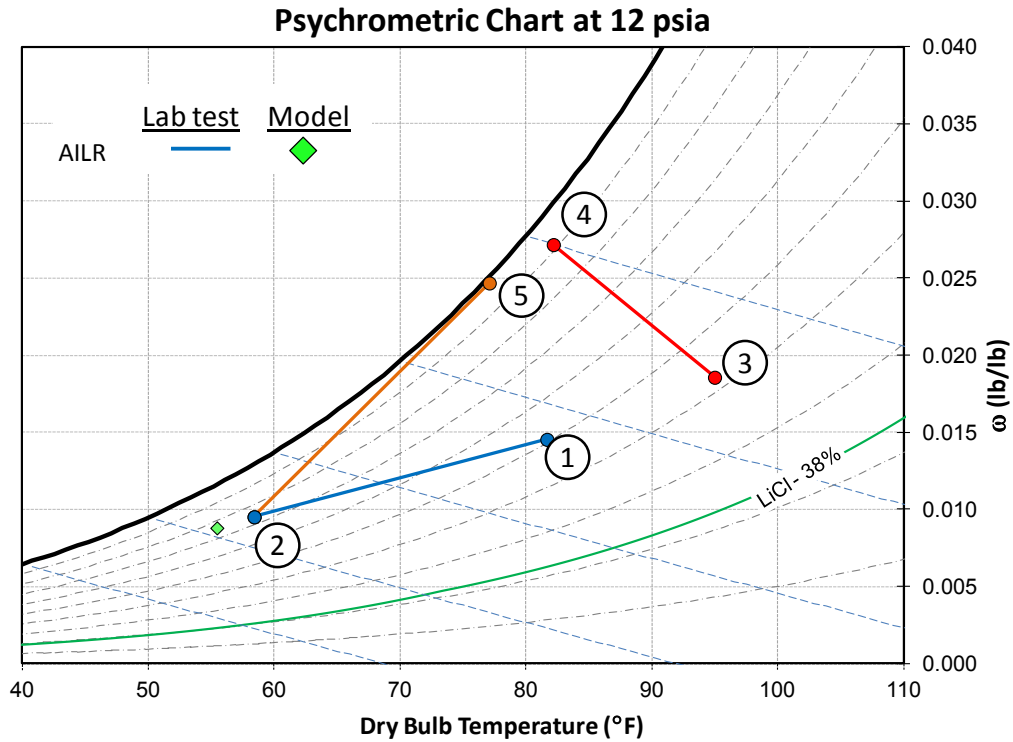


Figure 3–7 Measured performance of AIL Research first- and second-stage HMXs at AHRI standard conditions

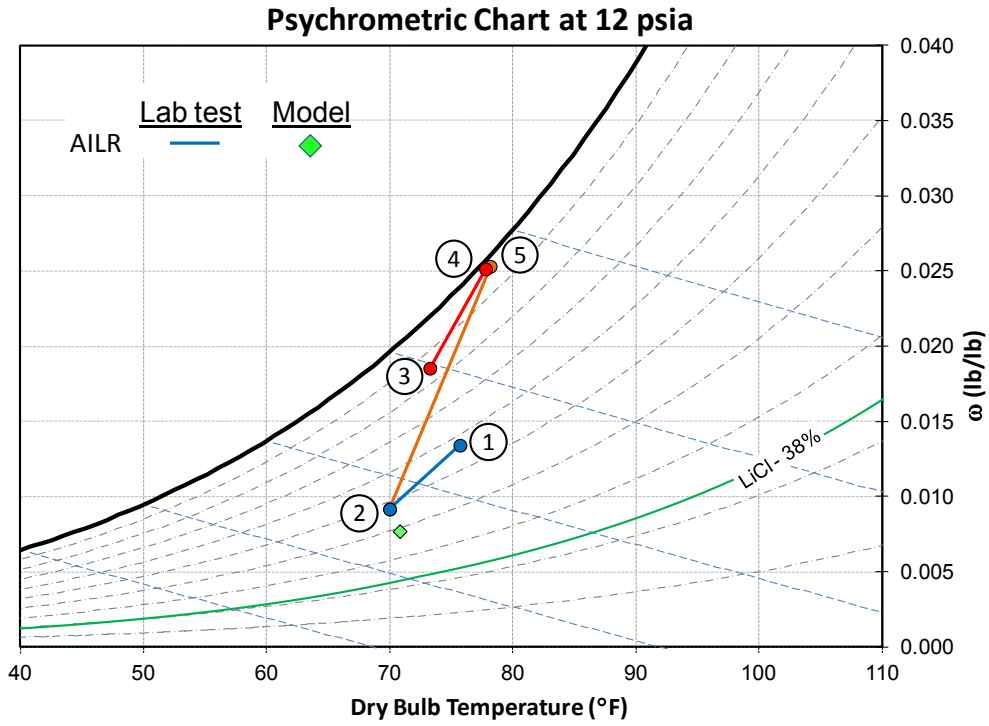


Figure 3–8 Measured performance of AIL Research first- and second-stage HMXs at a mild/humid condition

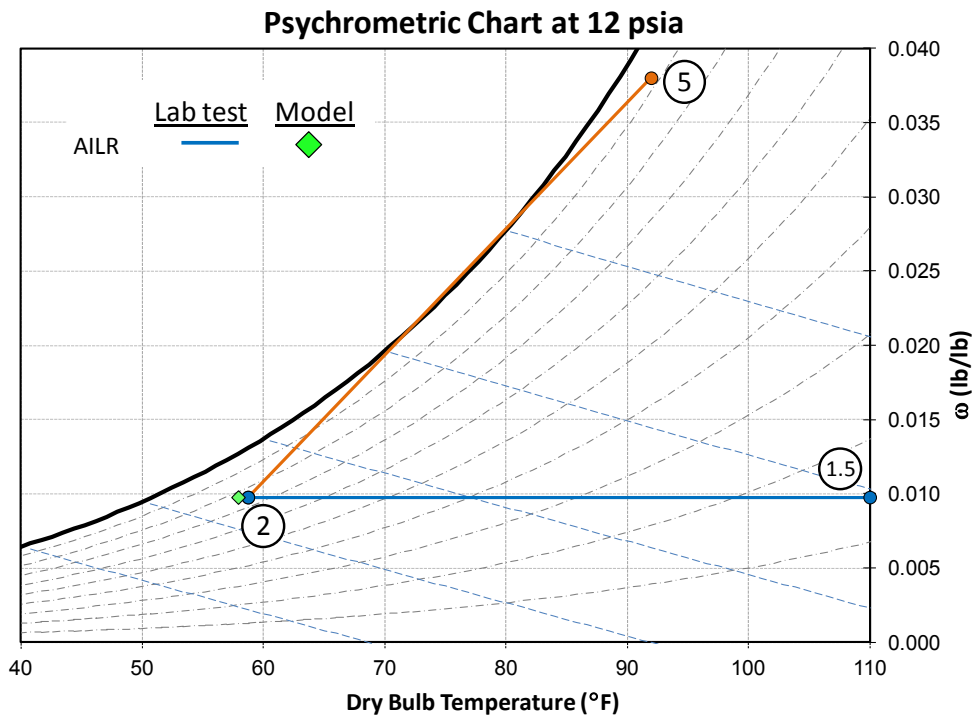


Figure 3–9 Measured performance of AIL Research second-stage HMX at a hot/dry condition

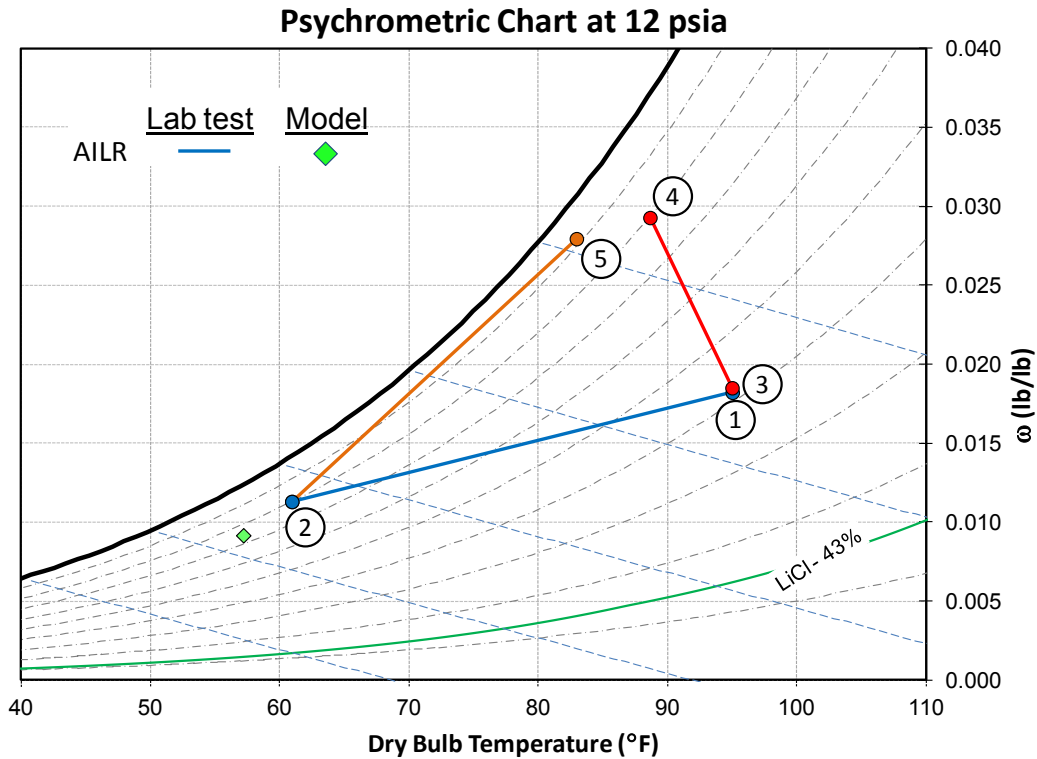


Figure 3–10 Measured performance of AIL Research first- and second-stage HMXs at AHRI condition and 100% OA

3.1.4 Energy Performance

The DEVAP AC energy performance was calculated with the numerical model in Kozubal et al. (2011). We compared this model with the calculated energy use of the two conditioner prototypes for each test we performed. This calculation considers the electric pump and fan energy and the thermal energy required by the regenerator. Assuming 50% efficient fans, we calculated the fan energy used with the measured airflow rate and pressure drop (Figure 3–11). We used the measured dehumidification and airflow rates to compute the required regeneration energy (Figure 3–12), with the regenerator efficiency modeled as described in Section 3.0. Figure 3–12 shows only the DH and standard mode (DH + IEC) of operation when desiccant is flowing and thus thermal energy is required. IEC mode does not require desiccant, and therefore does not require thermal energy. Figure 3–13 shows the source energy efficiency of cooling from S1 to S2 conditions (COP_{unit}). Experimental data use measured pressure drop with a 50% efficient fan, and a two-stage regenerator model to calculate COP_{unit} . The calculation uses site to source energy conversion factors of 1.1 for natural gas and 3.4 for electricity (Deru and Torcellini 2007). The DH + IEC test points are for standard mode, which are shown more closely in Figure 3–14. Explanations of cooling modes and source energy conversion are included in Kozubal et al. (2011). The COP_{unit} of the system improves when dehumidification is turned off (IEC mode). Building energy simulation is required to predict the year-round efficiency of the DEVAP AC, because the system will run in different modes throughout the year. The cooling load and time in each mode are also climate dependent. For example, in drier climates a unit will spend more time in IEC mode.

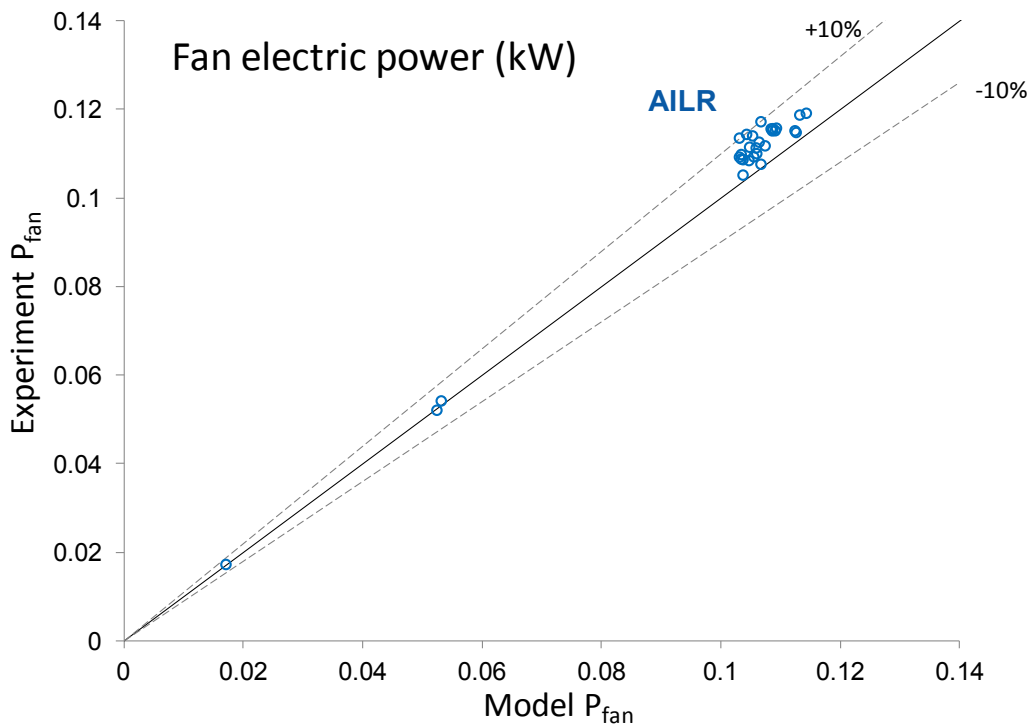


Figure 3–11 Modeled versus experimental measurement of fan power using pressure drop data and a 50% efficient fan

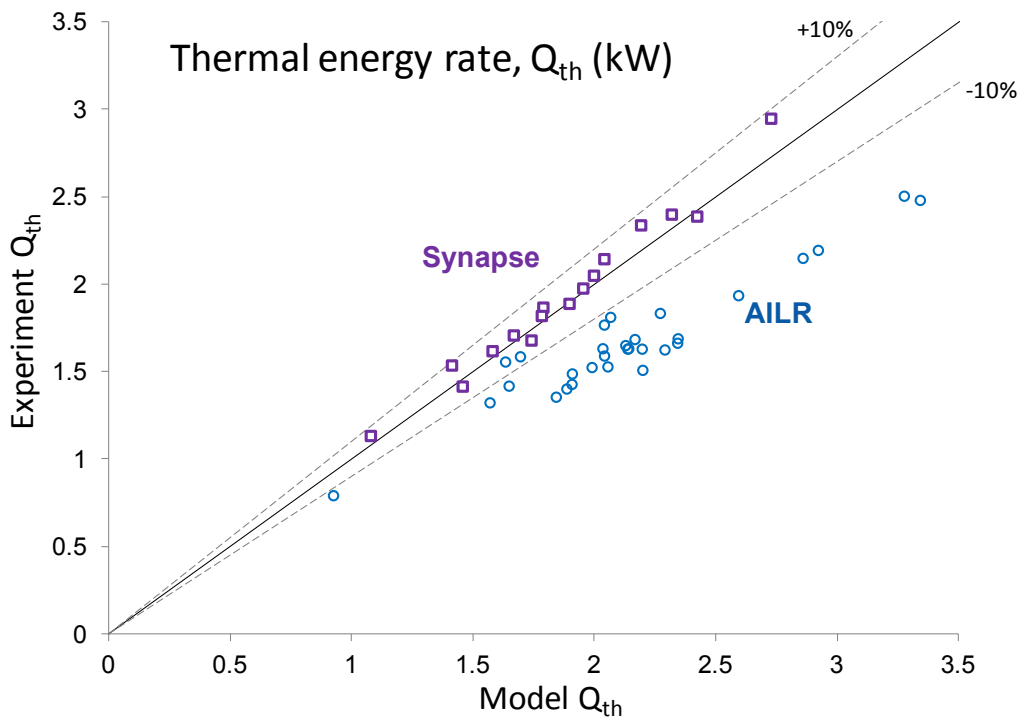


Figure 3–12 Modeled versus experimental measurement of thermal energy rate (Q_{th}) using the two-stage regeneration efficiency model

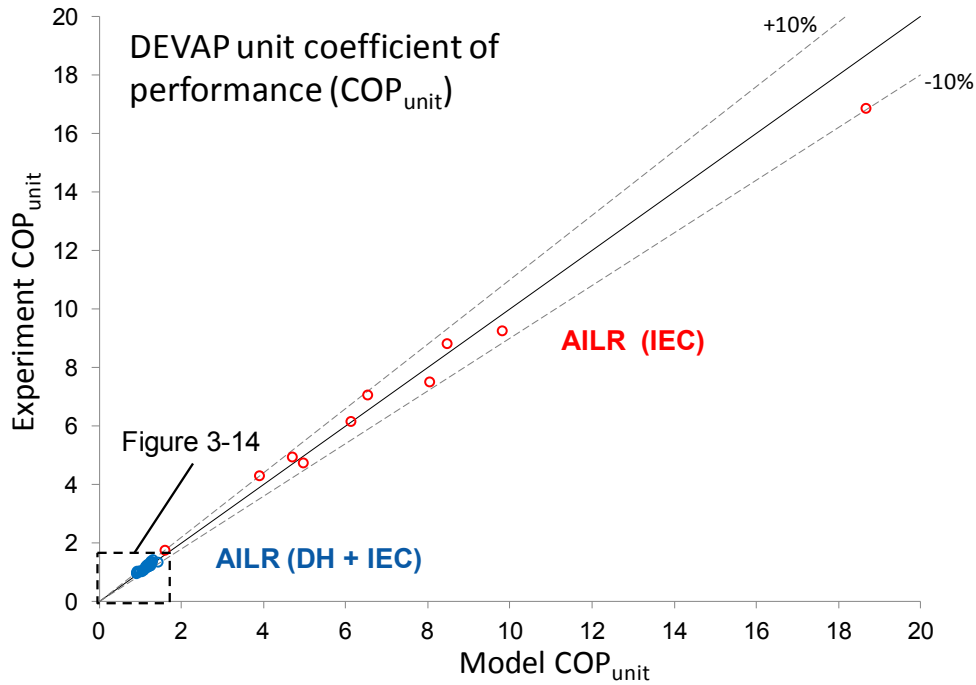


Figure 3-13 Modeled versus experimental measurement of source COP_{unit} .

DH + IEC mode is used when both latent and sensible cooling are required. These points are shown more clearly in Figure 3-14.

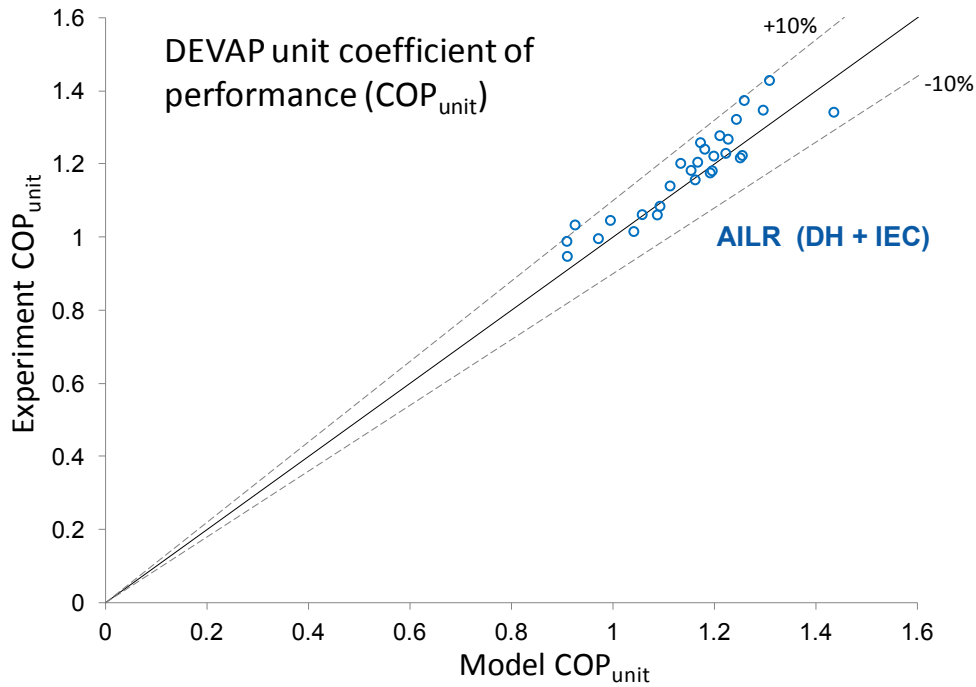


Figure 3-14 Modeled versus experimental measurement of source COP_{unit} for the standard mode of operation (when dehumidification is required).

The source efficiency of the AIL Research first-stage HMX met predicted performance because the lower latent cooling (combined with the lower thermal energy rate) results in the same efficiency. Therefore, the first-stage performance affects only the size and first cost of this component.

3.1.5 Water Use Performance

Figure 3–15 shows the predicted versus measured water use by the AIL Research dehumidifier + IEC HMXs. Measured water use is within 10% of the predicted values.

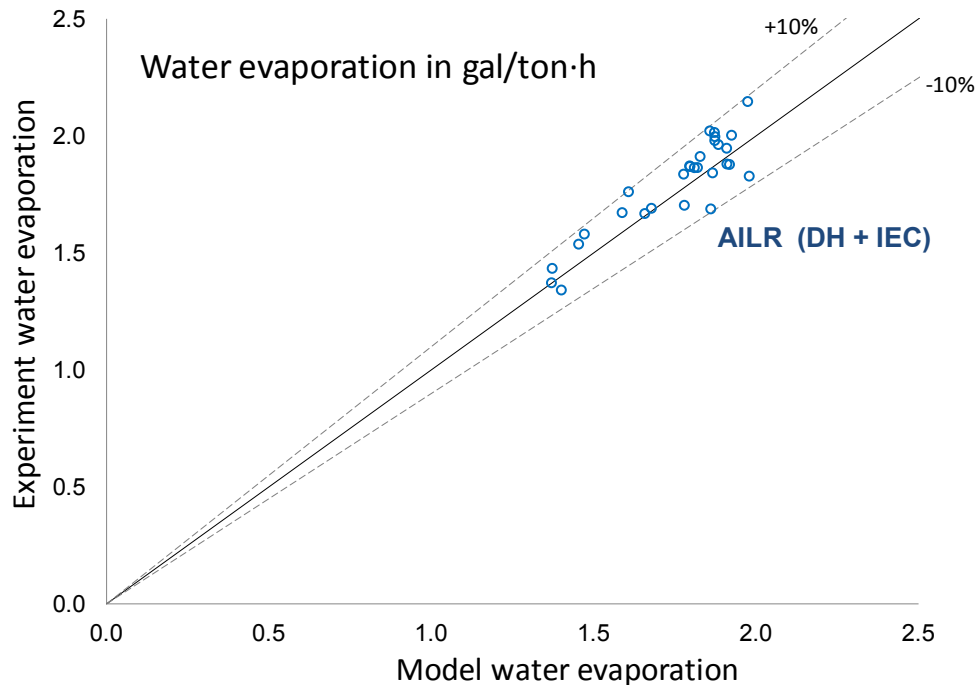


Figure 3–15 Modeled versus experimental measurement of specific water evaporation

3.2 Water Use Strategy Improvements for DEVAP

The second stage of the DEVAP AC is a staged, counterflow IEC. The airflow is staged because airstream 2-5 uses air that passes first through 1.5-2. This ensures an approach to the dew point temperature and is water efficient. The water efficiency approaches the theoretical limit of about 1.36 gal/ton·h of sensible cooling. Figure 3–16 and Figure 3–17 show the measured evaporation rate through the AIL Research second-stage HMX. In contrast, when the first-stage dehumidifier is running without desiccant flow, it operates much like standard cross-flow evaporative coolers. These units inherently use more water, primarily because OA is used for the evaporative cooling sink (airstream S3). As the outdoor wet bulb temperature rises and approaches the entering product airstream (S1) temperature, the water use approaches infinity (gallons evaporated per ton-hour of cooling goes to infinity). Measurements of the DEVAP dehumidifier stage in this configuration showed water use of 2.58–3.81 gal/ ton·h with outdoor conditions at 86°F, a wet bulb temperature of 61°F, and indoor air at 86°F.

