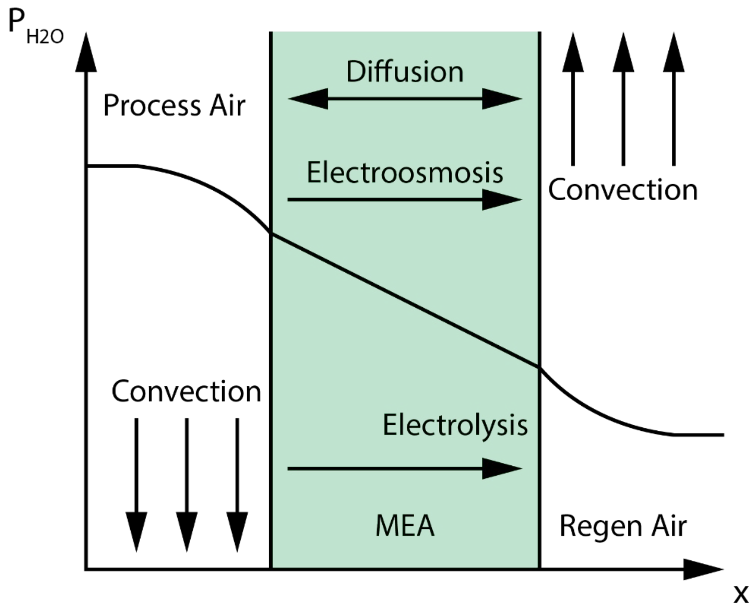
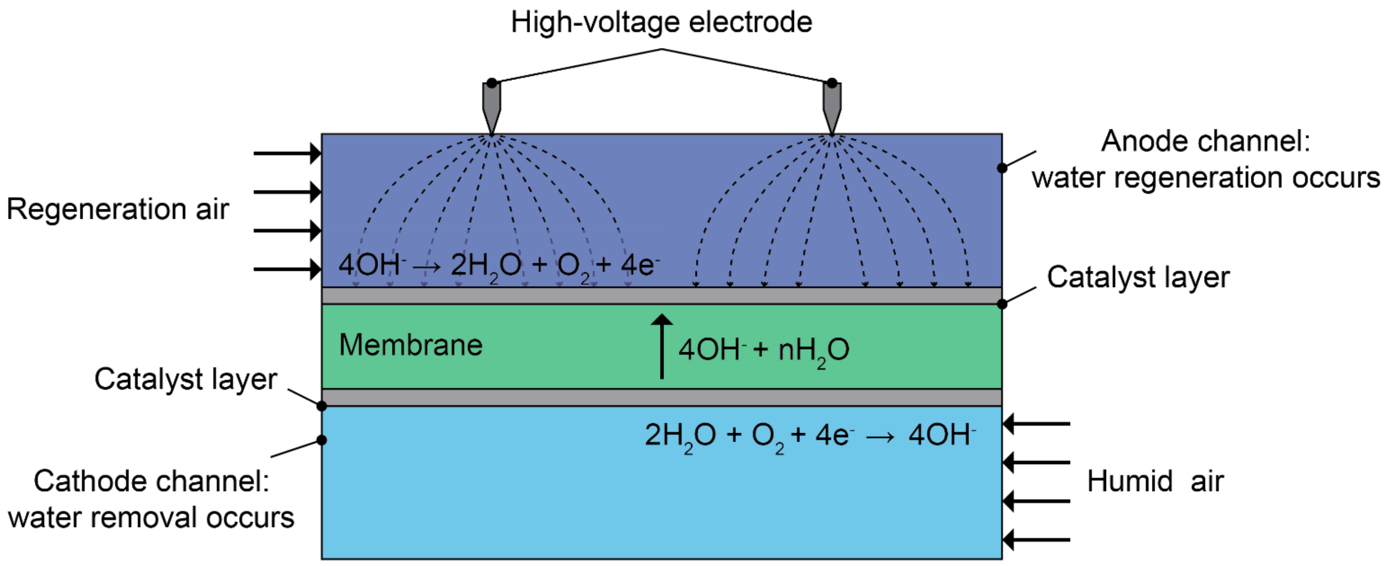
Electrohydrodynamic Enabled Electrochemical Dehumidification



Membrane Transport Phenomena



EHD Enhanced Water Transport

Performing Organization(s): University of Maryland, Daikin U.S.
PI Name and Title: Yunho Hwang, Research Professor
PI Tel and/or Email: 301-405-5247, yhhwang@umd.edu

CENTER FOR
ENVIRONMENTAL
ENERGY ENGINEERING

Project Summary

Timeline:

Start date: 06/01/2019

Planned end date: 11/30/2021

Key Milestones

- Laboratory-scale EHD/ECD Design Completed and Humidity Transfer Performance Determined; 06/15/2021
- ECD Stack Construction Completed; 07/15/2021
- Control Design Completed; 07/30/2021

Budget:

Total Project $ to Date:

- DOE: $ 1,000,000
- Cost Share: $250,000

Total Project $:

- DOE: $ 1,000,000
- Cost Share: $ 250,000

Key Partners

University of Maryland (Material Science)
Daikin U.S. (HVAC Systems)
Versogen (Membrane)
University of Delaware (Membrane)
SKYRE (Membrane)

Project Outcome:

The proposed project aims to design, develop, fabricate, evaluate, and optimize an advanced separate sensible and latent cooling (SSLC) air-conditioning (AC) system with an electro-hydro-dynamic (EHD)-enabled electrochemical dehumidification (ECD) system, resulting in a coefficient of performance (COP) improvement of 28% compared with a conventional AC system.

Team

CENTER FOR ENVIRONMENTAL ENERGY ENGINEERING

CREB CENTER FOR RESEARCH IN EXTREME BATTERIES

DAIKIN

- **PI: Yunho Hwang**
- **Center for Environmental Energy Engineering:** Energy efficiency, heat pump, heating and cooling systems
- **Key Members:**
  - Jan Muehlbauer (Experimental support)
  - Dr. Tao Cao (Modeling and control Support)
  - Joseph Baker (Main researcher)

- **Co-PI: Chunsheng Wang**
- **Center for Research In Extreme Batteries:** Electrochemistry, membrane
- **Key Members:**
  - Dr. Longsheng Cao (Membrane module design, development and optimization)

- **Chun-cheng Piao**
- **Daikin:** No.1 HVAC Manufacturer Globally
- **Industry partners:** System level design, evaluation and scaling; commercialization support

Challenge

Problem Definition: NZE building design results in a reduced sensible cooling load and a increased latent cooling load, but the energy efficiency enhancing AC design resulted in the latent cooling capacity degradation.

Project Goals: Our project aims to design, fabricate, evaluate, and optimize an advanced SSLC AC system integrated with a novel electrochemical dehumidification device to improve COP by 28% over a conventional VCS.

- Development of novel EHD-enabled ECD system for efficient latent cooling.
- Implementation of the sensible cooling VCS to provide the target sensible capacity at an elevated evaporating temperature.
- Development of controls to meet various sensible and latent cooling loads and optimization of all components.
- Concept validation through a laboratory prototype fabrication and experimental evaluations under a range of operating conditions.

Approach - Overview

Year-1: Develop the ECD, EHD and Sensible HE Design and Optimization

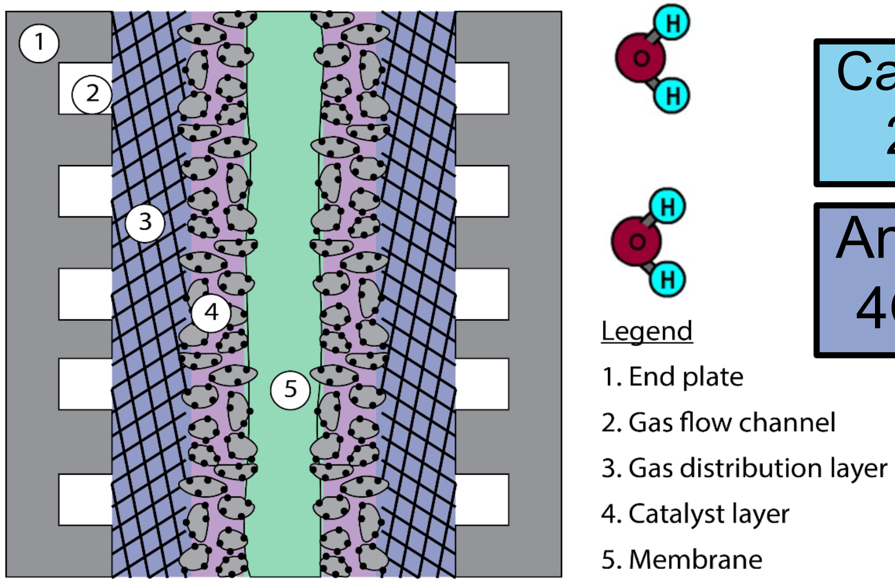
- *Development of Lab-scale ECD Prototype*
- *Development of EHD Water Vapor Transfer Device*
- *Development of EHDECD Prototype*
- *Development of Sensible Evaporator*
- *Market Transformation Plan*