The water use was not optimized in the analysis presented by Kozubal et al. (2011). The first-stage HMX was used as an IEC during hot and dry periods. The total yearly water use can be significantly reduced by turning the water off in the first-stage HMX when ambient dew point is lower than 50°F, when the second stage can deliver air at lower than 59°F. Table 3–2 compares the yearly specific water use from Kozubal et al. (2011) (Case 1) to this new strategy (Case 2). The new strategy saves 7% and 30% of the original water use prediction in Houston and Phoenix, respectively.

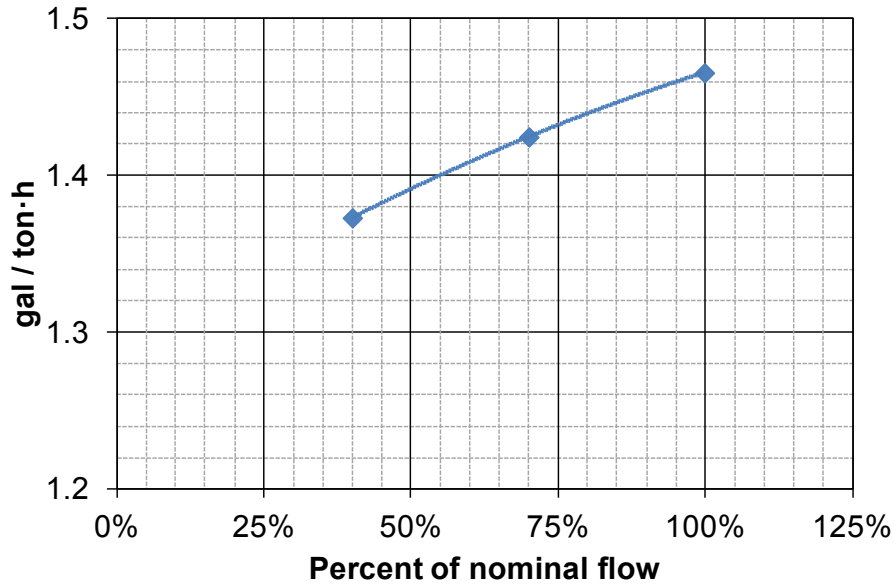


Figure 3–16 Measured water evaporation of the AIL Research second-stage IEC versus airflow

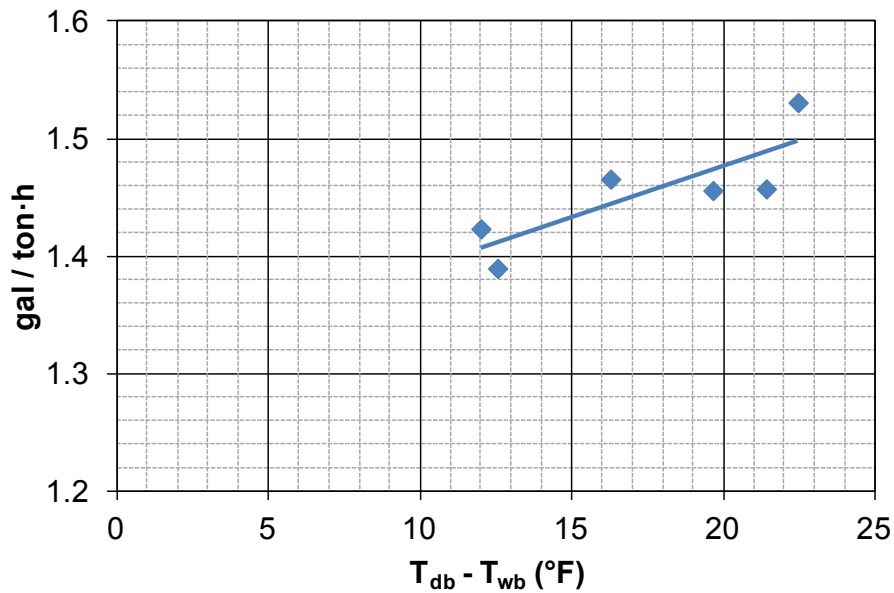


Figure 3–17 Water evaporation of AIL Research second-stage IEC versus wet bulb depression

Table 3–2 Table of yearly total site water evaporation comparing operation with (Case 1) and without (Case 2) the first-stage HMX running below ambient dew point of 50°F

| | Case 1 (gal/ton·h) | Case 2 (gal/ton·h) | Percent Difference |
|------------------|-----------------------|-----------------------|-----------------------|
| Phoenix, Arizona | 2.69 | 1.89 | –30% |
| Houston, Texas | 2.08 | 1.93 | –7% |

3.3 Performance Metric for Technology Comparison

In an attempt to present a reasonable metric for comparison of the DEVAP AC to other cooling technologies, we tested the AIL Research DEVAP prototype per the AHRI standard 340/360 rating procedure (AHRI 2007). We used the methods in this standard to measure an effective integrated energy efficiency ratio (IEER_{effective}) for the DEVAP prototypes because no industry standard rating condition compares vapor compression-based ACs against other technologies. We do not intend this measurement to be a rating of the DEVAP AC, because the IEER method is intended for rating only electrically driven, vapor compression-based ACs. The standard states:

2.1.1 Energy Source. This standard applies only to electrically operated, vapor compression refrigeration systems.

The standard is also not intended to be a measure of actual energy use. The standard states:

6.2.1 General. The IEER is intended to be a measure of merit for the part load performance of the unit. Each building may have different part load performance due to local occupancy schedules, building construction, building location and ventilation requirements. For specific building energy analysis an hour-by-hour analysis program should be used.

We adhered to the standard in all cases for test conditions, except one area. The standard limits the OA flow rate for systems to a maximum of 20% of total SA flow. The DEVAP AC requires 30% OA to obtain its maximum rated capacity. To properly compare it to rated equipment, we calculated its capacity based on a mixed air condition of 30% OA and 70% RA, which results in a lower IEER_{effective} than if 20% OA were used in the calculation. Table 3–3 shows the OA conditions and nominal percent of capacity for each test point. The test conditions are shown in Figure 3–18 on a psychrometric chart. For each test point, the energy efficiency ratio (EER) is calculated with equation 3-1 (the factor 3.4 is used to convert source energy to site electric energy). The table shows two columns where EER is calculated using 50% and 60% fan efficiency.

$$EER = \frac{3.4 \times Capacity}{Source\ Energy\ Use} \quad (3-1)$$

Table 3–3 Table of EER Values Used To Calculate IEER_{effective} per AHRI Standard 340/360*

| | Capacity | T _{OA} (°F) | T _{wb, OA} (°F) | EER – 50% (Btu/Wh) | EER – 60% (Btu/Wh) |
|---------------|----------|-------------------------|-----------------------------|-----------------------|-----------------------|
| Test 1 | 100% | 95.0 | 75.0 | 15.3 | 15.8 |
| Test 2 | 66% | 81.5 | 65.7 | 18.2 | 19.3 |
| Test 3 | 46% | 68.0 | 57.0 | 21.5 | 23.3 |
| Test 4 | 23% | 65.0 | 52.9 | 42.7 | 51.3 |

* Two sets of EERs are calculated using fan efficiency of 50% and 60% respectively.

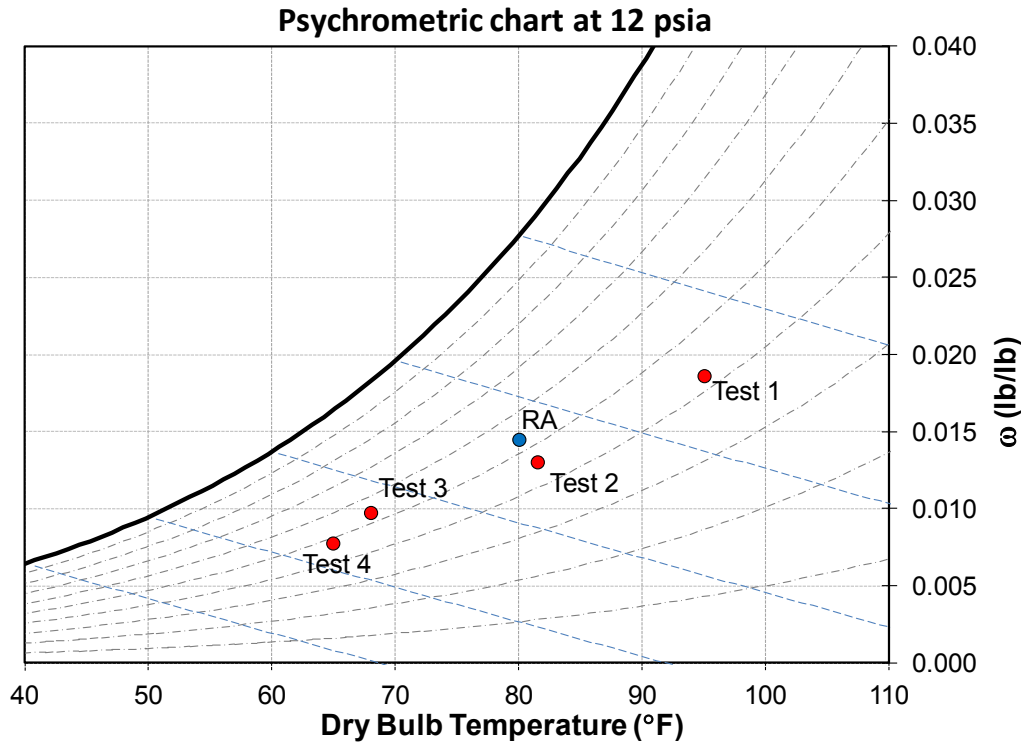


Figure 3–18 Four test conditions and RA condition for measuring IEER_{effective}

The IEER_{effective} calculation is taken directly from the standard. The method translates the test data to capacity steps at intervals of 25% of nominal capacity. The use of a constant RA condition at a wet bulb temperature of 67°F is appropriate for rating electrically driven, vapor compression-based ACs. However, this condition does not fully capture the energy savings for the DEVAP AC process. The DEVAP process would normally maintain a lower indoor humidity, which would allow for a higher degree of evaporative cooling operation and a lower degree of dehumidification. As a result, the IEER_{effective} would increase. Using IEER_{effective} to compare DEVAP against vapor compression cooling technologies is imperfect. We identify annual hourly building energy simulations as the best comparison technique.

Table 3–4 shows the EER at these capacity points. Each step is weighted and the sum is the IEER_{effective} value. Again, two values for IEER_{effective} are calculated using 50% and 60% fan efficiency.

Table 3–4 Capacity Step Values Used To Calculate IEER_{effective} per AHRI Standard 340/360*

| | Capacity | EER – 50% | EER – 60% |
|---------------------------------|-----------------|------------------|------------------|
| Step 1 | 100% | 15.3 | 15.8 |
| Step 2 | 75% | 17.4 | 18.4 |
| Step 3 | 50% | 20.9 | 21.7 |
| Step 4 | 25% | 40.8 | 48.8 |
| IEER_{effective} | | 21.1 | 23.2 |

* Two values for IEER_{effective} are calculated using fan efficiency of 50% and 60%, respectively.

4.0 Second-Generation DEVAP Design Description

After testing and validating the DEVAP AC numerical model, we had a third design review with AIL Research and Synapse to determine which aspects of each design worked well. We then developed a Gen-2 design concept for the first- and second-stages. Size and material use are reduced because channels are smaller and heat and mass transfer is enhanced.

For the Gen-2 first-stage design, we incorporated the following aspects from each prototype:

- Laminated layers of membrane, plastic, and nylon wicking fabric to create a simple roll-to-roll approach for attaching membranes
- Desiccant distributor method from the Synapse design (which distributes desiccant evenly across each plate)
- Coroplast frame and spacers with modifications to allow wicking material to be placed on the EA side
- Airside turbulators for airstream 1-1.5 heat and mass transfer enhancement from the AIL Research design.
- Desiccant manifold design from the AIL Research design (which manifolds the desiccant from plate to plate).

For the Gen-2 second-stage design, we removed the extruded flute construction method from the AIL Research design and replaced it with a formed aluminum in a similar airflow arrangement. Aluminum allows heat transfer enhancements to be placed into the air channels, which substantially reduces size.

Numerical modeling of the Gen-2 first- and second-stage concepts shows a reduction in size and weight of nearly 50% with no anticipated change in COP_{space} . Using methods shown in Section 2.0, Figure 4–1 shows how removing the Gen-1 limitations and incorporating the best ideas from each prototype enable us to better optimize the Gen-2 design and improve the COP_{space} versus heat transfer area. This figure also shows how these points compare to the sensitivity analysis in Figure 2–3. The higher heat and mass transfer performance of the Gen-2 design make it much smaller than the two prototypes. It also maintains efficiency by using open channels instead of the flutes in the first-stage EA channel, reducing fan energy use. Replacing the AIL Research fluted channels in the second stage with high conductivity aluminum surfaces improves heat transfer and reduces pressure drop.

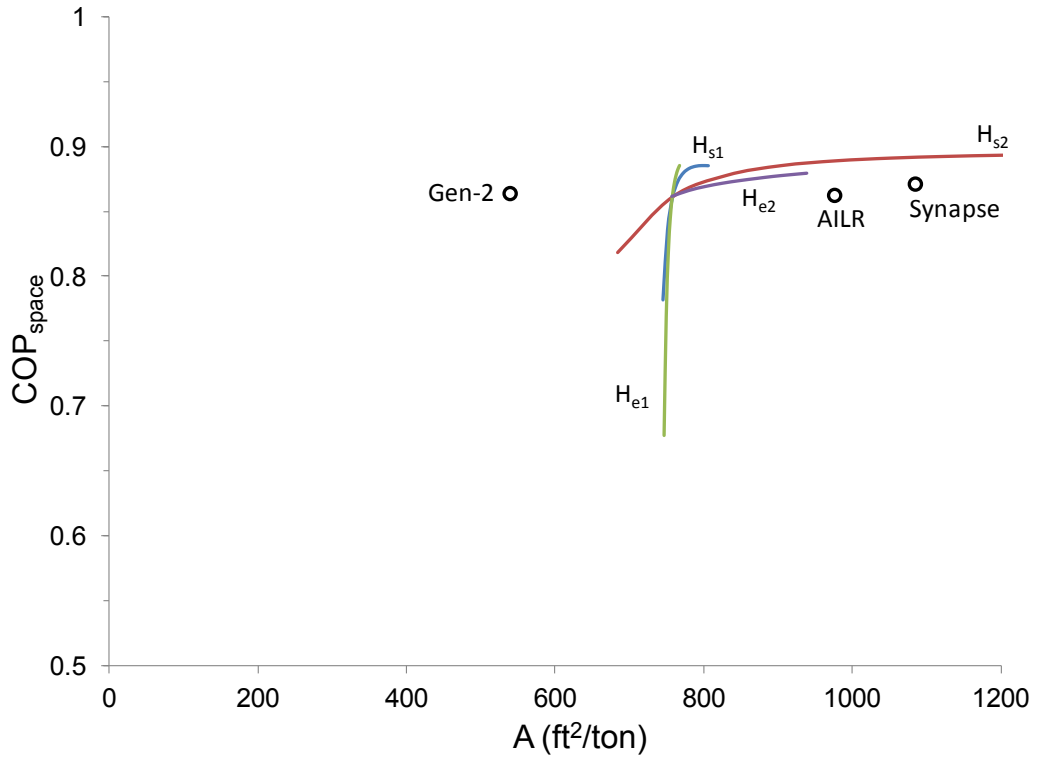


Figure 4–1 COP_{space} and area per space cooling ton of the two prototype designs and the modeled Gen-2 design, along with the effect of channel thicknesses, as shown in Figure 2–3

5.0 Cost, Size, and Weight Estimates

At this point, we shift from discussing performance based on the peak design condition to performance at an AHRI standard condition (test 1 from the $IEER_{\text{effective}}$ rating [Table 3–3]) and compare the DEVAP AC against a vapor compression AC. This is used to estimate the per-ton volume and weight of the HMXs of the AIL Research, Synapse, and Gen-2 designs. We then use the current AIL Research design and the Gen-2 design to calculate the dimensions, weight, and cost of a full 10-ton AC. DEVAP size, weight, and cost are conservatively estimated using this metric, because evaporative technologies inherently increase capacity when installed in locations where peak load is hotter than the AHRI standard conditions. In contrast, vapor compression AC capacity will decrease as the ambient temperature increases. The Synapse manufacturing method was sufficient for the prototype phase, but was not viable for a commercial-scale prototype and is therefore not included in the cost analysis.

The volume required for the HMXs, per ton, for each design are shown in Figure 5–1. The reduced size of the Gen-2 design is due to the changes outlined in Section 4.0. This translates to significant weight reduction, as shown in Figure 5–2.

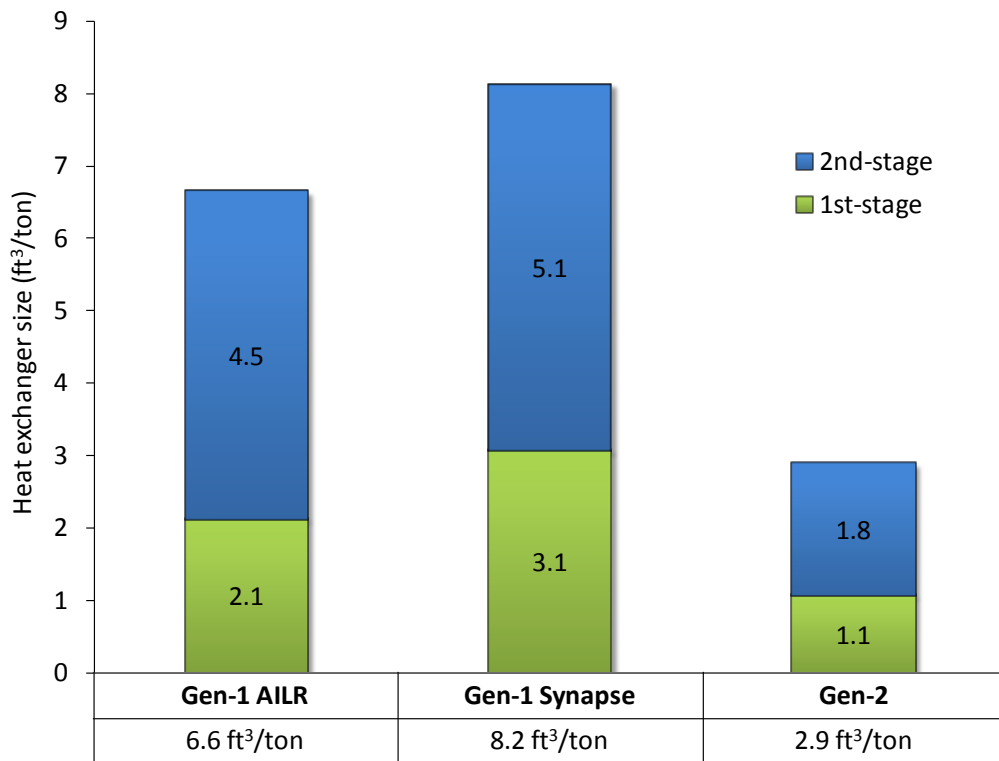


Figure 5–1 Volumetric comparison between the AIL Research and Synapse prototype HMXs and the Gen-2 HMX design

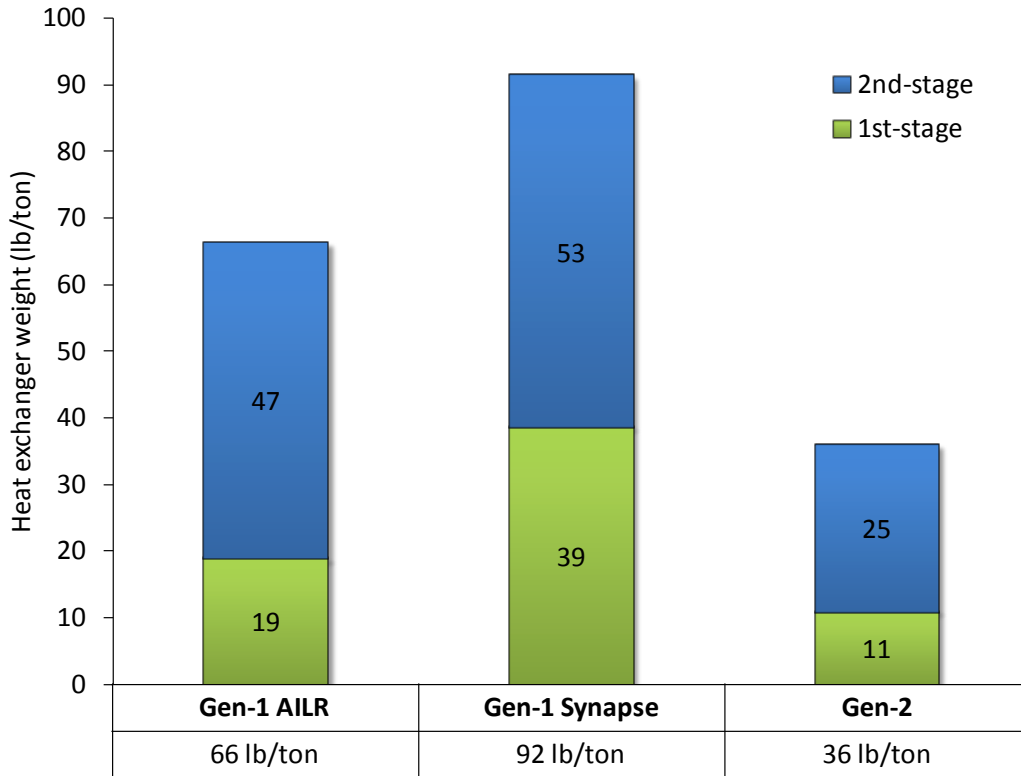


Figure 5–2 Dry weight comparison between the AIL Research and Synapse prototype HMXs and the Gen-2 HMX design

We also calculated weight and cost for a complete, packaged DEVAP AC. These estimates are based on a preliminary packaged design built around the HMXs. Figure 5–3 shows a packaged DEVAP AC based on the size of the Gen-2 HMXs. The optimal packaged arrangement was not explored and the DEVAP package size is based on a first-order attempt to assemble the components. The main components are the first-stage HMX, second-stage HMX, EA fans, airstream S1-2 plenum fan, LD tank, and scavenging and boiler stages of the regenerator. Figure 5–4 (isometric view) and Figure 5–5 (top view) show how these main components fit into the packaged unit. In this arrangement, the HMX cores account for 13% of the total packaged volume. This indicates significant wasted volume in the proposed packaging and that further size, cost, and weight improvements can be made. A similar package of the Gen 1 AIL Research design would be slightly larger because of the larger HMXs.