Year-2: Design, Fabricate and Test of Prototype Heat Exchangers According to the Frameworks' Outputs

- *Development of Control Logics*
- *Construction of SSLC Test Facility*
- *Experimental Evaluation of the Novel SSLC AC system*
- *Improvement of System*
- *Market Transformation Plan*

Approach - Electrochemical Dehumidifier and EHD Flow

- Applied electric fields induce chemical reactions of water vapor and oxygen in the air, producing hydroxide
- Hydroxide crosses membrane, transporting water molecules
- No moving parts, no vibration



Cathode Reaction:

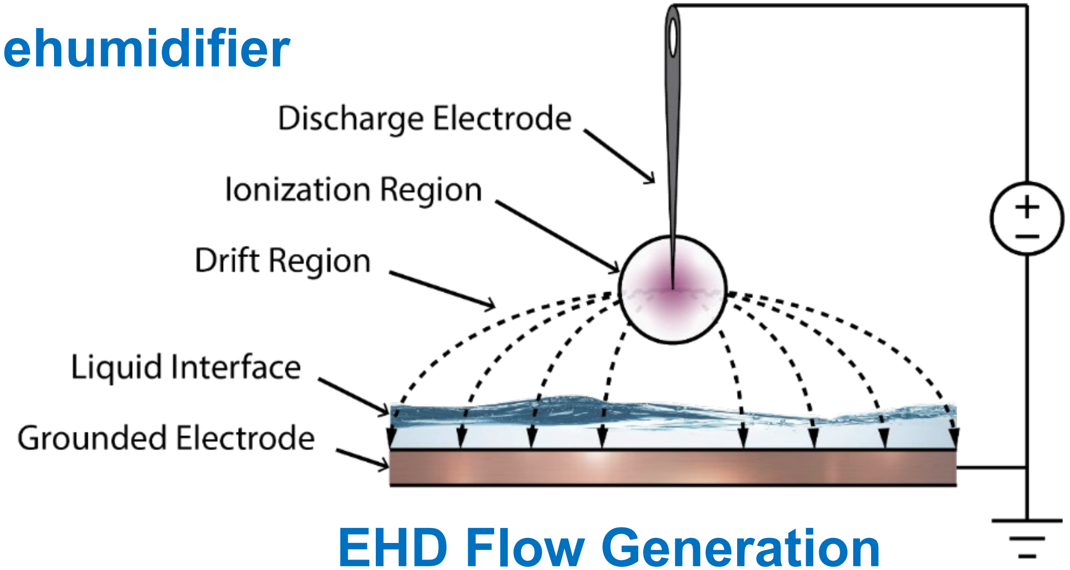
$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$

Anode Reaction:

$4OH^- \rightarrow 2H_2O + O_2 + 4e^-$

Electrochemical Dehumidifier

- High voltage source ionizes air molecules
- Ions collide with neutral particles, generating EHD flow
- Reactive gas flow is known as ionic wind
- EHD interactions affect rate of water evaporation