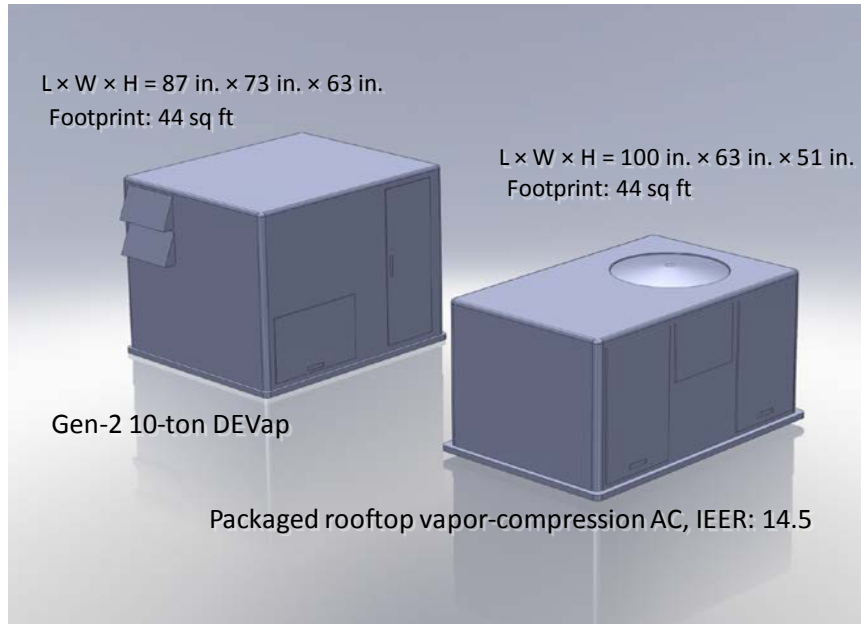


Figure 5–3 Gen-2 packaged AC compared to a packaged vapor compression AC with an IEER rating of 14.5
(Illustration by Jason Woods, NREL)

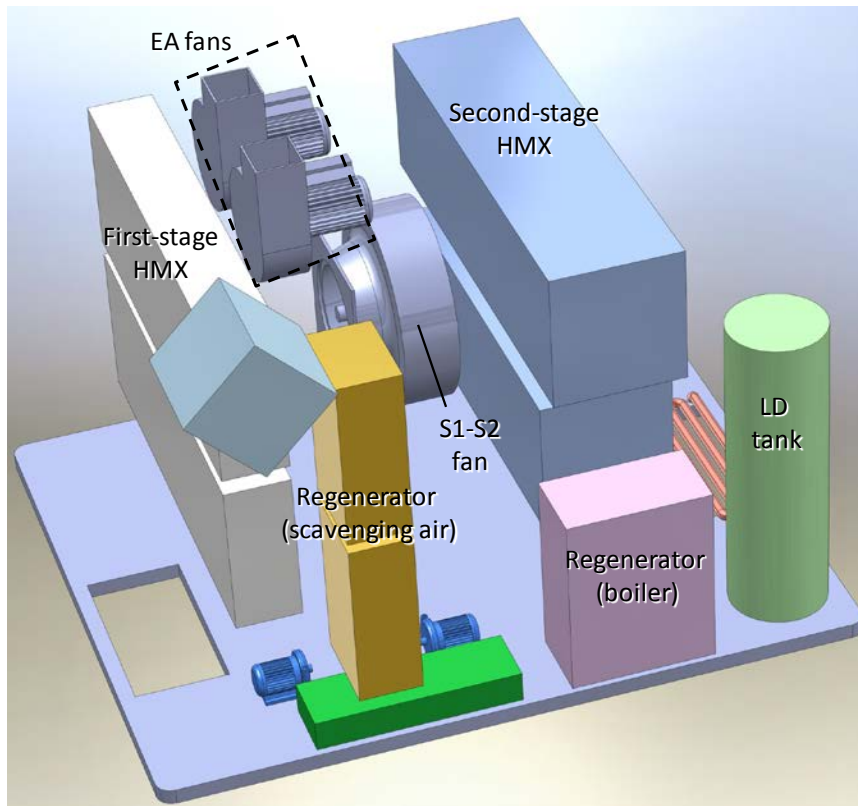


Figure 5–4 Components in the Gen-2 packaged AC, isometric view
(Illustration by Jason Woods, NREL)

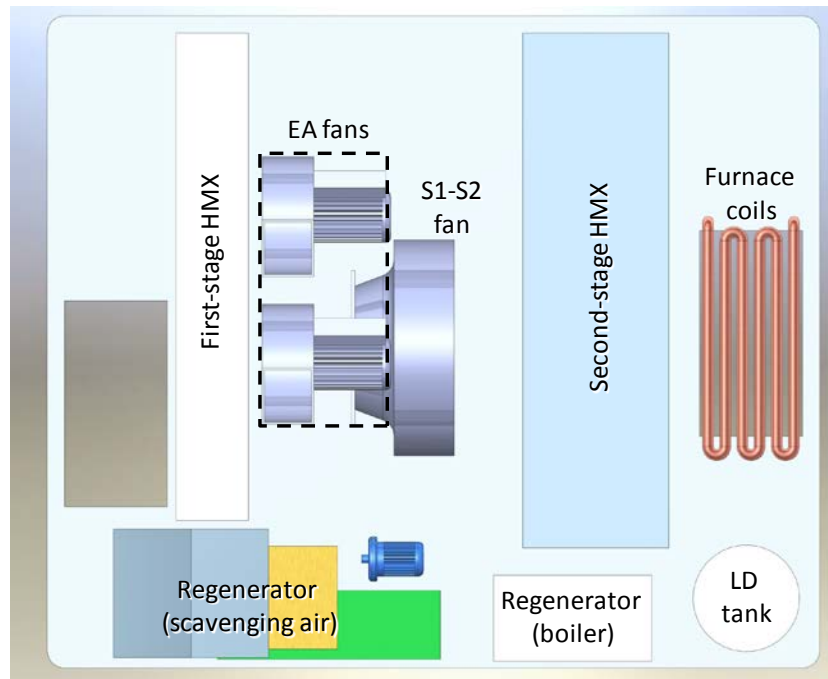


Figure 5–5 Components in the Gen-2 packaged AC, top view
(Illustration by Jason Woods, NREL)

Based on this packaged unit, the total weight of the DEVAP AC is compared to the weight of a vapor compression AC with a rated IEER of 14.5 (Figure 5–6). The weight of the DEVAP AC is calculated by summing the weights of the components (e.g., HMXs, regenerator, LD tank, fans). The weights of the HMXs are based on weights of each material used in their construction (e.g., Coroplast, wick, aluminum). The details of these calculations are included in Appendix D.

The estimated total cost of the DEVAP AC is about 25% higher than a typical 14.5 IEER rated AC (Figure 5–7). The DEVAP AC cost is based on estimates of all major components. The costs of the HMXs are based on information from suppliers about each material (e.g., the Celgard membrane); labor costs were estimated by AIL Research. The costs of the major balance-of-system components are from AIL Research quotes. Cost markups common in the AC industry are used to convert from wholesale to retail costs (single unit sale). Appendix E includes the details of these cost calculations.

Based on these cost estimates and the energy savings from Kozubal et al. (2011), we estimate a simple payback of less than two years in Phoenix and less than three years in Houston.

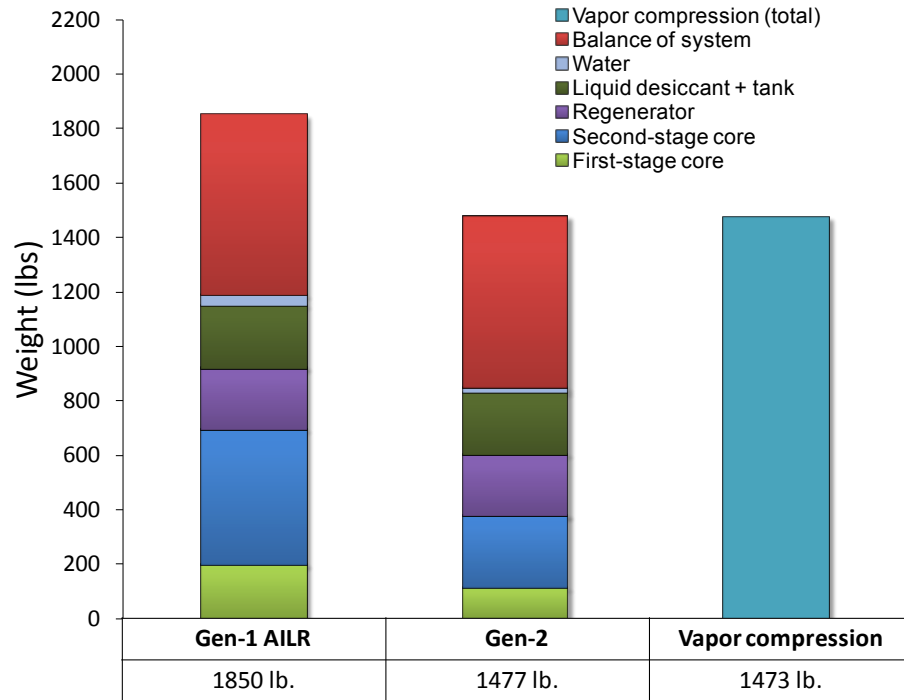


Figure 5–6 Weight of packaged 10-ton DEVAP AC compared to 10-ton packaged vapor compression AC with an IEER rating of 14.5

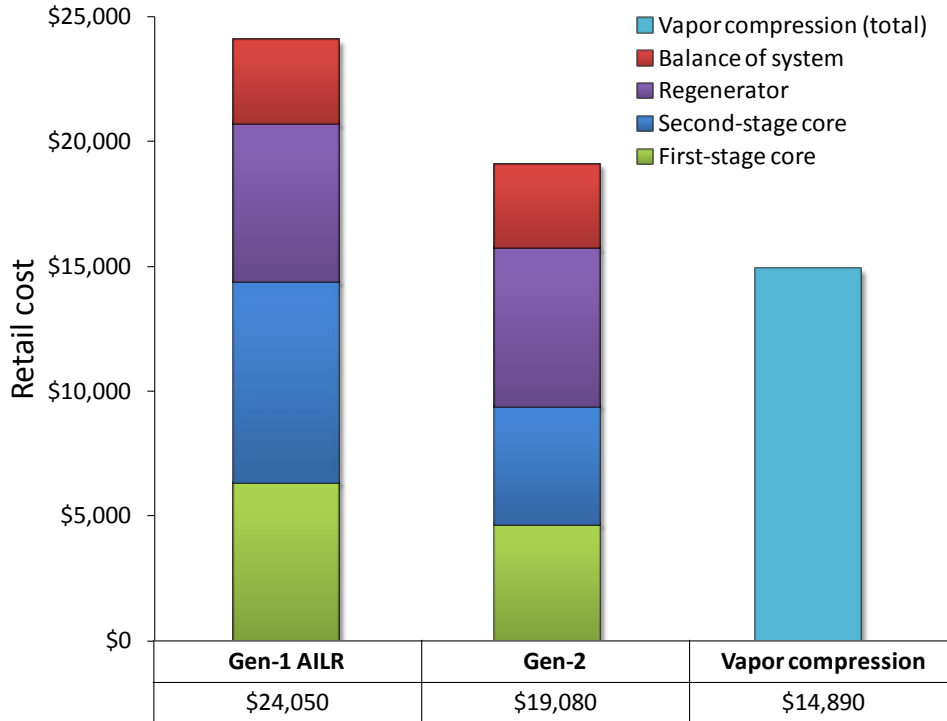


Figure 5–7 Estimated retail cost of packaged 10-ton DEVAP AC compared to 10-ton packaged vapor compression AC with an IEER rating of 14.5

6.0 Summary and Conclusions

In this report we described the development of two DEVAP AC prototypes and their tested performance. The design approach looked at all relevant variables in the design of the DEVAP AC HMXs. The approach focused on proving performance with the use of off-the-shelf components. Testing showed that cooling and energy use performance agree within 10% of predicted values for the Synapse first-stage and the AIL Research second-stage HMXs. The AIL Research first-stage HMX had latent cooling capacity about 22% less than predicted. Diagnosis revealed nonuniform desiccant distribution from plate to plate. Also, the lack of wicked surfaces in the Coroplast flutes in airstream 3-4 degraded the heat transfer. Despite the capacity issue, efficiency of the AIL Research first-stage HMX was still within 10% of predicted values. The Synapse second-stage HMX was not tested because manufacturing issues prevented the HMX from operating as designed. We also tested the AIL Research prototype at the conditions for rating IEER to compare the DEVAP AC to other technologies. An effective IEER was calculated to be 21.1 or 23.2 while using a 50% or 60% efficient fan respectively.

Testing of the two prototypes validates the numerical design approach and gives confidence in using the numerical model for:

- Energy estimation from building energy simulations (shown in the previous report)
- Use in a model-based design method to create a Gen-2 system.

We explored a Gen-2 DEVAP AC design with help from our vendors, and a design emerged that removed the constraints imposed on the Gen-1 design and included the aspects of each prototype that worked well. We then estimated the size, weight, and cost of a packaged DEVAP AC unit based on the Gen-1 and Gen-2 designs and compared them to those of a packaged vapor compression system with an IEER rating of 14.5. Using the Gen-2 design for comparison, the estimated DEVAP AC footprint and weight are about the same as a typical vapor compression AC; the cost is about 28% higher.

7.0 References

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Appendix A Schematics

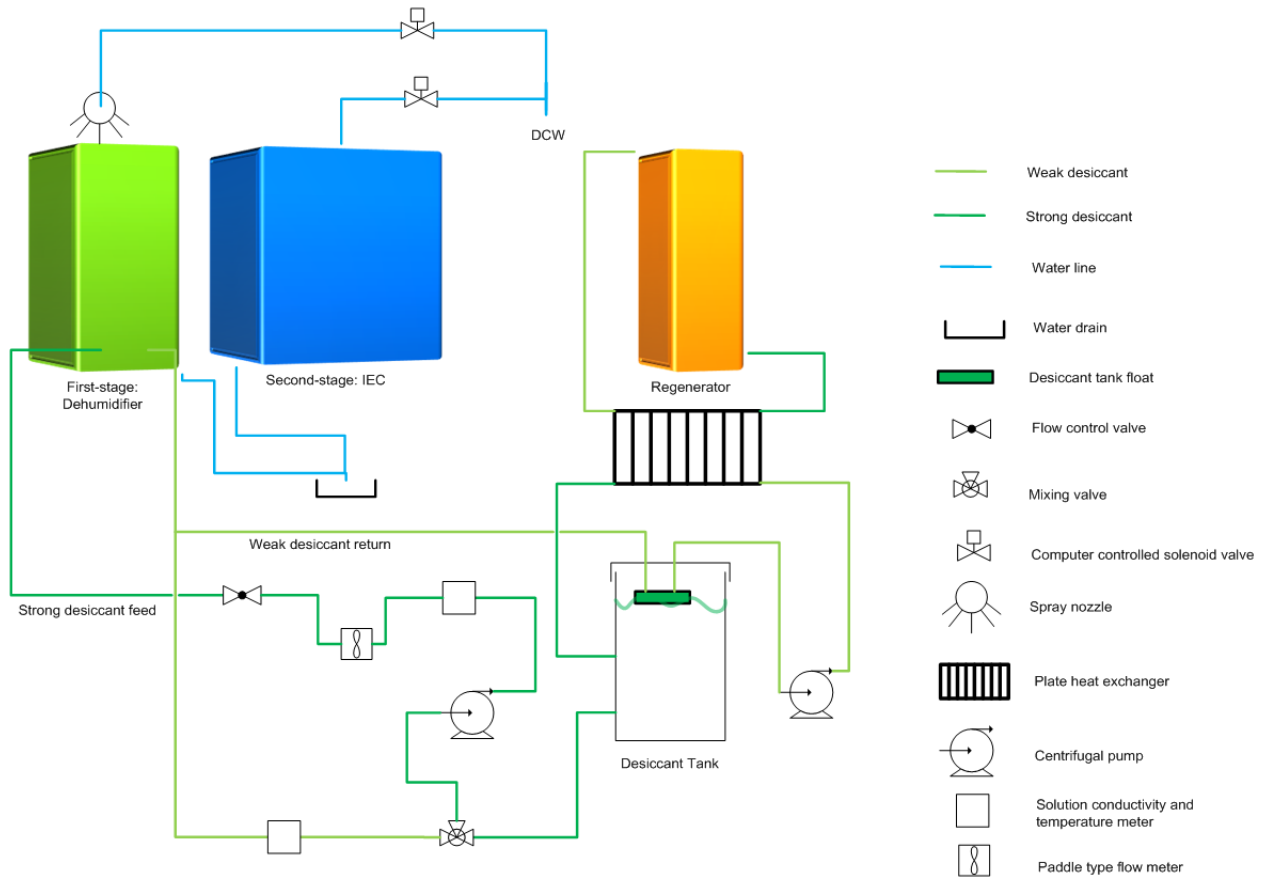


Figure A-1 Test schematic showing liquid flows and measurements

Illustration by Eric Kozubal, NREL

Appendix B Measured and Modeled Data for All AIL Research and Synapse Tests

The following pages show experimental and modeled data. They are presented in six tables, with each table in both IP and SI units. Symbols are defined in the Nomenclature section. The tables are in the following order:

| | |
|------------|---|
| Table B-1 | AIL Research Prototype – Measured and Model Input Data (IP units) |
| Table B-2 | AIL Research Prototype – Measured and Model Input Data (SI units) |
| Table B-3 | AIL Research Prototype – Measured Output Data (IP units) |
| Table B-4 | AIL Research Prototype – Measured Output Data (SI units) |
| Table B-5 | AIL Research Prototype – Modeled Output Data (IP units) |
| Table B-6 | AIL Research Prototype – Modeled Output Data (SI units) |
| Table B-7 | Synapse Prototype – Measured and Model Input Data (IP units) |
| Table B-8 | Synapse Prototype – Measured and Model Input Data (SI units) |
| Table B-9 | Synapse Prototype – Measured Output Data (IP units) |
| Table B-10 | Synapse Prototype – Measured Output Data (SI units) |
| Table B-11 | Synapse Prototype – Modeled Output Data (IP units) |
| Table B-12 | Synapse Prototype – Modeled Output Data (SI units) |

**Table B-1 AIL Research Prototype – Measured and Model Input Data
(IP units)**

| AILR - IP units | | | | | | | | | | | | | | |
|---------------------------------|-------|--------------|--------------|-------------|---------|-------|-------|-------|------|--------|--------|--------|---------------|---------------|
| Input data (measured & modeled) | | | | | | | | | | | | | | |
| Test number | P_amb | Air Flow S12 | Air Flow S34 | Airflow S25 | LD Flow | C_LD | T_LD | T S1 | T S3 | Tdp S1 | w_s1 | Tdp S3 | S1 Water Duty | S2 Water Duty |
| Full device | psi | SCFM | SCFM | SCFM | GPM | % | °F | °F | °F | °F | lb/lb | °F | % | % |
| 1 | 12.0 | 275.5 | 137.8 | - | 0.22 | 38.0% | 84.3 | 80.0 | 95.0 | 61.7 | 0.0144 | 68.5 | 100% | - |
| 2 | 12.0 | 275.7 | 137.7 | 82.6 | 0.22 | 38.0% | 90.1 | 80.0 | 95.0 | 61.7 | 0.0144 | 68.5 | 100% | 7.7% |
| 3 | 11.9 | 275.5 | 137.7 | 82.6 | 0.22 | 37.9% | 87.5 | 81.7 | 95.0 | 61.7 | 0.0145 | 68.5 | 100% | 11.1% |
| 4 | 11.9 | 275.2 | 137.7 | 82.7 | 0.22 | 38.1% | 87.6 | 81.7 | 95.0 | 61.7 | 0.0145 | 68.5 | 100% | 11.1% |
| 5 | 11.9 | 275.7 | 137.7 | 82.6 | 0.22 | 35.1% | 85.9 | 81.7 | 95.0 | 61.7 | 0.0145 | 68.5 | 100% | 11.1% |
| 6 | 11.9 | 275.5 | 137.7 | 27.5 | 0.22 | 38.3% | 89.1 | 77.9 | 95.0 | 59.4 | 0.0133 | 68.5 | 100% | 11.1% |
| 7 | 12.0 | 275.3 | 137.7 | 55.1 | 0.22 | 38.2% | 87.9 | 79.8 | 95.0 | 60.6 | 0.0139 | 68.5 | 100% | 11.1% |
| 8 | 12.1 | 275.3 | 137.6 | 82.5 | 0.13 | 43.8% | 88.0 | 81.7 | 95.0 | 61.7 | 0.0143 | 68.5 | 0% | 14.3% |
| 9 | 12.1 | 275.6 | 137.7 | 82.6 | 0.13 | 43.4% | 94.5 | 81.7 | 95.0 | 61.7 | 0.0143 | 68.5 | 100% | 14.3% |
| 10 | 12.1 | 277.5 | 137.7 | 82.5 | 0.16 | 43.5% | 103.2 | 95.0 | 95.0 | 68.5 | 0.0182 | 68.5 | 100% | 14.3% |
| 11 | 12.1 | 275.6 | 137.7 | 55.1 | 0.16 | 43.9% | 104.5 | 95.0 | 95.0 | 68.5 | 0.0181 | 68.5 | 100% | 14.3% |
| 12 | 12.1 | 275.5 | 137.7 | 55.0 | 0.16 | 40.3% | 96.5 | 95.0 | 95.0 | 68.5 | 0.0181 | 68.5 | 100% | 14.3% |
| 13 | 12.1 | 276.0 | 137.7 | 82.6 | 0.16 | 40.8% | 97.7 | 95.0 | 95.0 | 68.5 | 0.0181 | 68.5 | 100% | 14.3% |
| 14 | 12.1 | 276.0 | 137.7 | 82.7 | 0.16 | 40.7% | 91.3 | 81.7 | 95.0 | 61.7 | 0.0143 | 68.5 | 100% | 14.3% |
| 15 | 12.1 | 275.3 | 137.7 | 55.1 | 0.22 | 40.6% | 94.3 | 81.7 | 95.0 | 61.7 | 0.0143 | 68.5 | 100% | 14.3% |
| 16 | 12.1 | 275.4 | 137.7 | 55.1 | 0.22 | 41.0% | 93.3 | 79.8 | 95.0 | 60.6 | 0.0139 | 68.5 | 100% | 14.3% |
| 17 | 12.1 | 275.6 | 137.7 | 27.6 | 0.22 | 40.9% | 92.6 | 77.9 | 95.0 | 59.4 | 0.0132 | 68.5 | 100% | 14.3% |
| 18 | 12.0 | 275.5 | 137.8 | 82.6 | 0.22 | 37.9% | 87.4 | 76.3 | 77.0 | 61.7 | 0.0144 | 68.5 | 100% | 11.1% |
| 19 | 12.0 | 275.3 | 137.7 | 55.1 | 0.22 | 37.7% | 87.1 | 76.2 | 77.0 | 60.6 | 0.0139 | 68.5 | 100% | 11.1% |
| 20 | 12.0 | 274.9 | 137.8 | 27.6 | 0.22 | 37.7% | 86.1 | 76.1 | 77.0 | 59.4 | 0.0134 | 68.5 | 100% | 11.1% |
| 21 | 12.0 | 275.4 | 137.7 | 82.6 | 0.22 | 37.9% | 83.8 | 76.3 | 77.0 | 58.5 | 0.0128 | 59.0 | 100% | 11.1% |
| 22 | 11.9 | 275.3 | 137.7 | 55.1 | 0.22 | 37.7% | 83.1 | 76.2 | 77.0 | 58.4 | 0.0128 | 59.0 | 100% | 11.1% |
| 23 | 11.9 | 275.4 | 137.8 | 27.5 | 0.22 | 38.1% | 83.9 | 76.1 | 77.0 | 58.3 | 0.0128 | 59.0 | 100% | 11.1% |
| 24 | 11.9 | 275.8 | 137.7 | 82.6 | 0.22 | 37.9% | 86.1 | 81.7 | 95.0 | 58.5 | 0.0129 | 59.0 | 100% | 11.1% |
| 25 | 11.9 | 276.3 | 137.7 | 55.0 | 0.22 | 38.1% | 85.6 | 79.8 | 95.0 | 58.4 | 0.0128 | 59.0 | 100% | 11.1% |
| 26 | 11.9 | 275.8 | 137.7 | 27.5 | 0.22 | 37.5% | 83.4 | 77.9 | 95.0 | 58.3 | 0.0128 | 59.0 | 100% | 11.1% |
| 27 | 11.9 | 275.4 | 137.7 | 82.6 | 0.22 | 38.0% | 88.5 | 81.7 | 95.0 | 61.7 | 0.0145 | 68.5 | 100% | 11.1% |
| 28 | 11.9 | 193.1 | 96.4 | 57.8 | 0.22 | 38.3% | 87.8 | 81.7 | 95.0 | 61.7 | 0.0145 | 68.5 | 100% | 11.1% |
| 29 | 11.9 | 193.1 | 96.3 | 38.7 | 0.22 | 38.2% | 88.1 | 79.8 | 95.0 | 60.6 | 0.0140 | 68.5 | 100% | 11.1% |
| 30 | 11.9 | 110.4 | 55.1 | 33.0 | 0.22 | 38.1% | 85.3 | 82.8 | 98.6 | 59.6 | 0.0130 | 62.6 | 100% | 11.1% |
| AILR stage 2 | | | | | | | | | | | | | | |
| 1 | 11.7 | 275.5 | - | 82.7 | - | - | - | 95.0 | - | 26.6 | 0.0034 | - | - | 7.7% |
| 2 | 11.7 | 275.5 | - | 55.2 | - | - | - | 95.0 | - | 50.0 | 0.0096 | - | - | 7.7% |
| 3 | 11.7 | 275.4 | - | 27.6 | - | - | - | 95.0 | - | 50.0 | 0.0096 | - | - | 7.7% |
| 4 | 11.8 | 192.8 | - | 57.9 | - | - | - | 95.0 | - | 50.0 | 0.0095 | - | - | 7.7% |
| 5 | 11.8 | 110.2 | - | 33.0 | - | - | - | 95.0 | - | 50.0 | 0.0096 | - | - | 7.7% |
| 6 | 11.8 | 275.5 | - | 82.6 | - | - | - | 95.0 | - | 64.4 | 0.0162 | - | - | 7.7% |
| 7 | 12.0 | 270.0 | - | 80.7 | - | - | - | 84.0 | - | 51.2 | 0.0098 | - | - | 11.1% |
| 8 | 12.0 | 270.0 | - | 80.8 | - | - | - | 95.0 | - | 51.1 | 0.0098 | - | - | 11.1% |
| 9 | 12.0 | 270.0 | - | 80.6 | - | - | - | 110.0 | - | 51.5 | 0.0099 | - | - | 11.1% |
| 10 | 12.1 | 269.0 | - | 25.8 | - | - | - | 77.0 | - | 53.6 | 0.0107 | - | - | 11.1% |

**Table B-2 AIL Research Prototype – Measured and Model Input Data
(SI units)**

| Test number | P amb | Air Flow S12 | Air Flow S34 | Airflow S25 | LD Flow | C LD | T LD | T S1 | T S3 | Tdp S1 | w s1 | Tdp S3 | S1 Water Duty | S2 Water Duty |
|--------------|-------|--------------|--------------|-------------|---------|-------|------|------|------|--------|--------|--------|---------------|---------------|
| Full device | kPa | kg/s | kg/s | kg/s | LPM | % | °C | °C | °C | °C | kg/kg | °C | % | % |
| 1 | 82.6 | 0.154 | 0.077 | - | 0.83 | 38.0% | 29.1 | 26.7 | 35.0 | 16.5 | 0.0144 | 20.3 | 100% | - |
| 2 | 82.9 | 0.154 | 0.077 | 0.046 | 0.83 | 38.0% | 32.3 | 26.7 | 35.0 | 16.5 | 0.0144 | 20.3 | 100% | 7.7% |
| 3 | 82.4 | 0.154 | 0.077 | 0.046 | 0.83 | 37.9% | 30.8 | 27.6 | 35.0 | 16.5 | 0.0145 | 20.3 | 100% | 11.1% |
| 4 | 82.3 | 0.154 | 0.077 | 0.046 | 0.83 | 38.1% | 30.9 | 27.6 | 35.0 | 16.5 | 0.0145 | 20.3 | 100% | 11.1% |
| 5 | 82.2 | 0.154 | 0.077 | 0.046 | 0.83 | 35.1% | 29.9 | 27.6 | 35.0 | 16.5 | 0.0145 | 20.3 | 100% | 11.1% |
| 6 | 82.2 | 0.154 | 0.077 | 0.015 | 0.83 | 38.3% | 31.7 | 25.5 | 35.0 | 15.2 | 0.0133 | 20.3 | 100% | 11.1% |
| 7 | 82.8 | 0.154 | 0.077 | 0.031 | 0.83 | 38.2% | 31.0 | 26.6 | 35.0 | 15.9 | 0.0139 | 20.3 | 100% | 11.1% |
| 8 | 83.5 | 0.154 | 0.077 | 0.046 | 0.50 | 43.8% | 31.1 | 27.6 | 35.0 | 16.5 | 0.0143 | 20.3 | 0% | 14.3% |
| 9 | 83.4 | 0.154 | 0.077 | 0.046 | 0.50 | 43.4% | 34.7 | 27.6 | 35.0 | 16.5 | 0.0143 | 20.3 | 100% | 14.3% |
| 10 | 83.4 | 0.155 | 0.077 | 0.046 | 0.60 | 43.5% | 39.6 | 35.0 | 35.0 | 20.3 | 0.0182 | 20.3 | 100% | 14.3% |
| 11 | 83.4 | 0.154 | 0.077 | 0.031 | 0.60 | 43.9% | 40.3 | 35.0 | 35.0 | 20.3 | 0.0181 | 20.3 | 100% | 14.3% |
| 12 | 83.3 | 0.154 | 0.077 | 0.031 | 0.60 | 40.3% | 35.9 | 35.0 | 35.0 | 20.3 | 0.0181 | 20.3 | 100% | 14.3% |
| 13 | 83.4 | 0.154 | 0.077 | 0.046 | 0.60 | 40.8% | 36.5 | 35.0 | 35.0 | 20.3 | 0.0181 | 20.3 | 100% | 14.3% |
| 14 | 83.4 | 0.154 | 0.077 | 0.046 | 0.60 | 40.7% | 32.9 | 27.6 | 35.0 | 16.5 | 0.0143 | 20.3 | 100% | 14.3% |
| 15 | 83.4 | 0.154 | 0.077 | 0.031 | 0.83 | 40.6% | 34.6 | 27.6 | 35.0 | 16.5 | 0.0143 | 20.3 | 100% | 14.3% |
| 16 | 83.3 | 0.154 | 0.077 | 0.031 | 0.83 | 41.0% | 34.0 | 26.6 | 35.0 | 15.9 | 0.0139 | 20.3 | 100% | 14.3% |
| 17 | 83.4 | 0.154 | 0.077 | 0.015 | 0.83 | 40.9% | 33.7 | 25.5 | 35.0 | 15.2 | 0.0132 | 20.3 | 100% | 14.3% |
| 18 | 82.6 | 0.154 | 0.077 | 0.046 | 0.83 | 37.9% | 30.8 | 24.6 | 25.0 | 16.5 | 0.0144 | 20.3 | 100% | 11.1% |
| 19 | 82.7 | 0.154 | 0.077 | 0.031 | 0.83 | 37.7% | 30.6 | 24.6 | 25.0 | 15.9 | 0.0139 | 20.3 | 100% | 11.1% |
| 20 | 82.5 | 0.154 | 0.077 | 0.015 | 0.83 | 37.7% | 30.1 | 24.5 | 25.0 | 15.2 | 0.0134 | 20.3 | 100% | 11.1% |
| 21 | 82.4 | 0.154 | 0.077 | 0.046 | 0.83 | 37.9% | 28.8 | 24.6 | 25.0 | 14.7 | 0.0128 | 15.0 | 100% | 11.1% |
| 22 | 82.3 | 0.154 | 0.077 | 0.031 | 0.83 | 37.7% | 28.4 | 24.6 | 25.0 | 14.7 | 0.0128 | 15.0 | 100% | 11.1% |
| 23 | 82.3 | 0.154 | 0.077 | 0.015 | 0.83 | 38.1% | 28.8 | 24.5 | 25.0 | 14.6 | 0.0128 | 15.0 | 100% | 11.1% |
| 24 | 82.2 | 0.154 | 0.077 | 0.046 | 0.83 | 37.9% | 30.0 | 27.6 | 35.0 | 14.7 | 0.0129 | 15.0 | 100% | 11.1% |
| 25 | 82.2 | 0.154 | 0.077 | 0.031 | 0.83 | 38.1% | 29.8 | 26.6 | 35.0 | 14.7 | 0.0128 | 15.0 | 100% | 11.1% |
| 26 | 82.3 | 0.154 | 0.077 | 0.015 | 0.83 | 37.5% | 28.6 | 25.5 | 35.0 | 14.6 | 0.0128 | 15.0 | 100% | 11.1% |
| 27 | 82.2 | 0.154 | 0.077 | 0.046 | 0.83 | 38.0% | 31.4 | 27.6 | 35.0 | 16.5 | 0.0145 | 20.3 | 100% | 11.1% |
| 28 | 82.2 | 0.108 | 0.054 | 0.032 | 0.83 | 38.3% | 31.0 | 27.6 | 35.0 | 16.5 | 0.0145 | 20.3 | 100% | 11.1% |
| 29 | 82.2 | 0.108 | 0.054 | 0.022 | 0.83 | 38.2% | 31.2 | 26.6 | 35.0 | 15.9 | 0.0140 | 20.3 | 100% | 11.1% |
| 30 | 82.3 | 0.062 | 0.031 | 0.018 | 0.83 | 38.1% | 29.6 | 28.2 | 37.0 | 15.3 | 0.0130 | 17.0 | 100% | 11.1% |
| AILR stage 2 | | | | | | | | | | | | | | |
| 1 | 80.9 | 0.154 | - | 0.046 | - | - | - | 35.0 | - | -3.0 | 0.0034 | - | - | 7.7% |
| 2 | 81.0 | 0.154 | - | 0.031 | - | - | - | 35.0 | - | 10.0 | 0.0096 | - | - | 7.7% |
| 3 | 81.0 | 0.154 | - | 0.015 | - | - | - | 35.0 | - | 10.0 | 0.0096 | - | - | 7.7% |
| 4 | 81.0 | 0.108 | - | 0.032 | - | - | - | 35.0 | - | 10.0 | 0.0095 | - | - | 7.7% |
| 5 | 81.0 | 0.062 | - | 0.018 | - | - | - | 35.0 | - | 10.0 | 0.0096 | - | - | 7.7% |
| 6 | 81.1 | 0.154 | - | 0.046 | - | - | - | 35.0 | - | 18.0 | 0.0162 | - | - | 7.7% |
| 7 | 82.6 | 0.151 | - | 0.045 | - | - | - | 28.9 | - | 10.7 | 0.0098 | - | - | 11.1% |
| 8 | 82.6 | 0.151 | - | 0.045 | - | - | - | 35.0 | - | 10.6 | 0.0098 | - | - | 11.1% |
| 9 | 82.6 | 0.151 | - | 0.045 | - | - | - | 43.3 | - | 10.8 | 0.0099 | - | - | 11.1% |
| 10 | 83.2 | 0.150 | - | 0.014 | - | - | - | 25.0 | - | 12.0 | 0.0107 | - | - | 11.1% |

**Table B-3 AIL Research Prototype – Measured Output Data
(IP units)**

| AILR - IP units | | | | | | | | | | | | | | | |
|------------------------|-------|-------|-------|-----------|------|--------|--------|--------|-------|--------|-----------|------------|----------|--------|----------|
| Output data (measured) | | | | | | | | | | | | | | | |
| Test number | ΔP 12 | ΔP 34 | ΔP 25 | Fan power | T S2 | w S2 | h S2 | Δw 12 | ΔT 12 | Δh 12 | Q_cooling | Q_sensible | Q_latent | Q_th | COP_unit |
| Full device | in WC | in WC | in WC | hp | °C | lb/lb | BTU/lb | lb/lb | °F | BTU/lb | BTU/hr | BTU/hr | BTU/hr | BTU/hr | - |
| 1 | 0.169 | 0.472 | | 0.044 | 83.9 | 0.0098 | 23.2 | 0.0046 | -3.9 | 1.7 | 4956 | -667 | 5623 | 5623 | |
| 2 | 1.096 | 0.460 | 0.395 | 0.158 | 58.4 | 0.0100 | 17.2 | 0.0044 | 21.6 | 4.3 | 8662 | 4868 | 3794 | 5419 | 1.18 |
| 3 | 1.058 | 0.460 | 0.395 | 0.155 | 58.7 | 0.0096 | 16.9 | 0.0049 | 23.0 | 4.7 | 9410 | 5194 | 4216 | 6023 | 1.18 |
| 4 | 1.064 | 0.460 | 0.395 | 0.156 | 58.4 | 0.0095 | 16.7 | 0.0050 | 23.2 | 4.8 | 9567 | 5247 | 4320 | 6174 | 1.18 |
| 5 | 1.062 | 0.460 | 0.395 | 0.156 | 59.1 | 0.0102 | 17.6 | 0.0043 | 22.6 | 4.4 | 8785 | 5072 | 3713 | 5302 | 1.22 |
| 6 | 1.085 | 0.460 | 0.102 | 0.145 | 70.1 | 0.0092 | 19.2 | 0.0041 | 7.8 | 2.8 | 7059 | 2496 | 4563 | 5070 | 1.03 |
| 7 | 1.097 | 0.460 | 0.234 | 0.150 | 63.5 | 0.0097 | 18.1 | 0.0042 | 16.4 | 3.7 | 8448 | 4293 | 4155 | 5195 | 1.20 |
| 8 | 1.038 | 0.460 | 0.394 | 0.150 | 59.7 | 0.0099 | 17.4 | 0.0044 | 20.3 | 4.2 | 8377 | 4593 | 3784 | 5404 | 1.16 |
| 9 | 1.067 | 0.460 | 0.395 | 0.153 | 57.3 | 0.0089 | 15.7 | 0.0054 | 22.7 | 4.9 | 9784 | 5166 | 4618 | 6596 | 1.14 |
| 10 | 1.077 | 0.460 | 0.394 | 0.160 | 61.0 | 0.0113 | 19.2 | 0.0069 | 34.1 | 6.9 | 13768 | 7777 | 5992 | 8537 | 1.28 |
| 11 | 1.106 | 0.460 | 0.234 | 0.155 | 65.0 | 0.0112 | 20.2 | 0.0069 | 30.0 | 6.4 | 14621 | 7856 | 6765 | 8455 | 1.37 |
| 12 | 1.102 | 0.460 | 0.233 | 0.155 | 65.9 | 0.0121 | 21.4 | 0.0060 | 29.1 | 5.9 | 13420 | 7559 | 5861 | 7325 | 1.43 |
| 13 | 1.075 | 0.460 | 0.395 | 0.160 | 61.9 | 0.0121 | 20.3 | 0.0061 | 33.1 | 6.4 | 12705 | 7465 | 5240 | 7480 | 1.32 |
| 14 | 1.042 | 0.460 | 0.395 | 0.152 | 58.4 | 0.0098 | 16.9 | 0.0045 | 23.6 | 4.6 | 9182 | 5304 | 3878 | 5538 | 1.24 |
| 15 | 1.076 | 0.460 | 0.234 | 0.147 | 63.1 | 0.0097 | 18.0 | 0.0046 | 18.9 | 4.2 | 9450 | 4916 | 4535 | 5669 | 1.26 |
| 16 | 1.071 | 0.460 | 0.234 | 0.146 | 62.7 | 0.0093 | 17.4 | 0.0047 | 17.2 | 4.0 | 9127 | 4523 | 4605 | 5756 | 1.20 |
| 17 | 1.073 | 0.460 | 0.102 | 0.142 | 71.3 | 0.0090 | 19.2 | 0.0042 | 6.6 | 2.7 | 6800 | 2174 | 4626 | 5140 | 0.99 |
| 18 | 1.070 | 0.461 | 0.395 | 0.154 | 57.9 | 0.0093 | 16.3 | 0.0051 | 17.1 | 4.2 | 8332 | 3956 | 4376 | 6250 | 1.02 |
| 19 | 1.089 | 0.460 | 0.234 | 0.148 | 62.7 | 0.0093 | 17.5 | 0.0045 | 12.6 | 3.4 | 7843 | 3401 | 4442 | 5553 | 1.06 |
| 20 | 1.110 | 0.460 | 0.102 | 0.146 | 70.0 | 0.0092 | 19.1 | 0.0042 | 5.7 | 2.6 | 6626 | 1942 | 4684 | 5207 | 0.95 |
| 21 | 1.063 | 0.460 | 0.395 | 0.153 | 55.8 | 0.0082 | 14.6 | 0.0047 | 17.9 | 4.1 | 8100 | 4082 | 4019 | 5741 | 1.06 |
| 22 | 1.080 | 0.460 | 0.234 | 0.147 | 61.1 | 0.0083 | 16.0 | 0.0045 | 13.3 | 3.5 | 8013 | 3565 | 4447 | 5560 | 1.08 |
| 23 | 1.109 | 0.461 | 0.102 | 0.147 | 68.0 | 0.0083 | 17.7 | 0.0045 | 7.1 | 2.9 | 7347 | 2348 | 4998 | 5554 | 1.00 |
| 24 | 1.064 | 0.460 | 0.395 | 0.156 | 57.2 | 0.0091 | 15.9 | 0.0038 | 24.5 | 4.3 | 8655 | 5422 | 3233 | 4616 | 1.35 |
| 25 | 1.094 | 0.460 | 0.233 | 0.151 | 62.3 | 0.0089 | 16.9 | 0.0039 | 17.5 | 3.7 | 8437 | 4541 | 3895 | 4865 | 1.27 |
| 26 | 1.116 | 0.460 | 0.102 | 0.148 | 69.9 | 0.0089 | 18.8 | 0.0039 | 8.0 | 2.7 | 6834 | 2536 | 4299 | 4776 | 1.05 |
| 27 | 1.057 | 0.460 | 0.395 | 0.155 | 58.4 | 0.0100 | 17.2 | 0.0045 | 23.3 | 4.6 | 9112 | 5219 | 3893 | 5561 | 1.22 |
| 28 | 0.705 | 0.328 | 0.248 | 0.073 | 57.5 | 0.0089 | 15.8 | 0.0056 | 24.2 | 5.2 | 7236 | 3850 | 3386 | 4832 | 1.22 |
| 29 | 0.717 | 0.327 | 0.152 | 0.070 | 62.4 | 0.0088 | 16.8 | 0.0052 | 17.4 | 4.3 | 6839 | 3235 | 3604 | 4506 | 1.23 |
| 30 | 0.374 | 0.220 | 0.126 | 0.023 | 56.6 | 0.0075 | 14.0 | 0.0055 | 26.2 | 5.3 | 4244 | 2356 | 1888 | 2695 | 1.34 |
| AILR stage 2 | | | | | | | | | | | | | | | |
| 1 | 1.139 | - | 0.399 | 0.142 | 49.5 | 0.0036 | 8.1 | 0.000 | 45.5 | 10.8 | 9229 | 9404.21 | -174.74 | - | 7.50 |
| 2 | 1.178 | - | 0.236 | 0.140 | 64.5 | 0.0094 | 18.1 | 0.000 | 30.5 | 7.6 | 7430 | 7311.39 | 118.80 | - | 6.15 |
| 3 | 1.199 | - | 0.102 | 0.138 | 76.2 | 0.0095 | 21.0 | 0.000 | 18.8 | 4.7 | 5119 | 5052.15 | 67.26 | - | 4.30 |
| 4 | 0.786 | - | 0.251 | 0.069 | 57.6 | 0.0095 | 16.5 | 0.000 | 37.4 | 9.2 | 5496 | 5481.68 | 14.16 | - | 9.25 |
| 5 | 0.429 | - | 0.126 | 0.021 | 57.4 | 0.0097 | 16.6 | 0.000 | 37.6 | 9.1 | 3101 | 3138.95 | -37.50 | - | 16.86 |
| 6 | 1.169 | - | 0.399 | 0.148 | 66.8 | 0.0159 | 25.6 | 0.000 | 28.2 | 7.4 | 6324 | 5996.46 | 327.91 | - | 4.94 |
| 7 | 1.135 | - | 0.396 | 0.137 | 57.2 | 0.0098 | 16.7 | 0.000 | 26.8 | 6.6 | 5614 | 5613.88 | 0.34 | - | 4.73 |
| 8 | 1.015 | - | 0.397 | 0.126 | 58.1 | 0.0098 | 11.3 | 0.000 | 36.9 | 14.6 | 7721 | 7721.36 | 0.85 | - | 7.06 |
| 9 | 1.110 | - | 0.396 | 0.141 | 58.7 | 0.0099 | 11.4 | 0.000 | 51.3 | 18.3 | 10729 | 10729.10 | 1.02 | - | 8.81 |
| 10 | 1.186 | - | 0.096 | 0.128 | 69.8 | 0.0107 | 20.7 | 0.000 | 7.2 | 1.8 | 1933 | 1933.02 | 0.17 | - | 1.75 |