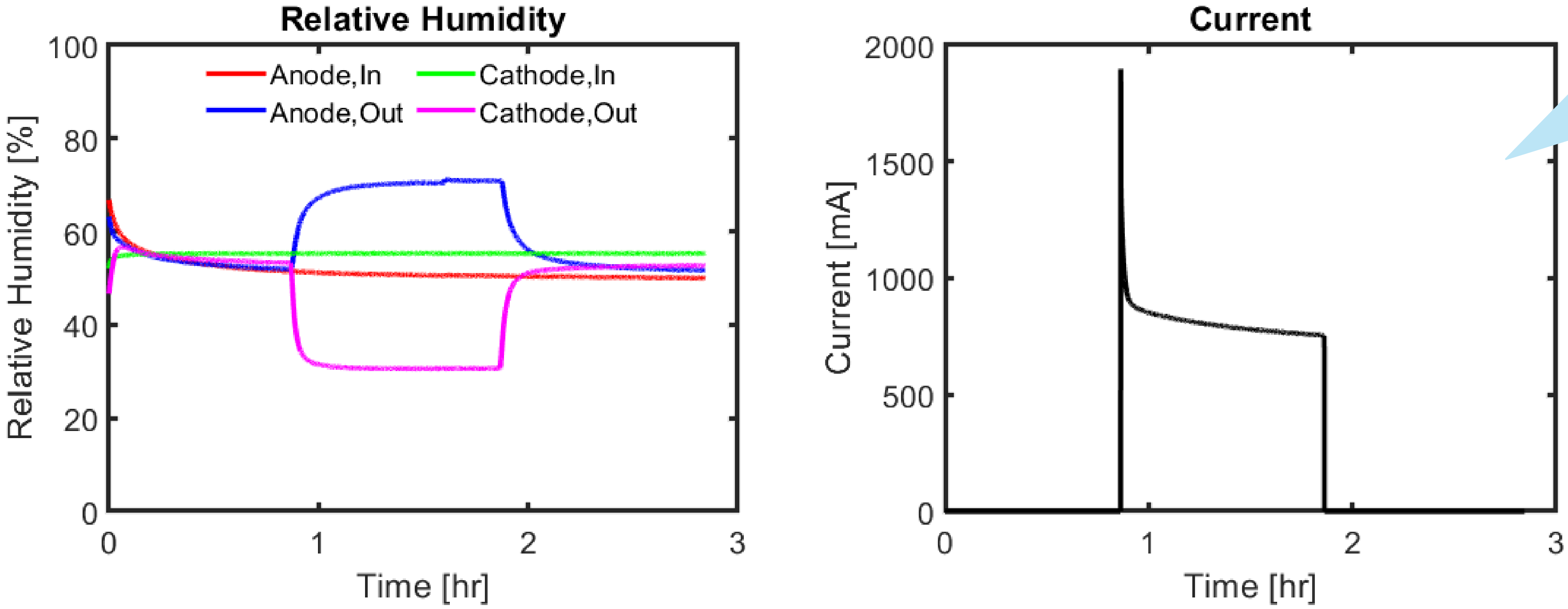
EHD Flow Generation

Impacts

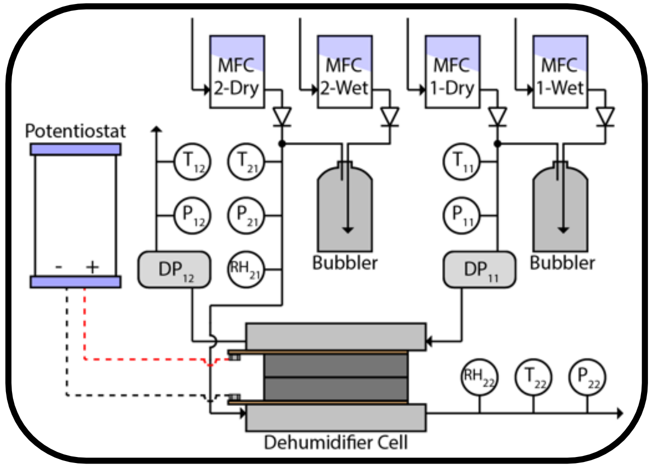
- **Technology Advancement**
  - Membrane module for state-of-the-art dehumidification performance
  - Integration mechanism of high voltage electrodes and membrane module
  - Innovative system level integration for cooling and dehumidification
- **Air conditioning Industry Impact**
  - Increase dehumidification capacity and efficiency of energy efficient cooling systems responding to high latent load applications like NZE buildings and humid climates
- **Energy Saving**
  - 28% COP enhancement (22% electricity savings) over conventional vapor compression systems at the same capacity
  - Applicable to residential and commercial building in all climate zones
  - Primary energy saving potential (nationally): 836 TBtu