**Table B-4 AIL Research Prototype – Measured Output Data
(SI units)**

| AILR - SI Units | | | | | | | | | | | | | | | |
|------------------------|-------|-------|-------|-----------|-------|--------|-------|--------|-------|-------|-----------|------------|----------|------|----------|
| Output data (measured) | | | | | | | | | | | | | | | |
| Test number | ΔP 12 | ΔP 34 | ΔP 25 | Fan power | T S2 | w S2 | h S2 | Δw 12 | ΔT 12 | Δh 12 | Q cooling | Q sensible | Q latent | Q th | COP unit |
| Full device | Pa | Pa | Pa | kW | °C | kg/kg | kJ/kg | kg/kg | °C | kJ/kg | kW | kW | kW | kW | - |
| 1 | 42 | 118 | - | 0.033 | 28.8 | 0.0098 | 54.1 | 0.0046 | -2.2 | 4.1 | 1.45 | -0.20 | 1.65 | 1.65 | - |
| 2 | 273 | 115 | 98 | 0.118 | 14.7 | 0.0100 | 40.1 | 0.0044 | 12.0 | 10.1 | 2.54 | 1.43 | 1.11 | 1.59 | 1.18 |
| 3 | 263 | 115 | 98 | 0.116 | 14.8 | 0.0096 | 39.3 | 0.0049 | 12.8 | 11.0 | 2.76 | 1.52 | 1.24 | 1.77 | 1.18 |
| 4 | 265 | 115 | 98 | 0.116 | 14.7 | 0.0095 | 38.8 | 0.0050 | 12.9 | 11.2 | 2.80 | 1.54 | 1.27 | 1.81 | 1.18 |
| 5 | 264 | 115 | 98 | 0.116 | 15.0 | 0.0102 | 41.0 | 0.0043 | 12.6 | 10.3 | 2.57 | 1.49 | 1.09 | 1.55 | 1.22 |
| 6 | 270 | 115 | 25 | 0.108 | 21.2 | 0.0092 | 44.7 | 0.0041 | 4.3 | 6.4 | 2.07 | 0.73 | 1.34 | 1.49 | 1.03 |
| 7 | 273 | 114 | 58 | 0.112 | 17.5 | 0.0097 | 42.2 | 0.0042 | 9.1 | 8.6 | 2.48 | 1.26 | 1.22 | 1.52 | 1.20 |
| 8 | 258 | 114 | 98 | 0.112 | 15.4 | 0.0099 | 40.5 | 0.0044 | 11.3 | 9.8 | 2.46 | 1.35 | 1.11 | 1.58 | 1.16 |
| 9 | 266 | 115 | 98 | 0.114 | 14.0 | 0.0089 | 36.7 | 0.0054 | 12.6 | 11.4 | 2.87 | 1.51 | 1.35 | 1.93 | 1.14 |
| 10 | 268 | 114 | 98 | 0.120 | 16.1 | 0.0113 | 44.8 | 0.0069 | 18.9 | 16.0 | 4.04 | 2.28 | 1.76 | 2.50 | 1.28 |
| 11 | 275 | 115 | 58 | 0.116 | 18.3 | 0.0112 | 46.9 | 0.0069 | 16.7 | 14.9 | 4.29 | 2.30 | 1.98 | 2.48 | 1.37 |
| 12 | 274 | 115 | 58 | 0.115 | 18.8 | 0.0121 | 49.7 | 0.0060 | 16.2 | 13.7 | 3.93 | 2.22 | 1.72 | 2.15 | 1.43 |
| 13 | 267 | 115 | 98 | 0.119 | 16.6 | 0.0121 | 47.3 | 0.0061 | 18.4 | 14.8 | 3.72 | 2.19 | 1.54 | 2.19 | 1.32 |
| 14 | 259 | 115 | 98 | 0.113 | 14.6 | 0.0098 | 39.4 | 0.0045 | 13.1 | 10.7 | 2.69 | 1.55 | 1.14 | 1.62 | 1.24 |
| 15 | 268 | 115 | 58 | 0.110 | 17.3 | 0.0097 | 41.9 | 0.0046 | 10.5 | 9.7 | 2.77 | 1.44 | 1.33 | 1.66 | 1.26 |
| 16 | 267 | 114 | 58 | 0.109 | 17.0 | 0.0093 | 40.6 | 0.0047 | 9.6 | 9.3 | 2.67 | 1.33 | 1.35 | 1.69 | 1.20 |
| 17 | 267 | 115 | 25 | 0.106 | 21.8 | 0.0090 | 44.8 | 0.0042 | 3.6 | 6.2 | 1.99 | 0.64 | 1.36 | 1.51 | 0.99 |
| 18 | 266 | 115 | 98 | 0.115 | 14.4 | 0.0093 | 38.0 | 0.0051 | 9.5 | 9.7 | 2.44 | 1.16 | 1.28 | 1.83 | 1.02 |
| 19 | 271 | 115 | 58 | 0.110 | 17.1 | 0.0093 | 40.8 | 0.0045 | 7.0 | 8.0 | 2.30 | 1.00 | 1.30 | 1.63 | 1.06 |
| 20 | 276 | 115 | 25 | 0.109 | 21.1 | 0.0092 | 44.5 | 0.0042 | 3.2 | 6.0 | 1.94 | 0.57 | 1.37 | 1.53 | 0.95 |
| 21 | 265 | 115 | 98 | 0.114 | 13.2 | 0.0082 | 33.9 | 0.0047 | 9.9 | 9.5 | 2.37 | 1.20 | 1.18 | 1.68 | 1.06 |
| 22 | 269 | 115 | 58 | 0.110 | 16.2 | 0.0083 | 37.3 | 0.0045 | 7.4 | 8.2 | 2.35 | 1.04 | 1.30 | 1.63 | 1.08 |
| 23 | 276 | 115 | 25 | 0.109 | 20.0 | 0.0083 | 41.3 | 0.0045 | 4.0 | 6.7 | 2.15 | 0.69 | 1.46 | 1.63 | 1.00 |
| 24 | 265 | 115 | 98 | 0.116 | 14.0 | 0.0091 | 37.1 | 0.0038 | 13.6 | 10.1 | 2.54 | 1.59 | 0.95 | 1.35 | 1.35 |
| 25 | 272 | 115 | 58 | 0.112 | 16.8 | 0.0089 | 39.4 | 0.0039 | 9.7 | 8.6 | 2.47 | 1.33 | 1.14 | 1.43 | 1.27 |
| 26 | 278 | 115 | 25 | 0.111 | 21.0 | 0.0089 | 43.8 | 0.0039 | 4.5 | 6.2 | 2.00 | 0.74 | 1.26 | 1.40 | 1.05 |
| 27 | 263 | 115 | 98 | 0.116 | 14.7 | 0.0100 | 40.0 | 0.0045 | 12.9 | 10.6 | 2.67 | 1.53 | 1.14 | 1.63 | 1.22 |
| 28 | 176 | 82 | 62 | 0.054 | 14.2 | 0.0089 | 36.8 | 0.0056 | 13.4 | 12.1 | 2.12 | 1.13 | 0.99 | 1.42 | 1.22 |
| 29 | 178 | 81 | 38 | 0.052 | 16.9 | 0.0088 | 39.2 | 0.0052 | 9.7 | 10.0 | 2.00 | 0.95 | 1.06 | 1.32 | 1.23 |
| 30 | 93 | 55 | 31 | 0.017 | 13.7 | 0.0075 | 32.7 | 0.0055 | 14.5 | 12.4 | 1.24 | 0.69 | 0.55 | 0.79 | 1.34 |
| AILR stage 2 | | | | | | | | | | | | | | | |
| 1 | 284 | - | 99 | 0.106 | 9.7 | 0.0036 | 18.9 | 0.000 | 25.3 | 25.1 | 2.70 | 2.76 | -0.05 | - | 7.50 |
| 2 | 293 | - | 59 | 0.104 | 18.0 | 0.0094 | 42.1 | 0.000 | 17.0 | 17.7 | 2.18 | 2.14 | 0.03 | - | 6.15 |
| 3 | 298 | - | 25 | 0.103 | 24.6 | 0.0095 | 48.9 | 0.000 | 10.4 | 10.8 | 1.50 | 1.48 | 0.02 | - | 4.30 |
| 4 | 196 | - | 62 | 0.051 | 14.2 | 0.0095 | 38.3 | 0.000 | 20.8 | 21.4 | 1.61 | 1.61 | 0.00 | - | 9.25 |
| 5 | 107 | - | 31 | 0.016 | 14.1 | 0.0097 | 38.6 | 0.000 | 20.9 | 21.1 | 0.91 | 0.92 | -0.01 | - | 16.86 |
| 6 | 291 | - | 99 | 0.110 | 19.3 | 0.0159 | 59.7 | 0.000 | 15.7 | 17.2 | 1.85 | 1.76 | 0.10 | - | 4.94 |
| 7 | 282 | - | 99 | 0.102 | 14 | 0.0098 | 38.9 | 0.000 | 14.9 | 15.3 | 1.65 | 1.65 | 0.00 | - | 4.73 |
| 8 | 253 | - | 99 | 0.094 | 14.49 | 0.0098 | 26.3 | 0.000 | 20.5 | 34.0 | 2.26 | 2.26 | 0.00 | - | 7.06 |
| 9 | 276 | - | 99 | 0.105 | 14.85 | 0.0099 | 26.7 | 0.000 | 28.5 | 42.5 | 3.14 | 3.14 | 0.00 | - | 8.81 |
| 10 | 295 | - | 24 | 0.095 | 21.01 | 0.0107 | 48.2 | 0.000 | 4.0 | 4.1 | 0.57 | 0.57 | 0.00 | - | 1.75 |

**Table B-5 AIL Research Prototype – Modeled Output Data
(IP units)**

| AILR - IP units | | | | | | | | | | | | | | | |
|-----------------------|-------|-------|-------|-----------|-------|--------|--------|--------|-------|--------|-----------|------------|----------|--------|----------|
| Output data (modeled) | | | | | | | | | | | | | | | |
| Test number | ΔP 12 | ΔP 34 | ΔP 25 | Fan power | T S2 | w S2 | h S2 | Δw 12 | ΔT 12 | Δh 12 | Q cooling | Q sensible | Q latent | Q th | COP_unit |
| Full device | in WC | in WC | in WC | hp | °F | lb/lb | BTU/lb | lb/lb | °F | BTU/lb | BTU/hr | BTU/hr | BTU/hr | BTU/hr | - |
| 1 | 1.21 | 0.33 | - | 0.040 | 84.0 | 0.0085 | 21.8 | 0.0059 | -4.0 | 5.5 | 6719 | -547 | 7266 | 7266 | - |
| 2 | 1.19 | 0.33 | 0.07 | 0.143 | 55.6 | 0.0088 | 15.2 | 0.0057 | 24.4 | 12.2 | 10416 | 5538 | 4879 | 6968 | 1.15 |
| 3 | 1.20 | 0.33 | 0.08 | 0.146 | 55.6 | 0.0089 | 15.3 | 0.0057 | 26.1 | 12.6 | 10762 | 5886 | 4877 | 6966 | 1.20 |
| 4 | 1.20 | 0.33 | 0.08 | 0.146 | 55.5 | 0.0088 | 15.2 | 0.0057 | 26.2 | 12.7 | 10849 | 5913 | 4936 | 7054 | 1.19 |
| 5 | 1.20 | 0.33 | 0.08 | 0.147 | 57.2 | 0.0100 | 16.9 | 0.0045 | 24.5 | 11.0 | 9388 | 5484 | 3905 | 5577 | 1.25 |
| 6 | 1.20 | 0.33 | 0.03 | 0.143 | 72.6 | 0.0080 | 18.5 | 0.0053 | 5.2 | 7.1 | 7790 | 1926 | 5864 | 6516 | 0.93 |
| 7 | 1.19 | 0.33 | 0.05 | 0.142 | 61.8 | 0.0084 | 16.3 | 0.0055 | 18.1 | 10.5 | 10231 | 4797 | 5433 | 6793 | 1.17 |
| 8 | 1.17 | 0.33 | 0.07 | 0.141 | 58.5 | 0.0096 | 16.8 | 0.0047 | 21.5 | 10.4 | 8902 | 4851 | 4051 | 5786 | 1.16 |
| 9 | 1.18 | 0.33 | 0.07 | 0.141 | 53.3 | 0.0071 | 12.8 | 0.0072 | 26.7 | 14.4 | 12307 | 6110 | 6198 | 8852 | 1.11 |
| 10 | 1.24 | 0.33 | 0.08 | 0.153 | 57.2 | 0.0092 | 16.0 | 0.0090 | 37.8 | 19.2 | 16565 | 8717 | 7848 | 11182 | 1.21 |
| 11 | 1.24 | 0.33 | 0.05 | 0.151 | 63.7 | 0.0088 | 17.2 | 0.0093 | 31.3 | 17.9 | 17479 | 8352 | 9127 | 11407 | 1.26 |
| 12 | 1.24 | 0.33 | 0.05 | 0.151 | 64.8 | 0.0102 | 18.9 | 0.0079 | 30.2 | 16.1 | 15792 | 7983 | 7809 | 9759 | 1.31 |
| 13 | 1.23 | 0.33 | 0.08 | 0.152 | 58.3 | 0.0100 | 17.2 | 0.0081 | 36.7 | 17.9 | 15354 | 8367 | 6987 | 9973 | 1.24 |
| 14 | 1.18 | 0.33 | 0.07 | 0.143 | 54.6 | 0.0079 | 14.0 | 0.0063 | 27.4 | 13.6 | 11700 | 6225 | 5475 | 7817 | 1.18 |
| 15 | 1.19 | 0.33 | 0.05 | 0.141 | 61.7 | 0.0078 | 15.6 | 0.0065 | 20.3 | 12.1 | 11803 | 5407 | 6396 | 7996 | 1.17 |
| 16 | 1.18 | 0.33 | 0.05 | 0.140 | 61.3 | 0.0074 | 15.1 | 0.0065 | 18.6 | 11.7 | 11407 | 5006 | 6402 | 8002 | 1.13 |
| 17 | 1.18 | 0.33 | 0.03 | 0.139 | 73.2 | 0.0071 | 17.6 | 0.0061 | 4.7 | 7.8 | 8619 | 1863 | 6756 | 7506 | 0.91 |
| 18 | 1.17 | 0.32 | 0.07 | 0.140 | 54.1 | 0.0081 | 14.1 | 0.0063 | 20.9 | 12.0 | 10261 | 4834 | 5428 | 7752 | 1.04 |
| 19 | 1.18 | 0.31 | 0.05 | 0.139 | 60.7 | 0.0079 | 15.5 | 0.0059 | 14.7 | 10.1 | 9837 | 4002 | 5835 | 7294 | 1.06 |
| 20 | 1.18 | 0.32 | 0.03 | 0.139 | 70.8 | 0.0077 | 17.7 | 0.0057 | 4.9 | 7.4 | 8173 | 1861 | 6311 | 7015 | 0.91 |
| 21 | 1.17 | 0.31 | 0.07 | 0.138 | 51.3 | 0.0068 | 12.0 | 0.0060 | 22.4 | 12.0 | 10282 | 5105 | 5177 | 7397 | 1.09 |
| 22 | 1.17 | 0.31 | 0.05 | 0.138 | 58.4 | 0.0069 | 13.8 | 0.0059 | 16.1 | 10.4 | 10171 | 4326 | 5846 | 7308 | 1.09 |
| 23 | 1.18 | 0.31 | 0.03 | 0.139 | 68.1 | 0.0067 | 16.0 | 0.0061 | 7.1 | 8.4 | 9239 | 2491 | 6748 | 7498 | 0.97 |
| 24 | 1.20 | 0.33 | 0.07 | 0.145 | 53.4 | 0.0078 | 13.5 | 0.0051 | 28.3 | 12.5 | 10709 | 6305 | 4405 | 6290 | 1.30 |
| 25 | 1.20 | 0.33 | 0.05 | 0.144 | 60.1 | 0.0075 | 14.9 | 0.0053 | 19.7 | 10.6 | 10383 | 5170 | 5213 | 6511 | 1.23 |
| 26 | 1.20 | 0.33 | 0.03 | 0.142 | 70.4 | 0.0076 | 17.5 | 0.0052 | 7.5 | 7.5 | 8320 | 2525 | 5796 | 6438 | 0.99 |
| 27 | 1.20 | 0.33 | 0.08 | 0.146 | 55.5 | 0.0089 | 15.3 | 0.0056 | 26.2 | 12.6 | 10763 | 5901 | 4861 | 6945 | 1.20 |
| 28 | 0.83 | 0.23 | 0.05 | 0.071 | 52.8 | 0.0080 | 13.7 | 0.0065 | 28.9 | 14.2 | 8530 | 4588 | 3942 | 5627 | 1.25 |
| 29 | 0.83 | 0.23 | 0.04 | 0.070 | 60.2 | 0.0078 | 15.2 | 0.0062 | 19.6 | 11.6 | 7945 | 3659 | 4286 | 5358 | 1.22 |
| 30 | 0.47 | 0.13 | 0.03 | 0.023 | 48.5 | 0.0065 | 11.0 | 0.0064 | 34.3 | 15.4 | 5271 | 3059 | 2212 | 3158 | 1.43 |
| AILR stage 2 | | | | | | | | | | | | | | | |
| 1 | 1.23 | - | 0.08 | 0.142 | 47.3 | 0.0034 | 7.3 | 0.0000 | 47.7 | 11.6 | 9894 | 9894 | 0 | - | 8.04 |
| 2 | 1.26 | - | 0.05 | 0.145 | 63.9 | 0.0096 | 18.1 | 0.0000 | 31.1 | 7.6 | 7402 | 7402 | 0 | - | 6.13 |
| 3 | 1.27 | - | 0.03 | 0.145 | 77.6 | 0.0096 | 21.4 | 0.0000 | 17.4 | 4.2 | 4651 | 4651 | 0 | - | 3.90 |
| 4 | 0.87 | - | 0.05 | 0.070 | 55.3 | 0.0095 | 15.9 | 0.0000 | 39.7 | 9.7 | 5829 | 5829 | 0 | - | 9.81 |
| 5 | 0.49 | - | 0.03 | 0.023 | 53.8 | 0.0096 | 15.6 | 0.0000 | 41.2 | 10.0 | 3434 | 3434 | 0 | - | 18.66 |
| 6 | 1.27 | - | 0.08 | 0.149 | 66.8 | 0.0162 | 26.0 | 0.0000 | 28.2 | 7.0 | 6024 | 6024 | 0 | - | 4.70 |
| 7 | 1.17 | - | 0.07 | 0.128 | 57.25 | 0.0098 | 16.7 | 0.0000 | 26.8 | 6.6 | 5617 | 5617 | 0 | - | 4.97 |
| 8 | 1.2 | - | 0.07 | 0.134 | 58.05 | 0.0098 | 16.9 | 0.0000 | 37.0 | 9.0 | 7707 | 7707 | 0 | - | 6.54 |
| 9 | 1.25 | - | 0.08 | 0.143 | 59.00 | 0.0099 | 17.2 | 0.0000 | 51.0 | 12.5 | 10687 | 10687 | 0 | - | 8.47 |
| 10 | 1.15 | - | 0.02 | 0.121 | 70.66 | 0.0107 | 21.0 | 0.0000 | 6.3 | 1.5 | 1646 | 1646 | 0 | - | 1.60 |