Progress 1 – ECD Water Vapor Transfer Measurements

- **Small-cell moisture transfer**
- **Electrolytic transfer, neutral humidity gradient**



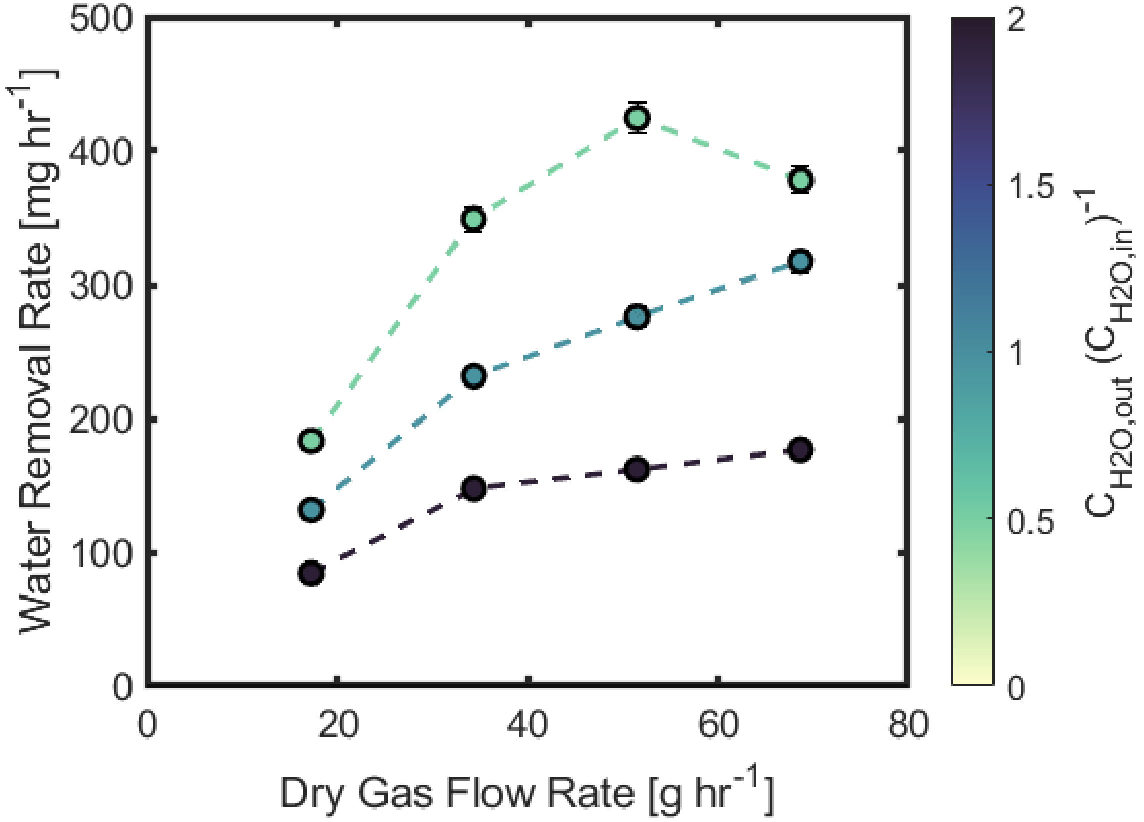
Moisture transfer occurs when current is non-zero