**Table B-6 AIL Research Prototype – Modeled Output Data
(SI units)**

| AILR - SI Units | | | | | | | | | | | | | | | |
|-----------------------|-------|-------|-------|-----------|-------|--------|-------|--------|-------|--------|-----------|------------|----------|------|----------|
| Output data (modeled) | | | | | | | | | | | | | | | |
| Test number | ΔP 12 | ΔP 34 | ΔP 25 | Fan power | T S2 | w S2 | h S2 | Δw 12 | ΔT 12 | Δh 12 | Q_cooling | Q_sensible | Q_latent | Q_th | COP_unit |
| Full device | Pa | Pa | Pa | kW | °C | kg/kg | kJ/kg | kg/kg | °C | BTU/lb | kW | kW | kW | kW | - |
| 1 | 301 | 82 | - | 0.030 | 28.8 | 0.0085 | 21.8 | 0.0059 | -2.2 | 12.8 | 1.97 | -0.16 | 2.13 | 2.13 | - |
| 2 | 296 | 82 | 19 | 0.107 | 28.8 | 0.0088 | 15.2 | 0.0057 | 13.6 | 28.3 | 3.05 | 1.62 | 1.43 | 2.04 | 1.15 |
| 3 | 299 | 82 | 19 | 0.109 | 28.8 | 0.0089 | 15.3 | 0.0057 | 14.5 | 29.3 | 3.15 | 1.72 | 1.43 | 2.04 | 1.20 |
| 4 | 299 | 82 | 19 | 0.109 | 28.8 | 0.0088 | 15.2 | 0.0057 | 14.6 | 29.5 | 3.18 | 1.73 | 1.45 | 2.07 | 1.19 |
| 5 | 299 | 82 | 19 | 0.109 | 28.8 | 0.0100 | 16.9 | 0.0045 | 13.6 | 25.5 | 2.75 | 1.61 | 1.14 | 1.63 | 1.25 |
| 6 | 299 | 82 | 6 | 0.107 | 28.8 | 0.0080 | 18.5 | 0.0053 | 2.9 | 16.5 | 2.28 | 0.56 | 1.72 | 1.91 | 0.93 |
| 7 | 296 | 82 | 13 | 0.106 | 28.8 | 0.0084 | 16.3 | 0.0055 | 10.1 | 24.4 | 3.00 | 1.41 | 1.59 | 1.99 | 1.17 |
| 8 | 291 | 81 | 18 | 0.105 | 28.8 | 0.0096 | 16.8 | 0.0047 | 11.9 | 24.2 | 2.61 | 1.42 | 1.19 | 1.70 | 1.16 |
| 9 | 294 | 81 | 18 | 0.105 | 28.8 | 0.0071 | 12.8 | 0.0072 | 14.8 | 33.5 | 3.61 | 1.79 | 1.82 | 2.59 | 1.11 |
| 10 | 309 | 82 | 19 | 0.114 | 28.8 | 0.0092 | 16.0 | 0.0090 | 21.0 | 44.7 | 4.85 | 2.55 | 2.30 | 3.28 | 1.21 |
| 11 | 309 | 82 | 13 | 0.112 | 28.8 | 0.0088 | 17.2 | 0.0093 | 17.4 | 41.6 | 5.12 | 2.45 | 2.67 | 3.34 | 1.26 |
| 12 | 309 | 82 | 13 | 0.113 | 28.8 | 0.0102 | 18.9 | 0.0079 | 16.8 | 37.6 | 4.63 | 2.34 | 2.29 | 2.86 | 1.31 |
| 13 | 306 | 82 | 19 | 0.113 | 28.8 | 0.0100 | 17.2 | 0.0081 | 20.4 | 41.7 | 4.50 | 2.45 | 2.05 | 2.92 | 1.24 |
| 14 | 294 | 81 | 18 | 0.106 | 28.8 | 0.0079 | 14.0 | 0.0063 | 15.2 | 31.8 | 3.43 | 1.82 | 1.60 | 2.29 | 1.18 |
| 15 | 296 | 81 | 13 | 0.106 | 28.8 | 0.0078 | 15.6 | 0.0065 | 11.3 | 28.1 | 3.46 | 1.58 | 1.87 | 2.34 | 1.17 |
| 16 | 294 | 81 | 13 | 0.105 | 28.8 | 0.0074 | 15.1 | 0.0065 | 10.3 | 27.2 | 3.34 | 1.47 | 1.88 | 2.35 | 1.13 |
| 17 | 294 | 81 | 6 | 0.104 | 28.8 | 0.0071 | 17.6 | 0.0061 | 2.6 | 18.2 | 2.53 | 0.55 | 1.98 | 2.20 | 0.91 |
| 18 | 291 | 78 | 19 | 0.104 | 28.8 | 0.0081 | 14.1 | 0.0063 | 11.6 | 27.9 | 3.01 | 1.42 | 1.59 | 2.27 | 1.04 |
| 19 | 294 | 78 | 13 | 0.103 | 28.8 | 0.0079 | 15.5 | 0.0059 | 8.1 | 23.4 | 2.88 | 1.17 | 1.71 | 2.14 | 1.06 |
| 20 | 294 | 78 | 6 | 0.104 | 28.8 | 0.0077 | 17.7 | 0.0057 | 2.7 | 17.3 | 2.40 | 0.55 | 1.85 | 2.06 | 0.91 |
| 21 | 291 | 77 | 18 | 0.103 | 28.8 | 0.0068 | 12.0 | 0.0060 | 12.4 | 28.0 | 3.01 | 1.50 | 1.52 | 2.17 | 1.09 |
| 22 | 291 | 77 | 12 | 0.103 | 28.8 | 0.0069 | 13.8 | 0.0059 | 8.9 | 24.2 | 2.98 | 1.27 | 1.71 | 2.14 | 1.09 |
| 23 | 294 | 77 | 6 | 0.103 | 28.8 | 0.0067 | 16.0 | 0.0061 | 4.0 | 19.5 | 2.71 | 0.73 | 1.98 | 2.20 | 0.97 |
| 24 | 299 | 81 | 19 | 0.108 | 28.8 | 0.0078 | 13.5 | 0.0051 | 15.7 | 29.1 | 3.14 | 1.85 | 1.29 | 1.84 | 1.30 |
| 25 | 299 | 81 | 13 | 0.107 | 28.8 | 0.0075 | 14.9 | 0.0053 | 10.9 | 24.6 | 3.04 | 1.52 | 1.53 | 1.91 | 1.23 |
| 26 | 299 | 81 | 6 | 0.106 | 28.8 | 0.0076 | 17.5 | 0.0052 | 4.2 | 17.6 | 2.44 | 0.74 | 1.70 | 1.89 | 0.99 |
| 27 | 299 | 82 | 19 | 0.109 | 28.8 | 0.0089 | 15.3 | 0.0056 | 14.5 | 29.3 | 3.15 | 1.73 | 1.42 | 2.04 | 1.20 |
| 28 | 207 | 58 | 13 | 0.053 | 28.8 | 0.0080 | 13.7 | 0.0065 | 16.1 | 33.1 | 2.50 | 1.34 | 1.16 | 1.65 | 1.25 |
| 29 | 207 | 58 | 9 | 0.052 | 28.8 | 0.0078 | 15.2 | 0.0062 | 10.9 | 27.0 | 2.33 | 1.07 | 1.26 | 1.57 | 1.22 |
| 30 | 117 | 33 | 7 | 0.017 | 28.8 | 0.0065 | 11.0 | 0.0064 | 19.0 | 35.8 | 1.54 | 0.90 | 0.65 | 0.93 | 1.43 |
| AILR stage 2 | | | | | | | | | | | | | | | |
| 1 | 306 | - | 19 | 0.106 | 47.3 | 0.0034 | 7.3 | 0.0000 | 26.5 | 26.9 | 2.90 | 2.90 | 0.00 | - | 8.04 |
| 2 | 314 | - | 13 | 0.108 | 63.9 | 0.0096 | 18.1 | 0.0000 | 17.3 | 17.6 | 2.17 | 2.17 | 0.00 | - | 6.13 |
| 3 | 316 | - | 7 | 0.108 | 77.6 | 0.0096 | 21.4 | 0.0000 | 9.7 | 9.8 | 1.36 | 1.36 | 0.00 | - | 3.90 |
| 4 | 216 | - | 13 | 0.053 | 55.3 | 0.0095 | 15.9 | 0.0000 | 22.0 | 22.6 | 1.71 | 1.71 | 0.00 | - | 9.81 |
| 5 | 122 | - | 8 | 0.017 | 53.8 | 0.0096 | 15.6 | 0.0000 | 22.9 | 23.3 | 1.01 | 1.01 | 0.00 | - | 18.66 |
| 6 | 316 | - | 20 | 0.111 | 66.8 | 0.0162 | 26.0 | 0.0000 | 15.7 | 16.4 | 1.77 | 1.77 | 0.00 | - | 4.70 |
| 7 | 291 | - | 18 | 0.095 | 57.25 | 0.0098 | 16.7 | 0.0000 | 14.9 | 15.3 | 1.65 | 1.65 | 0.00 | - | 4.97 |
| 8 | 299 | - | 19 | 0.100 | 58.05 | 0.0098 | 16.9 | 0.0000 | 20.5 | 21.0 | 2.26 | 2.26 | 0.00 | - | 6.54 |
| 9 | 311 | - | 19 | 0.107 | 59.00 | 0.0099 | 17.2 | 0.0000 | 28.3 | 29.1 | 3.13 | 3.13 | 0.00 | - | 8.47 |
| 10 | 286 | - | 6 | 0.090 | 70.66 | 0.0107 | 21.0 | 0.0000 | 3.5 | 3.5 | 0.48 | 0.48 | 0.00 | - | 1.60 |

**Table B-7 Synapse Prototype – Measured and Model Input Data
(IP units)**

| Synapse - IP Units | | | | | | | | | | | | |
|---------------------------------|-------|--------------|--------------|---------|---------|------|-------|-------|---------|---------|--------|---------------|
| Input data (measured & modeled) | | | | | | | | | | | | |
| Test number | P_amb | Air Flow S12 | Air Flow S34 | LD Flow | C_LD_in | T LD | T S12 | T S33 | Tdp S14 | w S1 | Tdp S3 | S1 Water Duty |
| | psi | SCFM | SCFM | GPM | - | °F | °F | °F | °F | lb/lb | °F | % |
| 1 | 12.0 | 274.0 | 0.1 | 0.089 | 0.378 | 83.1 | 69.6 | - | 61.7 | 0.01440 | - | 0.0% |
| 2 | 12.0 | 193.5 | 0.1 | 0.082 | 0.378 | 78.8 | 69.6 | - | 61.7 | 0.01436 | - | 0.0% |
| 3 | 12.0 | 355.1 | 0.1 | 0.089 | 0.378 | 82.2 | 69.6 | - | 61.7 | 0.01441 | - | 0.0% |
| 4 | 12.0 | 275.5 | 110.1 | 0.089 | 0.373 | 81.4 | 80.1 | 95.0 | 61.7 | 0.01440 | 68.5 | 9.1% |
| 5 | 12.0 | 275.4 | 110.0 | 0.095 | 0.379 | 83.7 | 80.1 | 80.0 | 61.7 | 0.01441 | 68.5 | 9.1% |
| 6 | 12.0 | 275.4 | 110.0 | 0.089 | 0.377 | 82.7 | 80.1 | 80.1 | 61.7 | 0.01439 | 59.0 | 9.1% |
| 7 | 12.0 | 275.5 | 110.2 | 0.089 | 0.376 | 82.6 | 80.1 | 95.0 | 61.7 | 0.01437 | 59.0 | 9.1% |
| 8 | 12.0 | 275.4 | 110.2 | 0.095 | 0.385 | 89.2 | 80.1 | 95.0 | 68.5 | 0.01832 | 68.5 | 9.1% |
| 9 | 12.0 | 275.4 | 82.6 | 0.089 | 0.379 | 84.2 | 80.1 | 95.0 | 61.7 | 0.01440 | 68.5 | 9.1% |
| 10 | 12.0 | 275.5 | 55.1 | 0.089 | 0.376 | 82.9 | 80.1 | 95.0 | 61.7 | 0.01441 | 68.5 | 9.1% |
| 11 | 12.0 | 192.8 | 77.1 | 0.082 | 0.381 | 85.7 | 80.1 | 95.0 | 61.7 | 0.01444 | 68.5 | 9.1% |
| 12 | 11.8 | 330.5 | 132.2 | 0.089 | 0.379 | 81.9 | 80.1 | 95.0 | 61.7 | 0.01464 | 68.5 | 9.1% |
| 13 | 11.9 | 275.4 | 110.2 | 0.089 | 0.378 | 85.8 | 80.1 | 95.0 | 61.7 | 0.01459 | 68.5 | 9.1% |
| 14 | 11.8 | 275.5 | 110.2 | 0.079 | 0.424 | 95.4 | 80.1 | 95.0 | 68.5 | 0.01868 | 68.5 | 9.1% |
| 15 | 11.8 | 275.6 | 110.2 | 0.079 | 0.428 | 91.5 | 80.0 | 95.0 | 61.7 | 0.01462 | 68.5 | 9.1% |
| 16 | 11.9 | 275.4 | 110.2 | 0.154 | 0.377 | 84.6 | 80.1 | 95.0 | 61.7 | 0.01458 | 68.5 | 9.1% |
| 17 | 12.0 | 275.4 | 110.2 | 0.151 | 0.334 | 78.5 | 80.0 | 95.0 | 61.7 | 0.01417 | 68.5 | 9.1% |
| 18 | 12.0 | 275.4 | 110.2 | 0.117 | 0.362 | 77.4 | 80.0 | 95.0 | 61.7 | 0.01435 | 66.2 | 9.1% |
| 19 | 12.0 | 275.4 | 110.3 | 0.136 | 0.343 | 84.8 | 80.0 | 95.0 | 61.7 | 0.01431 | 61.7 | 9.1% |
| 20 | 12.0 | 275.5 | 82.7 | 0.136 | 0.345 | 86.5 | 80.0 | 95.0 | 61.7 | 0.01427 | 59.0 | 9.1% |

**Table B-8 Synapse Prototype – Measured and Model Input Data
(SI units)**

| Synapse - SI units | | | | | | | | | | | | |
|---------------------------------|-------|--------------|--------------|---------|---------|------|-------|-------|---------|---------|--------|---------------|
| Input data (measured & modeled) | | | | | | | | | | | | |
| Test number | P_amb | Air Flow S12 | Air Flow S34 | LD Flow | C_LD_in | T LD | T S12 | T S33 | Tdp S14 | w S1 | Tdp S3 | S1 Water Duty |
| | kPa | ka/s | ka/s | LPM | - | °C | °C | °C | °C | ka/ka | °C | % |
| 1 | 82.9 | 0.1531 | 0.0001 | 0.337 | 0.378 | 28.4 | 20.9 | - | 16.5 | 0.01440 | - | 0.0% |
| 2 | 83.0 | 0.1081 | 0.0001 | 0.310 | 0.378 | 26.0 | 20.9 | - | 16.5 | 0.01436 | - | 0.0% |
| 3 | 82.9 | 0.1984 | 0.0001 | 0.337 | 0.378 | 27.9 | 20.9 | - | 16.5 | 0.01441 | - | 0.0% |
| 4 | 82.8 | 0.1540 | 0.0615 | 0.337 | 0.373 | 27.4 | 26.7 | 35.0 | 16.5 | 0.01440 | 20.3 | 9.1% |
| 5 | 82.9 | 0.1539 | 0.0615 | 0.360 | 0.379 | 28.7 | 26.7 | 26.7 | 16.5 | 0.01441 | 20.3 | 9.1% |
| 6 | 82.9 | 0.1539 | 0.0615 | 0.337 | 0.377 | 28.2 | 26.7 | 26.7 | 16.5 | 0.01439 | 15.0 | 9.1% |
| 7 | 82.8 | 0.1540 | 0.0616 | 0.337 | 0.376 | 28.1 | 26.7 | 35.0 | 16.5 | 0.01437 | 15.0 | 9.1% |
| 8 | 82.8 | 0.1539 | 0.0616 | 0.360 | 0.385 | 31.8 | 35.0 | 35.0 | 20.3 | 0.01832 | 20.3 | 9.1% |
| 9 | 82.7 | 0.1539 | 0.0462 | 0.337 | 0.379 | 29.0 | 26.7 | 35.0 | 16.5 | 0.01440 | 20.3 | 9.1% |
| 10 | 82.7 | 0.1539 | 0.0308 | 0.337 | 0.376 | 28.3 | 26.7 | 35.0 | 16.5 | 0.01441 | 20.3 | 9.1% |
| 11 | 82.6 | 0.1078 | 0.0431 | 0.310 | 0.381 | 29.8 | 26.7 | 35.0 | 16.5 | 0.01444 | 20.3 | 9.1% |
| 12 | 81.6 | 0.1847 | 0.0739 | 0.337 | 0.379 | 27.7 | 26.7 | 35.0 | 16.5 | 0.01464 | 20.3 | 9.1% |
| 13 | 81.8 | 0.1539 | 0.0616 | 0.337 | 0.378 | 29.9 | 26.7 | 35.0 | 16.5 | 0.01459 | 20.3 | 9.1% |
| 14 | 81.7 | 0.1539 | 0.0616 | 0.299 | 0.424 | 35.2 | 35.0 | 35.0 | 20.3 | 0.01868 | 20.3 | 9.1% |
| 15 | 81.6 | 0.1540 | 0.0616 | 0.299 | 0.428 | 33.1 | 26.7 | 35.0 | 16.5 | 0.01462 | 20.3 | 9.1% |
| 16 | 81.8 | 0.1539 | 0.0616 | 0.583 | 0.377 | 29.2 | 26.7 | 35.0 | 16.5 | 0.01458 | 20.3 | 9.1% |
| 17 | 83.0 | 0.1539 | 0.0616 | 0.572 | 0.334 | 25.9 | 26.7 | 35.0 | 16.5 | 0.01417 | 20.3 | 9.1% |
| 18 | 83.0 | 0.1539 | 0.0616 | 0.443 | 0.362 | 25.2 | 26.7 | 35.0 | 16.5 | 0.01435 | 19.0 | 9.1% |
| 19 | 82.9 | 0.1539 | 0.0616 | 0.515 | 0.343 | 29.3 | 26.7 | 35.0 | 16.5 | 0.01431 | 16.5 | 9.1% |
| 20 | 82.9 | 0.1540 | 0.0462 | 0.515 | 0.345 | 30.3 | 26.7 | 35.0 | 16.5 | 0.01427 | 15.0 | 9.1% |

Table B-9 Synapse Prototype – Measured Output Data (IP units)

| Synapse - IP Units | | | | | | | | | | | | | | |
|------------------------|--------------------|------------------|-----------|--------|--------|--------|--------------------|--------------------|--------------------|-----------|------------|----------|--------|--------|
| Output data (measured) | | | | | | | | | | | | | | |
| Test number | $\Delta P_{1-1.5}$ | ΔP_{S34} | Fan power | T_S1.5 | w_S1.5 | h_S1.5 | $\Delta w_{1-1.5}$ | $\Delta T_{1-1.5}$ | $\Delta h_{1-1.5}$ | Q_cooling | Q_sensible | Q_latent | Q_th | |
| | in WC | in WC | hp | °F | lb/lb | BTU/lb | lb/lb | °F | BTU/lb | BTU/hr | BTU/hr | BTU/hr | BTU/hr | BTU/hr |
| 1 | 0.23 | 0.0 | 0.10 | 86.7 | 0.0101 | 24.2 | 0.0043 | -17.0 | 0.5 | 633 | -4612 | 5245 | 5245 | 5245 |
| 2 | 0.14 | 0.0 | 0.04 | 88.2 | 0.0099 | 24.3 | 0.0045 | -18.2 | 0.4 | 378 | -3491 | 3870 | 3870 | 3870 |
| 3 | 0.31 | 0.0 | 0.16 | 85.9 | 0.0107 | 24.7 | 0.0037 | -15.5 | 0.2 | 346 | -5485 | 5830 | 5830 | 5830 |
| 4 | 0.24 | 1.04 | 0.27 | 81.0 | 0.0098 | 22.5 | 0.0046 | -1.0 | 4.8 | 5914 | 209 | 5705 | 6374 | 6374 |
| 5 | 0.24 | 0.99 | 0.26 | 79.4 | 0.0092 | 21.5 | 0.0052 | 0.6 | 5.9 | 7155 | 750 | 6405 | 7319 | 7319 |
| 6 | 0.23 | 0.99 | 0.26 | 76.6 | 0.0088 | 20.3 | 0.0056 | 3.4 | 7.0 | 8519 | 1627 | 6892 | 7979 | 7979 |
| 7 | 0.24 | 1.01 | 0.27 | 78.9 | 0.0093 | 21.4 | 0.0051 | 1.1 | 5.8 | 7127 | 896 | 6231 | 6996 | 6996 |
| 8 | 0.25 | 1.02 | 0.27 | 86.5 | 0.0123 | 26.6 | 0.0060 | 8.5 | 8.7 | 10619 | 3254 | 7365 | 8150 | 8150 |
| 9 | 0.24 | 0.65 | 0.18 | 82.1 | 0.0101 | 23.1 | 0.0043 | -2.0 | 4.2 | 5105 | -135 | 5240 | 5732 | 5732 |
| 10 | 0.24 | 0.37 | 0.13 | 82.7 | 0.0103 | 23.5 | 0.0041 | -2.6 | 3.9 | 4714 | -339 | 5053 | 5524 | 5524 |
| 11 | 0.14 | 0.59 | 0.11 | 80.8 | 0.0093 | 21.9 | 0.0051 | -0.7 | 5.4 | 4656 | 244 | 4412 | 4834 | 4834 |
| 12 | 0.36 | 1.26 | 0.43 | 81.2 | 0.0103 | 23.1 | 0.0044 | -1.2 | 4.5 | 6608 | 154 | 6455 | 6746 | 6746 |
| 13 | 0.24 | 0.98 | 0.26 | 81.0 | 0.0099 | 22.6 | 0.0047 | -1.0 | 4.9 | 6025 | 230 | 5795 | 6211 | 6211 |
| 14 | 0.25 | 0.97 | 0.26 | 87.1 | 0.0108 | 25.1 | 0.0078 | 7.9 | 10.6 | 12937 | 3288 | 9648 | 10059 | 10059 |
| 15 | 0.26 | 1.01 | 0.27 | 82.8 | 0.0084 | 21.4 | 0.0062 | -2.8 | 6.1 | 7478 | -146 | 7624 | 8189 | 8189 |
| 16 | 0.25 | 0.99 | 0.27 | 81.0 | 0.0097 | 22.4 | 0.0049 | -1.0 | 5.1 | 6246 | 229 | 6017 | 6448 | 6448 |
| 17 | 0.26 | 1.06 | 0.28 | 79.1 | 0.0109 | 23.2 | 0.0033 | 1.0 | 3.8 | 4648 | 644 | 4004 | 4381 | 4381 |
| 18 | 0.26 | 1.06 | 0.28 | 79.9 | 0.0102 | 22.6 | 0.0042 | 0.1 | 4.6 | 5647 | 492 | 5155 | 5638 | 5638 |
| 19 | 0.26 | 1.04 | 0.28 | 78.6 | 0.0104 | 22.6 | 0.0039 | 1.4 | 4.6 | 5613 | 839 | 4773 | 5207 | 5207 |
| 20 | 0.23 | 0.89 | 0.21 | 78.0 | 0.0101 | 22.1 | 0.0042 | 2.0 | 5.1 | 6232 | 1058 | 5174 | 5661 | 5661 |

Table B-10 Synapse Prototype – Measured Output Data (SI units)

| Synapse - SI units | | | | | | | | | | | | | | |
|------------------------|--------------------|------------------|-----------|--------|--------|--------|--------------------|--------------------|--------------------|-----------|------------|----------|------|------|
| Output data (measured) | | | | | | | | | | | | | | |
| Test number | $\Delta P_{1-1.5}$ | ΔP_{S34} | Fan power | T_S1.5 | w_S1.5 | h_S1.5 | $\Delta w_{1-1.5}$ | $\Delta T_{1-1.5}$ | $\Delta h_{1-1.5}$ | Q_cooling | Q_sensible | Q_latent | Q_th | |
| | Pa | Pa | kW | °C | kg/kg | kJ/kg | kg/kg | °C | kJ/kg | kW | kW | kW | kW | kW |
| 1 | 58 | 0 | 0.07 | 30.4 | 0.0101 | 56.4 | 0.0043 | -9.4 | 1.2 | 0.19 | -1.35 | 1.54 | 1.54 | 1.54 |
| 2 | 35 | 0 | 0.03 | 31.2 | 0.0099 | 56.7 | 0.0045 | -10.1 | 1.0 | 0.11 | -1.02 | 1.13 | 1.13 | 1.13 |
| 3 | 76 | 0 | 0.12 | 29.9 | 0.0107 | 57.5 | 0.0037 | -8.6 | 0.5 | 0.10 | -1.61 | 1.71 | 1.71 | 1.71 |
| 4 | 60 | 258 | 0.20 | 27.2 | 0.0098 | 52.3 | 0.0046 | -0.6 | 11.3 | 1.73 | 0.06 | 1.67 | 1.87 | 1.87 |
| 5 | 59 | 246 | 0.19 | 26.3 | 0.0092 | 50.0 | 0.0052 | 0.3 | 13.6 | 2.10 | 0.22 | 1.88 | 2.14 | 2.14 |
| 6 | 58 | 245 | 0.19 | 24.8 | 0.0088 | 47.3 | 0.0056 | 1.9 | 16.2 | 2.50 | 0.48 | 2.02 | 2.34 | 2.34 |
| 7 | 59 | 252 | 0.20 | 26.0 | 0.0093 | 49.9 | 0.0051 | 0.6 | 13.6 | 2.09 | 0.26 | 1.83 | 2.05 | 2.05 |
| 8 | 63 | 253 | 0.20 | 30.3 | 0.0123 | 62.0 | 0.0060 | 4.7 | 20.2 | 3.11 | 0.95 | 2.16 | 2.39 | 2.39 |
| 9 | 60 | 162 | 0.13 | 27.8 | 0.0101 | 53.9 | 0.0043 | -1.1 | 9.7 | 1.50 | -0.04 | 1.54 | 1.68 | 1.68 |
| 10 | 60 | 92 | 0.10 | 28.2 | 0.0103 | 54.6 | 0.0041 | -1.5 | 9.0 | 1.38 | -0.10 | 1.48 | 1.62 | 1.62 |
| 11 | 35 | 146 | 0.08 | 27.1 | 0.0093 | 51.0 | 0.0051 | -0.4 | 12.7 | 1.36 | 0.07 | 1.29 | 1.42 | 1.42 |
| 12 | 89 | 314 | 0.32 | 27.4 | 0.0103 | 53.7 | 0.0044 | -0.7 | 10.5 | 1.94 | 0.05 | 1.89 | 1.98 | 1.98 |
| 13 | 60 | 245 | 0.19 | 27.2 | 0.0099 | 52.6 | 0.0047 | -0.5 | 11.5 | 1.77 | 0.07 | 1.70 | 1.82 | 1.82 |
| 14 | 63 | 242 | 0.20 | 30.6 | 0.0108 | 58.5 | 0.0078 | 4.4 | 24.6 | 3.79 | 0.96 | 2.83 | 2.95 | 2.95 |
| 15 | 65 | 250 | 0.20 | 28.2 | 0.0084 | 49.9 | 0.0062 | -1.5 | 14.2 | 2.19 | -0.04 | 2.23 | 2.40 | 2.40 |
| 16 | 62 | 246 | 0.20 | 27.2 | 0.0097 | 52.1 | 0.0049 | -0.6 | 11.9 | 1.83 | 0.07 | 1.76 | 1.89 | 1.89 |
| 17 | 64 | 263 | 0.21 | 26.1 | 0.0109 | 54.1 | 0.0033 | 0.5 | 8.8 | 1.36 | 0.19 | 1.17 | 1.28 | 1.28 |
| 18 | 64 | 264 | 0.21 | 26.6 | 0.0102 | 52.7 | 0.0042 | 0.1 | 10.8 | 1.66 | 0.14 | 1.51 | 1.65 | 1.65 |
| 19 | 64 | 260 | 0.21 | 25.9 | 0.0104 | 52.6 | 0.0039 | 0.8 | 10.7 | 1.64 | 0.25 | 1.40 | 1.53 | 1.53 |
| 20 | 58 | 221 | 0.15 | 25.6 | 0.0101 | 51.4 | 0.0042 | 1.1 | 11.9 | 1.83 | 0.31 | 1.52 | 1.66 | 1.66 |