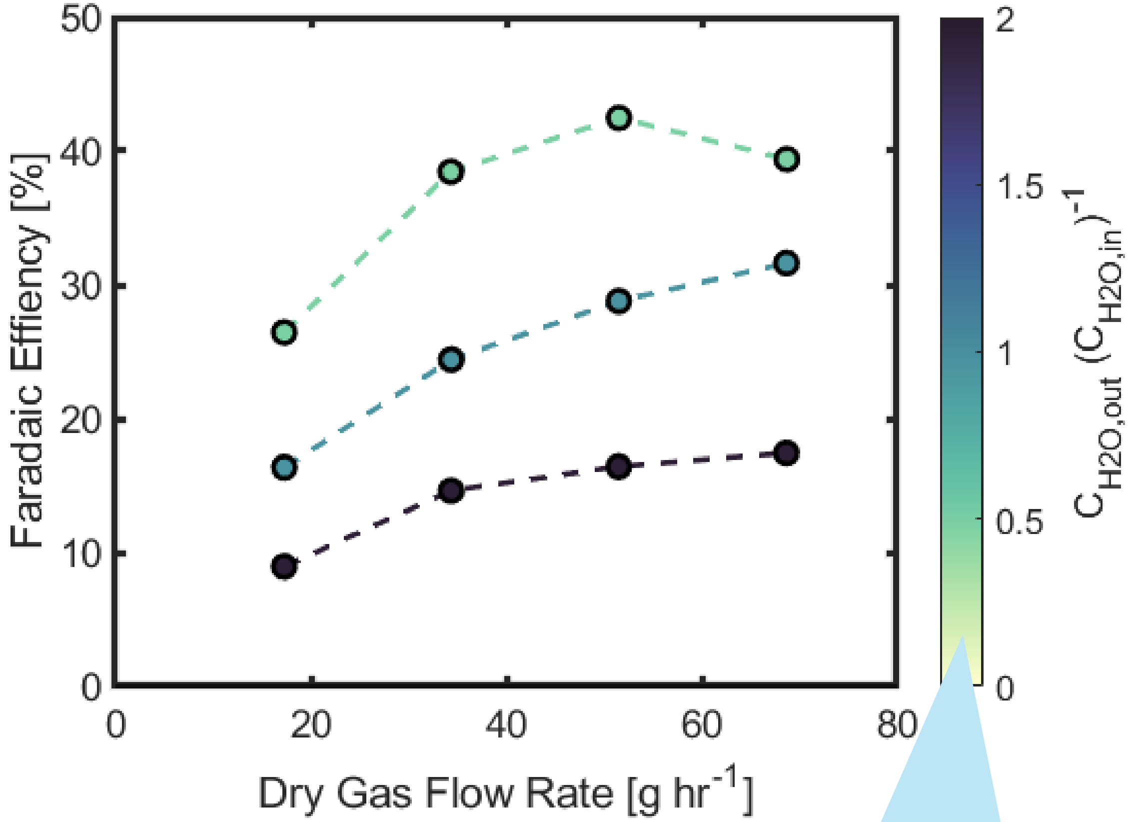


ECD Test Bench

Data set example: Relative humidity and cell current; Tests conducted under neutral moisture gradient at 2V applied potential.

Progress 1 – ECD Net Water Transfer and Energy Efficiency





Summary of Experimental Results
Tests conducted at 2 V applied potential using membrane with 50 cm^2 active area.

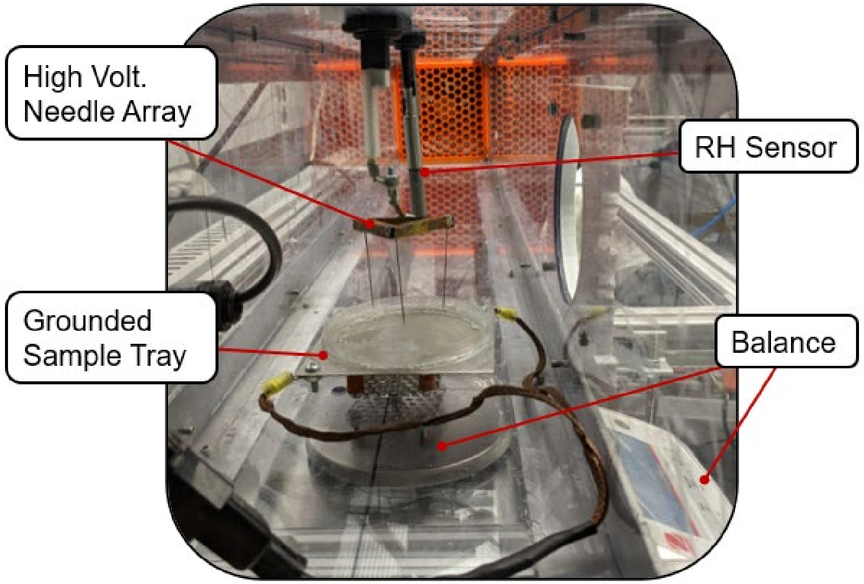
Faradaic Efficiency:

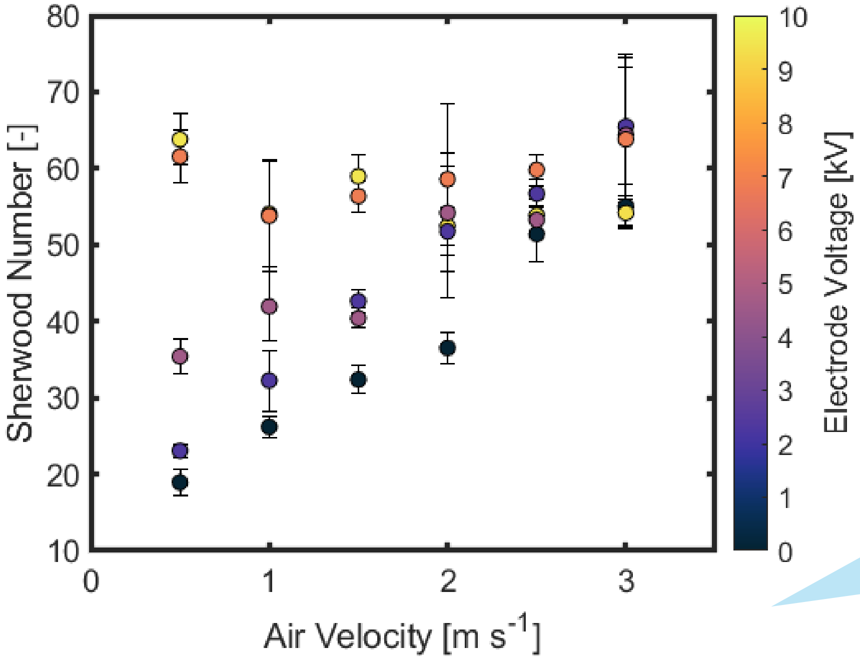
$$\eta_{far} = \frac{\dot{m}_{H_2O}}{\left(\frac{IM}{2F}\right)}$$

2 ⟶ adverse,
1 ⟶ neutral
0 ⟶ favorable

Progress 2 - EHD Mass Transfer Enhancement

- **Baseline effectiveness of EHD mass transfer enhancement**
- **Better enhancement at low air velocity, high electrode voltage**





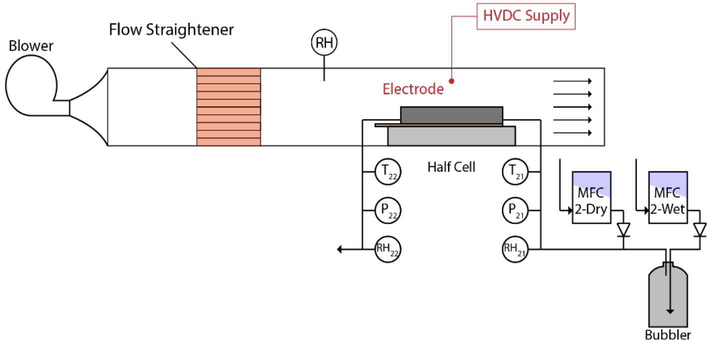
Sherwood Number: Ratio of convective to diffusive rates of mass transfer

Inertial forces dominate EHD force at high air velocity

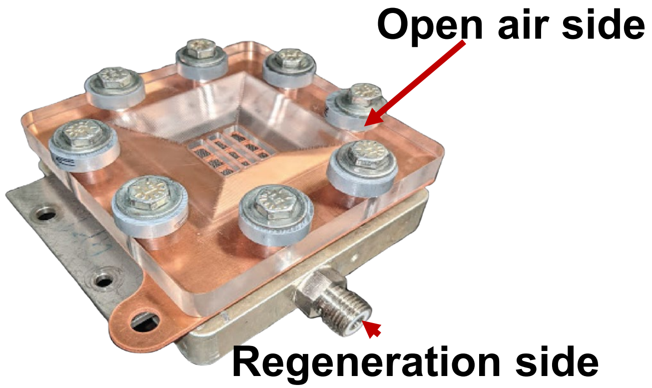
Multiple Needle Electrode: Prototype and corresponding experimental data from room-temperature drying experiments