**Table B-11 Synapse Prototype – Modeled Output Data
(IP units)**

| Synapse - IP Units | | | | | | | | | | | | | | |
|-----------------------|--------------------|------------------|-----------|--------|--------|--------|--------------------|--------------------|--------------------|-----------|------------|----------|--------|--------|
| Output data (modeled) | | | | | | | | | | | | | | |
| Test number | $\Delta P_{1-1.5}$ | ΔP_{S34} | Fan power | T_S1.5 | w_S1.5 | h_S1.5 | $\Delta w_{1-1.5}$ | $\Delta T_{1-1.5}$ | $\Delta h_{1-1.5}$ | Q_cooling | Q_sensible | Q_latent | Q_th | |
| | in WC | in WC | hp | °F | lb/lb | BTU/lb | lb/lb | °F | BTU/lb | BTU/hr | BTU/hr | BTU/hr | BTU/hr | BTU/hr |
| 1 | 0.40 | 0.00 | 0.16 | 87.49 | 0.0103 | 24.7 | 0.0041 | -17.9 | 0.1 | 124 | -4870 | 4994 | 4994 | |
| 2 | 0.22 | 0.00 | 0.06 | 88.01 | 0.0100 | 24.5 | 0.0043 | -18.4 | 0.3 | 260 | -3473 | 3733 | 3733 | |
| 3 | 0.62 | 0.00 | 0.33 | 86.67 | 0.0107 | 24.9 | 0.0037 | -17.0 | 0.1 | 111 | -5785 | 5896 | 5896 | |
| 4 | 0.41 | 0.74 | 0.29 | 82.41 | 0.0097 | 22.8 | 0.0047 | -2.3 | 4.5 | 5545 | -203 | 5747 | 6421 | |
| 5 | 0.40 | 0.78 | 0.29 | 81.08 | 0.0092 | 21.9 | 0.0052 | -1.0 | 5.5 | 6666 | 252 | 6414 | 7329 | |
| 6 | 0.40 | 0.77 | 0.29 | 78.22 | 0.0089 | 20.8 | 0.0055 | 1.8 | 6.5 | 7948 | 1143 | 6805 | 7878 | |
| 7 | 0.40 | 0.79 | 0.29 | 79.97 | 0.0092 | 21.6 | 0.0052 | 0.1 | 5.7 | 6978 | 583 | 6394 | 7179 | |
| 8 | 0.41 | 0.81 | 0.30 | 88.57 | 0.0119 | 26.7 | 0.0064 | 6.4 | 8.7 | 10590 | 2691 | 7899 | 8740 | |
| 9 | 0.40 | 0.49 | 0.23 | 83.84 | 0.0098 | 23.2 | 0.0046 | -3.8 | 4.1 | 5057 | -625 | 5682 | 6215 | |
| 10 | 0.40 | 0.25 | 0.19 | 85.25 | 0.0102 | 24.0 | 0.0042 | -5.2 | 3.3 | 4033 | -1092 | 5125 | 5602 | |
| 11 | 0.22 | 0.44 | 0.11 | 82.88 | 0.0090 | 22.0 | 0.0055 | -2.8 | 5.3 | 4551 | -166 | 4717 | 5169 | |
| 12 | 0.55 | 1.10 | 0.49 | 82.56 | 0.0101 | 23.2 | 0.0046 | -2.5 | 4.4 | 6453 | -295 | 6747 | 7052 | |
| 13 | 0.40 | 0.81 | 0.30 | 82.77 | 0.0097 | 22.9 | 0.0049 | -2.7 | 4.6 | 5678 | -293 | 5971 | 6400 | |
| 14 | 0.42 | 0.82 | 0.31 | 90.23 | 0.0110 | 26.1 | 0.0077 | 4.8 | 9.6 | 11755 | 2337 | 9417 | 9819 | |
| 15 | 0.40 | 0.81 | 0.30 | 84.68 | 0.0083 | 21.8 | 0.0063 | -4.7 | 5.8 | 7065 | -685 | 7750 | 8323 | |
| 16 | 0.40 | 0.81 | 0.30 | 82.89 | 0.0094 | 22.5 | 0.0052 | -2.8 | 5.0 | 6087 | -293 | 6380 | 6836 | |
| 17 | 0.40 | 0.80 | 0.30 | 80.65 | 0.0107 | 23.4 | 0.0035 | -0.6 | 3.7 | 4497 | 195 | 4302 | 4707 | |
| 18 | 0.40 | 0.79 | 0.30 | 81.18 | 0.0097 | 22.5 | 0.0046 | -1.2 | 4.8 | 5827 | 158 | 5669 | 6201 | |
| 19 | 0.40 | 0.79 | 0.29 | 79.66 | 0.0101 | 22.5 | 0.0042 | 0.3 | 4.7 | 5692 | 564 | 5129 | 5594 | |
| 20 | 0.40 | 0.49 | 0.22 | 80.34 | 0.0102 | 22.8 | 0.0041 | -0.3 | 4.4 | 5341 | 349 | 4992 | 5462 | |

**Table B-12 Synapse Prototype – Modeled Output Data
(SI units)**

| Synapse - SI units | | | | | | | | | | | | | | |
|-----------------------|--------------------|------------------|-----------|--------|--------|--------|--------------------|--------------------|--------------------|-----------|------------|----------|------|----|
| Output data (modeled) | | | | | | | | | | | | | | |
| Test number | $\Delta P_{1-1.5}$ | ΔP_{S34} | Fan power | T_S1.5 | w_S1.5 | h_S1.5 | $\Delta w_{1-1.5}$ | $\Delta T_{1-1.5}$ | $\Delta h_{1-1.5}$ | Q_cooling | Q_sensible | Q_latent | Q_th | |
| | | | kW | °C | kg/kg | kJ/kg | kg/kg | °C | kJ/kg | kW | kW | kW | kW | kW |
| 1 | 55 | 0 | 0.12 | 30.8 | 0.0103 | 57.4 | 0.0041 | -9.9 | 0.2 | 0.04 | -1.43 | 1.46 | 1.46 | |
| 2 | 154 | 0 | 0.05 | 31.1 | 0.0100 | 57.0 | 0.0043 | -10.2 | 0.7 | 0.08 | -1.02 | 1.09 | 1.09 | |
| 3 | 103 | 185 | 0.25 | 30.4 | 0.0107 | 57.9 | 0.0037 | -9.5 | 0.2 | 0.03 | -1.70 | 1.73 | 1.73 | |
| 4 | 99 | 194 | 0.22 | 28.0 | 0.0097 | 53.0 | 0.0047 | -1.3 | 10.6 | 1.62 | -0.06 | 1.68 | 1.88 | |
| 5 | 99 | 192 | 0.22 | 27.3 | 0.0092 | 50.9 | 0.0052 | -0.6 | 12.7 | 1.95 | 0.07 | 1.88 | 2.15 | |
| 6 | 99 | 197 | 0.22 | 25.7 | 0.0089 | 48.4 | 0.0055 | 1.0 | 15.1 | 2.33 | 0.33 | 1.99 | 2.31 | |
| 7 | 103 | 200 | 0.22 | 26.7 | 0.0092 | 50.2 | 0.0052 | 0.0 | 13.3 | 2.04 | 0.17 | 1.87 | 2.10 | |
| 8 | 99 | 123 | 0.23 | 31.4 | 0.0119 | 62.1 | 0.0064 | 3.6 | 20.2 | 3.10 | 0.79 | 2.31 | 2.56 | |
| 9 | 99 | 62 | 0.17 | 28.8 | 0.0098 | 54.0 | 0.0046 | -2.1 | 9.6 | 1.48 | -0.18 | 1.67 | 1.82 | |
| 10 | 54 | 109 | 0.14 | 29.6 | 0.0102 | 55.9 | 0.0042 | -2.9 | 7.7 | 1.18 | -0.32 | 1.50 | 1.64 | |
| 11 | 137 | 274 | 0.09 | 28.3 | 0.0090 | 51.3 | 0.0055 | -1.6 | 12.4 | 1.33 | -0.05 | 1.38 | 1.51 | |
| 12 | 100 | 201 | 0.37 | 28.1 | 0.0101 | 54.0 | 0.0046 | -1.4 | 10.2 | 1.89 | -0.09 | 1.98 | 2.07 | |
| 13 | 104 | 204 | 0.22 | 28.2 | 0.0097 | 53.2 | 0.0049 | -1.5 | 10.8 | 1.66 | -0.09 | 1.75 | 1.88 | |
| 14 | 101 | 202 | 0.23 | 32.3 | 0.0110 | 60.8 | 0.0077 | 2.7 | 22.4 | 3.45 | 0.69 | 2.76 | 2.88 | |
| 15 | 100 | 202 | 0.22 | 29.3 | 0.0083 | 50.7 | 0.0063 | -2.6 | 13.4 | 2.07 | -0.20 | 2.27 | 2.44 | |
| 16 | 99 | 198 | 0.22 | 28.3 | 0.0094 | 52.4 | 0.0052 | -1.6 | 11.6 | 1.78 | -0.09 | 1.87 | 2.00 | |
| 17 | 99 | 198 | 0.22 | 27.0 | 0.0107 | 54.4 | 0.0035 | -0.4 | 8.6 | 1.32 | 0.06 | 1.26 | 1.38 | |
| 18 | 99 | 197 | 0.22 | 27.3 | 0.0097 | 52.3 | 0.0046 | -0.7 | 11.1 | 1.71 | 0.05 | 1.66 | 1.82 | |
| 19 | 99 | 121 | 0.22 | 26.5 | 0.0101 | 52.5 | 0.0042 | 0.2 | 10.8 | 1.67 | 0.17 | 1.50 | 1.64 | |
| 20 | 0 | 0 | 0.17 | 26.9 | 0.0102 | 53.1 | 0.0041 | -0.2 | 10.2 | 1.57 | 0.10 | 1.46 | 1.60 | |

Appendix C Numerical Modeling and Experiments for the AIL Research First-Stage HMX

The purposes of this appendix are to (1) show the performance of the AIL Research HMX compared to the numerical model, and (2) illustrate the differences between the Synapse and AIL Research first-stage HMXs and how these differences impact their performance.

C.1 Experimental

The AIL Research HMX is a stack of 41 channel pairs. The dimensions are specified in Table C–1. In addition to slight differences in the dimensions between the AIL Research first-stage HMX and the Synapse first-stage HMX, five other differences relate to the stack structure, the LD distribution method, the water distribution method, the membrane, and the spacer.

Table C–1 Prototype Specifications for Dehumidifier

| Dimension | Symbol | Value | Units |
|--|---------------------|-------|------------------------|
| Process/supply channel thickness | δ_s | 3 | mm |
| Exhaust channel thickness | δ_e | 3.67 | mm |
| Plate length | L | 190 | mm |
| Plate height | W | 560 | mm |
| Total plate thickness | δ_{plate} | 0.25 | mm |
| Flocking thickness | $\delta_{flocking}$ | 0.3 | mm |
| Membrane | | | |
| Property | Symbol | Value | Units |
| Membrane thickness | δ_{mem} | 30 | μm |
| Mean pore size | d_{pore} | 0.1 | μm |
| Porosity | ε | 0.72 | |
| Tortuosity ^a | τ | 2.3 | |
| Membrane diffusivity ^b | D_{mem} | 0.02 | cm^2/s |
| Membrane thermal conductivity ^c | k_{mem} | 0.06 | W/m-K |

^a Calculated with relation $\tau = \frac{(2 - \varepsilon)^2}{\varepsilon}$

^b Calculated as in Woods and Kozubal (2012a) for Synapse HMX, except membrane here is unbacked

^c Calculated as in Woods and Kozubal (2012a) for Synapse HMX

Instead of laminated sheets that were bonded together to make up a channel pair in the Synapse HMX, the AIL Research HMX uses PP extrusions (inexpensive Coroplast sheets).

The LD distribution system, which is proprietary to AIL Research, was also different. The key difference is that the Synapse HMX used several high-pressure-drop holes feeding into the flocking, which ensured even distribution across the plate. The AIL Research HMX used the pressure applied to the stack from the external frame to ensure even distribution. This method, as shown below, was inconsistent; it worked for some plates but not for others.

The water method used in the AIL Research HMX did not use wicked surfaces on the exhaust side to help the water wet the wall surface. This required a higher water flow rate.

The AIL Research HMX used the unbacked version of the backed membrane used in the Synapse HMX. Thus, the properties of the microporous membrane layer are the same, but no correction is required for the membrane backing.

The spacer in the AIL Research HMX is different than that in the Synapse HMX. This spacer is proprietary to AIL Research, and thus the data are not shown, but the heat transfer was measured similarly to the Synapse spacers. The same methods that were used for the Synapse first-stage HMX were used to take the results of these tests and estimate the heat and mass transfer performance of the AIL Research spacer.

The experimental setup for the AIL Research first-stage HMX is the same as that for the Synapse first-stage HMX, except that a sump and a pump were used for the continuous water flow, rather than the mains water pressure used for the once-through, cycled water flow in the Synapse HMX. The test points are shown in Table B–1 (IP units) and Table B–2 (SI units). These include different process and EA flow rates, LD flow rates and concentrations, and inlet air temperatures and humidities.

C.2 Model

The model used for the AIL Research HMX was the same as that used for the Synapse HMX, which is outlined in a separate publication Woods and Kozubal (2012a), except for the different inputs for dimensions and transport coefficients.

C.3 Results and Discussion

C.3.1 Experimental Results

This section focuses on the first-stage of the AIL Research HMX, although some of the presented results are for the AIL Research first- and second-stage HMXs together. The data are used to show two issues with the AIL Research first stage that make the model-predicted values different from the experimentally measured values:

- The model assumes that the LD is distributed evenly from one plate to the next.
- The model assumes a completely wetted surface on the exhaust side, which is the case for the wicked surface in the Synapse HMX.

The Synapse HMX used wicks on the exhaust side. For ease of construction, the AIL Research HMX used the flutes of the Coroplast extrusions as the exhaust side channels. Applying a wick inside these flutes would be difficult, so the AIL Research HMX instead uses a high water flow with no wicked surface. This section shows the effect of this wicked surface by first showing a test point with dry cooling from the first-stage exhaust (no water flow), and then showing a point with evaporative cooling from the first-stage exhaust (with water flow).

Figure C–1 shows the test results for the AIL Research HMX with no first-stage water flow (Test 8). The model does not match the experiments because of the uneven LD distribution, as discussed in the main body of the report. Figure C–2 shows the test results for the AIL Research HMX with continuous first-stage water flow (Test 9). This test is even further from predicted because of the lack of wetting on the exhaust side in addition to the imperfect LD distribution.

Psychrometric Chart at 82 kPa

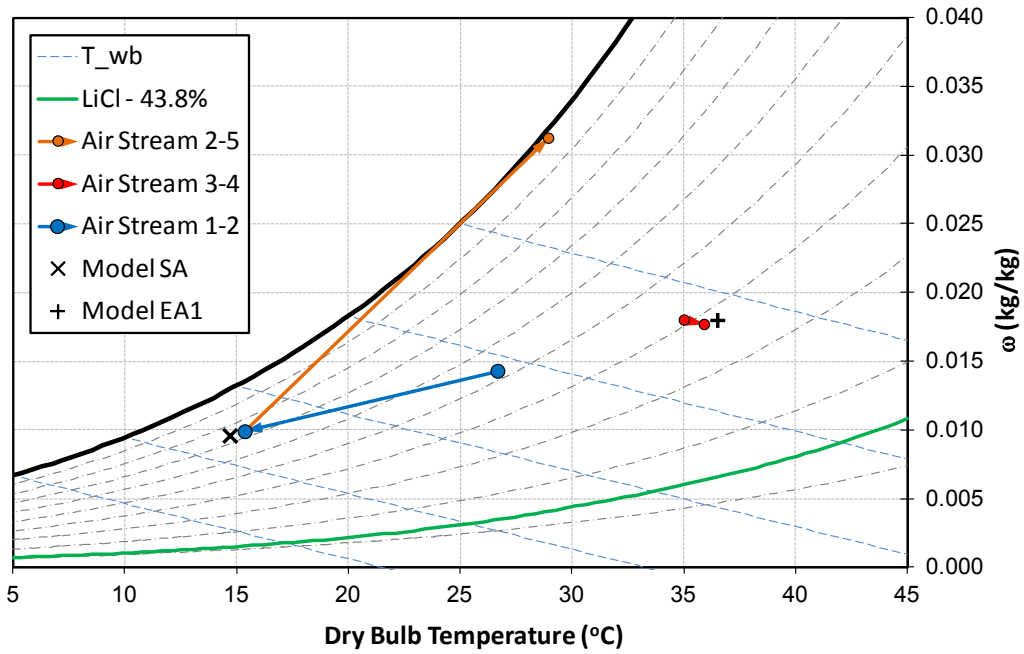


Figure C-1 Test #8, adiabatic test psychrometric chart at 82 kPa

Psychrometric Chart at 82 kPa

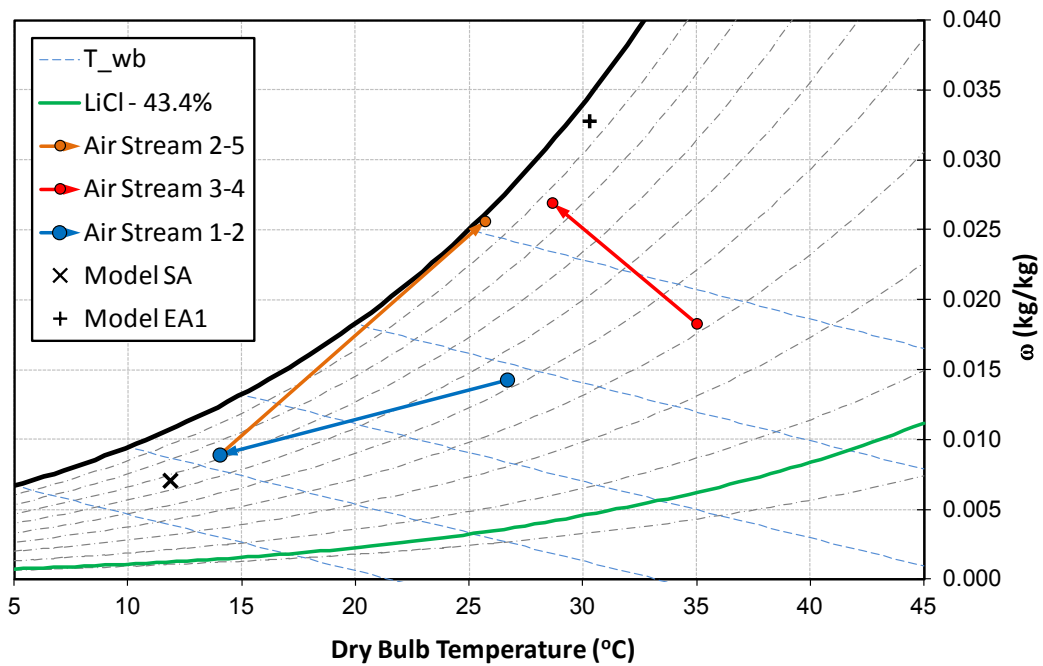


Figure C-2 Test #9 psychrometric chart at 82 kPa

C.3.2 Model-Experiment Comparison

This section compares the experiments and the model predictions for the key first-stage measurement ($\Delta\omega_s$) as well as the total enthalpy change (Δh_s) with the two stages combined.

The model over predicts the change in humidity ratio of the process air for the AIL Research HMX for the reasons discussed above (Figure C-3). On average, the experiments are 22% below the model predictions. This discrepancy is due to the reasons discussed in the previous section.

Figure C-4 shows the model-experiment agreement for the total enthalpy change of the first- and second-stages combined. The disagreement here is almost entirely from the first-stage HMX. As discussed in Section 3.1.2, the second-stage HMX matched the model predictions. On average, the experiments are 17% below the model predictions. This is primarily due to the lower latent cooling in the first-stage, but is also due to lower sensible cooling in the second stage. Even though the model and experiment match for the second stage, the sensible cooling in these tests in the second stage is less than the model prediction because of the higher humidity entering the second stage.

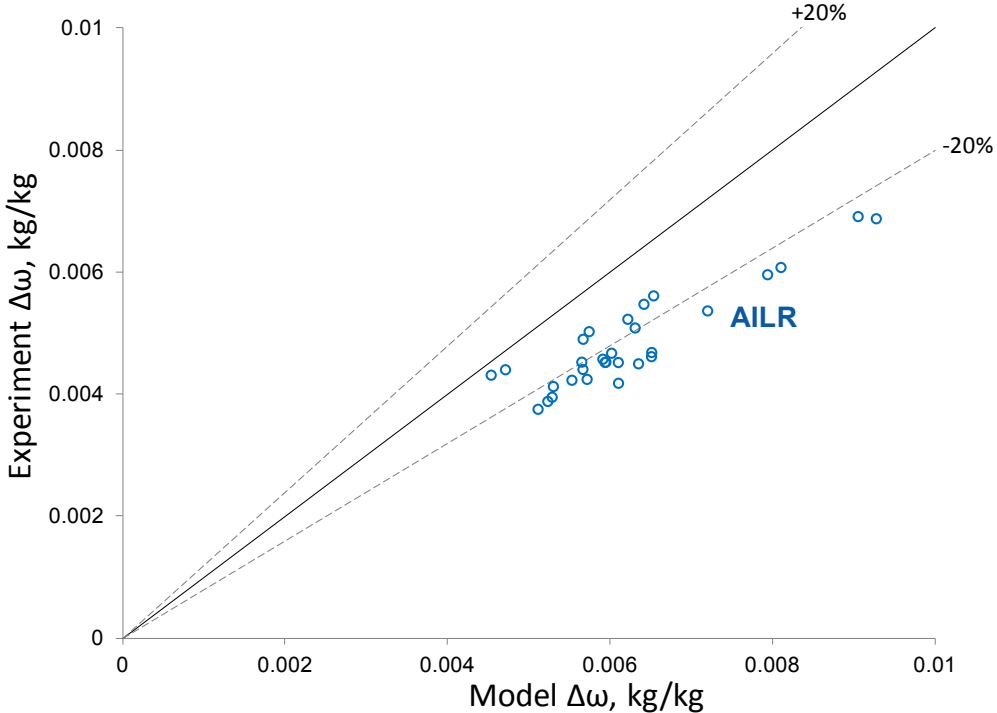


Figure C-3 Model-experiment comparison for change in humidity ratio for AIL Research first-stage

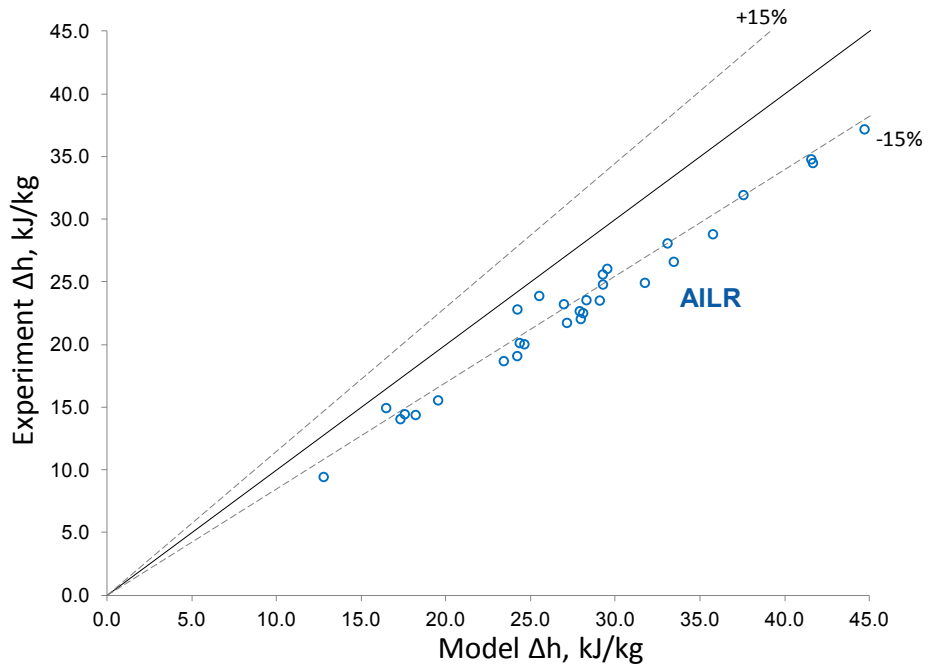


Figure C-4 Model-experiment comparison for change in enthalpy for AIL Research first- and second-stages combined

Appendix D Weight Calculations

**Table D-1 Synapse Weights – HMXs
(not selected for packaged unit weight analysis)**

| <u>Synapse - stage 1</u> | | |
|--|---|--------------------------|
| Module specs | channel pairs | 45 per ton |
| | Area / ton | 10.9 m ² /ton |
| Headers | <u>Custom synapse spacers</u> | |
| | header weight | 0.01 kg |
| | Weight / ton | 0.9 kg / ton |
| Separation plate | <u>PET sheet</u> | |
| | Density | 1400 kg/m ³ |
| | Thickness | 0.0002 m |
| | Weight / ton | 3.052 kg |
| Membrane | <u>Backed Celgard membrane</u> | |
| | Density | 225 kg/m ³ |
| | Thickness | 0.00008 m |
| | Weight / ton | 0.1962 kg |
| Support / frame | <u>Spacer (x2)</u> | |
| | weight / m ² | 0.3896 kg/m ² |
| | Weight / ton | 8.49328 kg |
| Flocking | <u>Flocking / wick (x2)</u> | |
| | Density | 500 kg/m ³ |
| | Thickness | 0.00025 m |
| | Weight / ton | 2.725 kg |
| Adhesive | <u>Pressure-sensitive adhesive (x2)</u> | |
| | Density | 1000 kg/m ³ |
| | Thickness | 0.0001 m |
| | % area of application | 100% (for all of sheet) |
| | Weight / ton | 2.18 kg |
| Stage 1 total | | 17.5 kg / ton |
| | | 38.6 lbs/ton |
| <u>Synapse - stage 2</u> | | |
| | Area / ton | 45.8 m ² /ton |
| Flocking | <u>Flocking / wick</u> | |
| | Density | 500 kg/m ³ |
| | Thickness | 0.00025 m |
| | Weight / ton | 5.725 kg |
| Separator | <u>PET sheet</u> | |
| | Density | 1400 kg/m ³ |
| | Thickness | 0.00025 m |
| | Weight / ton | 16.03 kg |
| Adhesive | <u>Pressure sensitive adhesive (x2)</u> | |
| | Density | 1000 kg/m ³ |
| | Thickness | 0.0001 m |
| | % area of application | 100% (for all of sheet) |
| | Weight / ton | 2.18 kg |
| Stage 2 total | | 23.9 kg / ton |
| | | 52.7 lbs/ton |
| Synapse total (stage 1 + stage 2) | | 91.3 lbs / ton |

x2 - times 2 since applied to both sides

x1/2 - times 0.5 since 1 unit takes the place of two plates

Table D-2 AIL Research Weight – HMXs

| AILR - stage 1 | | |
|---------------------------------------|---|---------------------------|
| Module specs | channel pairs | 51 per ton |
| | Area / ton | 12.84 m ² /ton |
| Headers | <u>Custom silicone headers (x2)</u> | |
| | header weight | 0.025 kg |
| | Weight / ton | 2.55 kg / ton |
| Separation plate | <i>no additional plate; coroplast serves as separator</i> | |
| <hr/> | | |
| Membrane | <u>Celgard membrane</u> | |
| | Density | 225 kg/m ³ |
| | Thickness | 0.0003 m |
| | Weight / ton | 0.08667 kg |
| Support / frame | <u>coroplast (x1/2)</u> | |
| | weight / m ² | 0.6 kg/m ² |
| | %extra for support | 10% |
| | Weight / ton | 4.2372 kg |
| Flocking | <u>Flocking / wick</u> | |
| | Density | 500 kg/m ³ |
| | Thickness | 0.00025 m |
| Adhesive | <u>Adhesive (x2)</u> | |
| | Density | 1000 kg/m ³ |
| | Thickness | 0.0001 m |
| | % area of application | 5% (around edges) |
| | Weight / ton | 0.1284 kg |
| Stage 1 total | | 8.6 kg / ton |
| | | 18.9 lbs/ton |
| <hr/> | | |
| AILR - stage 2 | | |
| | Area / ton | 48.63 m ² /ton |
| Flocking | <u>Flocking / wick</u> | |
| | Density | 500 kg/m ³ |
| | Thickness | 0.00025 m |
| Separator | <u>Coroplast (x1/2)</u> | |
| | Density | 0.6 kg/m ² |
| | % extra for support | 5% |
| | Weight / ton | 15.31845 kg |
| Separator | <u>Adhesive (x2)</u> | |
| | Density | 1000 kg/m ³ |
| | Thickness | 0.0001 m |
| | % area of application | 5% (around edges) |
| | Weight / ton | 0.1284 kg |
| Stage 2 total | | 21.5 kg / ton |
| | | 47.4 lbs/ton |
| AILR total (stage 1 + stage 2) | | 66.3 lbs / ton |

x2 - times 2 since applied to both sides

x1/2 - times 0.5 since 1 unit takes the place of two plates

Table D-3 AIL Research Packaged 10-Ton Unit Weight

DEVap, AILR Gen-1

| Component | Weight (lbs) | comment |
|------------------|--------------|---|
| Liquid desiccant | 215 | 20 gallons of 44% LiCl |
| Tank | 15 | 30 gallon polypropylene cylindrical tank |
| Shell | 201 | 20-gauge std. steel sheet metal, top and sides |
| Skid | 100 | Estimate |
| Supply fan | 90 | EBM Papst 6000 cfm plenum fan, K3G500 series |
| Exhaust fans | 100 | 50 lbs each |
| Pumps | 20 | 2 Desiccant pumps |
| Regenerator | 225 | Estimate from AIL Research for 2-stage regenerator |
| Stage 1 core | 199 | See table on AILR stage 1 weight per ton |
| Stage 2 core | 497 | See table on AILR stage 2 weight per ton |
| Water | 38 | Assuming 50% porous flocking with flocking half filled |
| Misc. | 150 | Tubing, plenums, filters, heating coils, hinged doors, fittings |
| Total | 1850 | |

Table D-4 Gen-2 Weight – HMXs

| Gen-2 - stage 1 | | |
|--|-------------------------------|---------------------------|
| Module specs | channel pairs | 40 per ton |
| | Area / ton | 7.53 m ² /ton |
| Headers | <u>Synapse-design headers</u> | |
| | header weight | 0.01 kg |
| | Weight / ton | 0.8 kg / ton |
| Separation plate | <u>Polypropylene sheet</u> | |
| | Density | 900 kg/m ³ |
| | Thickness | 0.00025 m |
| | Weight / ton | 1.69425 kg |
| Membrane | <u>Celgard membrane</u> | |
| | Density | 225 kg/m ³ |
| | Thickness | 0.00003 m |
| | Weight / ton | 0.0508275 kg |
| Support / frame | <u>coroplast (frame)</u> | |
| | weight / m ² | 0.6 kg/m ² |
| | amount removed | 90% |
| | Weight / ton | 0.4518 kg |
| Flocking | <u>Flocking / wick (x2)</u> | |
| | Density | 500 kg/m ³ |
| | Thickness | 0.00025 m |
| | Weight / ton | 1.8825 kg |
| Adhesive | <u>Adhesive (x2)</u> | |
| | Density | 1000 kg/m ³ |
| | Thickness | 0.0001 m |
| | % area of application | 5% (around edges) |
| | Weight / ton | 0.0753 kg |
| Stage 1 total | | 5.0 kg / ton |
| | | 10.9 lbs/ton |
| Gen 2 - stage 2 | | |
| Area / ton | | 21.31 m ² /ton |
| Flocking | <u>Flocking / wick</u> | |
| | Density | 500 kg/m ³ |
| | Thickness | 0.00025 m |
| | Weight / ton | 2.66375 kg |
| Separator | <u>Aluminum</u> | |
| | Density | 2700 kg/m ³ |
| | Thickness | 0.00015 m |
| | Weight / ton | 8.63055 kg |
| Separator | <u>Adhesive (x2)</u> | |
| | Density | 1000 kg/m ³ |
| | Thickness | 0.0001 m |
| | % area of application | 5% (around edges) |
| | Weight / ton | 0.0753 kg |
| Stage 2 total | | 11.4 kg / ton |
| | | 25.0 lbs/ton |
| Gen-2 total (stage 1 + stage 2) | | 35.9 lbs / ton |

x2 - times 2 since applied to both sides

x1/2 - times 0.5 since 1 unit takes the place of two plates

Table D-5 Gen-2 Packaged 10-Ton Unit Weight

| DEVap, Gen-2 | |
|---------------------|---|
| Component | Weight (lbs) comment |
| Liquid desiccant | 215 20 gallons of 44% LiCl |
| Tank | 15 30 gallon polypropylene cylindrical tank |
| Shell | 167 20-gauge std. steel sheet metal, top and sides |
| Skid | 100 Estimate |
| Supply fan | 90 EBM Papst 6000 cfm plenum fan, K3G500 series |
| Exhaust fans | 100 50 lbs each |
| Pumps | 20 2 Desiccant pumps |
| Regenerator | 225 Estimate from AIL Research for 2-stage regenerator |
| Stage 1 core | 114 See table on Gen-2 stage 1 weight per ton |
| Stage 2 core | 263 See table on Gen-2 stage 2 weight per ton |
| Water | 18 Assuming 50% porous flocking with flocking half filled |
| Misc. | 150 Tubing, plenums, filters, heating coils, hinged doors, fittings |
| Total | 1477 |

Table D-6 High-Efficiency 10-Ton Vapor Compression Unit Weight

| Vapor Compression Unit With 14.5 IEER | |
|--|----------------|
| Component | Weight |
| Baseline | 1372 lb |
| Economizer | 36 lb |
| Hinged doors | 12 lb |
| Reheat coil | 53 lb |
| Total | 1473 lb |

Appendix E Cost Calculations

Table E-1 ALL Research Cost Spreadsheet – HMXs

| <u>Design</u> | (Metric units) | | (IP units) | |
|---------------------------------|----------------|---------------------------|------------|--------------------------|
| | 1st stage | 2nd stage | 1st stage | 2nd stage |
| plate length | 0.231 | 0.584 m | 0.8 | 1.9 ft |
| plate height | 0.546 | 0.457 m | 1.8 | 1.5 ft |
| area / ton-modeled | 12.84 | 48.63 m ² /ton | 138 | 523 ft ² /ton |
| channel pairs / ton | 51 | 91 # / ton | 51 | 91 # / ton |
| <u>Coroplast</u> | | | | |
| coroplast / plate | 0.5 | 0.5 | 0.5 | 0.5 |
| m ² / ton | 6.4 | 24.3 m ² | 69.1 | 261.7 ft ² |
| <u>Aluminum</u> | | | | |
| sheets / plate | 0 | 0 | 0 | 0 |
| m ² / ton | 0.0 | 0.0 m ² | 0.0 | 0.0 ft ² |
| <u>Membrane</u> | | | | |
| membranes / plate | 1 | 0 | 1 | 0 |
| m ² / ton | 12.8 | 0.0 m ² | 138.2 | 0.0 ft ² |
| <u>Flocking / Wick</u> | | | | |
| wicked surfaces / plate | 1 | 1 | 1 | 1 |
| m ² / ton | 12.8 | 48.6 m ² | 138.2 | 523.4 ft ² |
| <u>Desiccant headers</u> | | | | |
| # / channel pair | 1 | 0 | 1 | 0 |
| # / ton | 51 | 0 | 51 | 0 |

| <u>Unit costs</u> | |
|-------------------|------------------------|
| Coroplast | 2.41 \$/m ² |
| Aluminum sheet | 1.5 \$/m ² |
| Membrane | 2.69 \$/m ² |
| Flocking | 1.02 \$/m ² |
| Headers | 2.52 \$/header |
| Labor (stage1) | 1.5 \$/plate pair |
| Labor (stage2) | 2.5 \$/plate pair |

| <u>% waste *</u> |
|------------------|
| 0.1 |
| 0 |
| 0.02 |
| 0.02 |
| 0 |

* inactive area included in area/ton

| <u>Costs per ton</u> | 1st stage | 2nd stage | Total |
|----------------------|-----------|-----------|-------|
| Coroplast | \$17 | \$64 | \$81 |
| Aluminum | \$0 | \$0 | \$0 |
| Membrane | \$35 | \$0 | \$35 |
| Flocking | \$13 | \$51 | \$64 |
| Headers | \$129 | \$0 | \$129 |
| Total materials | \$194 | \$115 | \$309 |
| Labor | \$77 | \$228 | \$304 |
| Total costs | \$271 | \$343 | \$613 |

shaded cells = inputs
unshaded cells = calculations

Table E-2 AIL Research Cost Spreadsheet – Full AC

| A/C Mark-ups | Mark-up | Total Mark-up to retail | Total Mark down to mfg cost |
|------------------|---------|-------------------------|-----------------------------|
| 1 - Manufacturer | 1.23 | 2.35 | 1.23 |
| 2 - Distributer | 1.49 | 1.91 | 1.83 |
| 3 - Retailer | 1.28 | 1.28 | 2.35 |
| 4 - Retail cost | 1.00 | 1.00 | |

| Component cost estimates | Cost Estimate | Price Level | Markup | Retail Cost | Comments |
|--------------------------|---------------|-------------|--------|-------------|---|
| \$/ton, core | \$ 613 | 1 | 2.35 | \$ 1,438 | |
| \$/kg LiCl | \$ 18 | 4 | 1.00 | \$ 18 | \$/kg anhydrous |
| Total fixed costs | | | | \$ 8,897 | |
| 2-stage regenerator | \$ 2,700 | 1 | 2.35 | \$ 6,334 | AILR Estimate -e-mail correspondance |
| Tank | \$ 100 | 4 | 1.00 | \$ 100 | 30 gal tank |
| Supply/mixed-air fan | \$ 360 | 4 | 1.00 | \$ 360 | Based on AILR estimate |
| Exhaust fan | \$ 300 | 4 | 1.00 | \$ 300 | Based on AILR estimate |
| Gas furnace | \$ 400 | 4 | 1.00 | \$ 400 | |
| Electronics | \$ 400 | 4 | 1.00 | \$ 400 | Estimate from Coolerado |
| Packaging | \$ 600 | 3 | 1.28 | \$ 768 | Estimate from Coolerado distribution cost |
| 2 desiccant pumps | \$ 60 | 4 | 1.00 | \$ 60 | pumps, 5 gpm each |
| Solenoid | \$ 75 | 4 | 1.00 | \$ 75 | retail estimate |
| Filters | \$ 25 | 4 | 1.00 | \$ 25 | retail estimate |
| Pressure regulator | \$ 75 | 4 | 1.00 | \$ 75 | retail estimate |

| | |
|----------------------|--------------------------------------|
| System size | 10.0 tons |
| LiCl storage density | 7.3 kg/tonh_L |
| LiCl storage | 0.6 0.5 hours + 20% for pipe volumes |
| LiCl required | 43.8 kg |
| LiCl cost | \$ 771 |

| | | |
|--|-----------|--|
| System Retail Cost | \$ 24,052 | 10-ton system cost with 30-min storage |
| Mark-up level to estimate cost | 4 | |
| Mark-up factor | 1.00 | |
| Total system cost at level shown above | \$ 24,052 | |

shaded cells = inputs
unshaded cells = calculations

Table E-3 Gen-2 Cost Spreadsheet – HMXs

| Design | (Metric units) | | (IP units) | |
|--------------------------|----------------|---------------------------|------------|--------------------------|
| | 1st stage | 2nd stage | 1st stage | 2nd stage |
| plate length | 0.186 | 0.4 m | 0.6 | 1.3 ft |
| plate height | 0.5 | 0.45 m | 1.6 | 1.5 ft |
| area / ton (modeled) | 7.53 | 21.31 m ² /ton | 81 | 229 ft ² /ton |
| channel pairs / ton | 40 | 59 # / ton | 40 | 59 # / ton |
| Coroplast | | | | |
| coroplast / plate | 1 | 0 | 1 | 0 |
| m ² / ton | 7.5 | 0.0 m ² | 81.1 | 0.0 ft ² |
| Aluminum | | | | |
| sheets / plate | 0 | 1 | 0 | 1 |
| m ² / ton | 0.0 | 21.3 m ² | 0.0 | 229.4 ft ² |
| Membrane | | | | |
| membranes / plate | 1 | 0 | 1 | 0 |
| m ² / ton | 7.5 | 0.0 m ² | 81.1 | 0.0 ft ² |
| Flocking / Wick | | | | |
| wicked surfaces / plate | 2 | 1 | 2 | 1 |
| m ² / ton | 15.1 | 21.3 m ² | 162.1 | 229.4 ft ² |
| Desiccant headers | | | | |
| # / channel pair | 2 | 0 | 2 | 0 |
| # / ton | 80 | 0 | 80 | 0 |

| Unit costs | | % waste + inactive area |
|-------------------|------------------------|--------------------------------|
| Coroplast | 2.41 \$/m ² | 0.15 |
| Aluminum sheet | 1.5 \$/m ² | 0.02 |
| Membrane | 2.69 \$/m ² | 0.05 |
| Flocking | 1.02 \$/m ² | 0.05 |
| Headers | 1 \$/header | 0 |
| Labor (stage1) | 1.5 \$/plate pair | |
| Labor (stage2) | 2.5 \$/plate pair | |

| Costs per ton | 1st stage | 2nd stage | Total |
|------------------------|--------------|--------------|--------------|
| Coroplast | \$21 | \$0 | \$21 |
| Aluminum | \$0 | \$33 | \$33 |
| Membrane | \$21 | \$0 | \$21 |
| Flocking | \$16 | \$23 | \$39 |
| Headers | \$80 | \$0 | \$80 |
| Total materials | \$138 | \$55 | \$194 |
| Total materials | \$138 | \$55 | \$194 |
| Labor | \$60 | \$148 | \$208 |
| Total costs | \$198 | \$203 | \$401 |

shaded cells = inputs
unshaded cells = calculations

Table E-4 Gen-2 Cost Spreadsheet – Full AC

| A/C Mark-ups | Mark-up | Total Mark-up to retail | Total Mark down to mfg cost |
|---------------------|---------|-------------------------|-----------------------------|
| 1 - Manufacturer | 1.23 | 2.35 | 1.23 |
| 2 - Distributer | 1.49 | 1.91 | 1.83 |
| 3 - Retailer | 1.28 | 1.28 | 2.35 |
| 4 - Retail cost | 1.00 | 1.00 | |

| Component cost estimates | Cost Estimate | Price Level | Markup | Retail Cost | Comments |
|---------------------------------|---------------|-------------|--------|-------------|---|
| \$/ton, core | \$ 401 | 1 | 2.35 | \$ 941 | From HMX core calculations |
| \$/kg LiCl | \$ 18 | 4 | 1.00 | \$ 18 | \$/kg anhydrous |
| Total fixed costs | | | | \$ 8,897 | |
| 2-stage regenerator | \$ 2,700 | 1 | 2.35 | \$ 6,334 | AILR Estimate -e-mail correspondance |
| Tank | \$ 100 | 4 | 1.00 | \$ 100 | 30 gal tank |
| Supply/mixed-air fan | \$ 360 | 4 | 1.00 | \$ 360 | Based on AILR estimate |
| Exhaust fan | \$ 300 | 4 | 1.00 | \$ 300 | Based on AILR estimate |
| Gas furnace | \$ 400 | 4 | 1.00 | \$ 400 | |
| Electronics | \$ 400 | 4 | 1.00 | \$ 400 | Estimate from Coolerado |
| Packaging | \$ 600 | 3 | 1.28 | \$ 768 | Estimate from Coolerado distribution cost |
| 2 desiccant pumps | \$ 60 | 4 | 1.00 | \$ 60 | pumps, 5 gpm each |
| Solenoid | \$ 75 | 4 | 1.00 | \$ 75 | retail estimate |
| Filters | \$ 25 | 4 | 1.00 | \$ 25 | retail estimate |
| Pressure regulator | \$ 75 | 4 | 1.00 | \$ 75 | retail estimate |

| | |
|----------------------|---|
| System size | 10.0 tons |
| LiCl storage density | 7.3 kg/tonh_L |
| LiCl storage | 0.6 <i>0.5 hours + 20% for pipe volumes</i> |
| LiCl required | 43.8 kg |
| LiCl cost | \$ 771 |

| | | |
|--|-----------|---|
| System Retail Cost | \$ 19,079 | <i>10-ton system cost with 30-min storage</i> |
| Mark-up level to estimate cost | 4 | |
| Mark-up factor | 1.00 | |
| Total system cost at level shown above | \$ 19,079 | |

shaded cells = inputs
unshaded cells = calculations