Progress 3 - EHD-ECD Integration Experiments

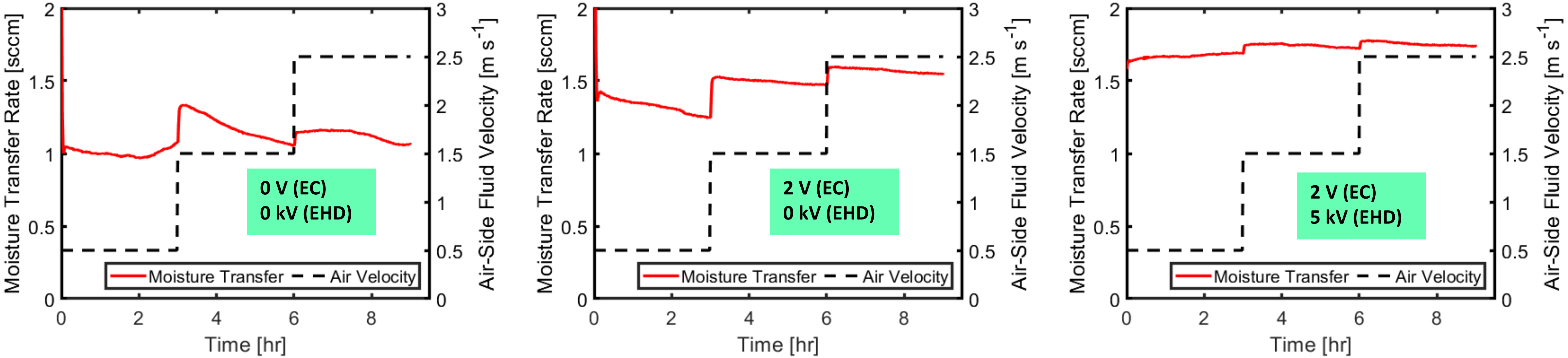
- **Constructed and open-air EC prototype**
- **Completed preliminary tests with applied voltages**



EHD Integrated ECD Device



Prototype of ECD Design

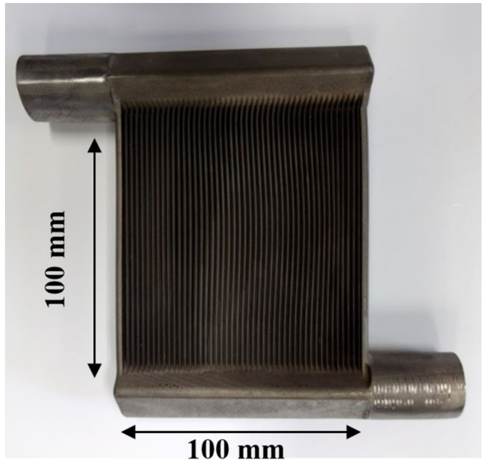


Preliminary Test Results: Comparison of effects of applied EC voltage and applied EHD voltage; Ambient conditions; 100 sccm inlet flow at 80% RH

Progress 4 - Sensible Evaporator Development

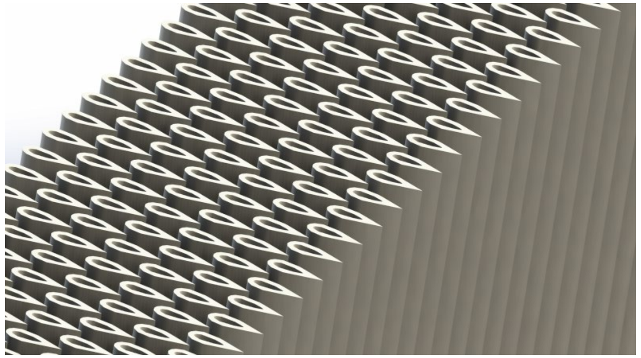
- **NTHX: NURBS Tube Heat Exchanger; Design Capacity: up to 1 kW; Material: Titanium**
- **Reliable data and verified numerical model; Achieved 11 K sensible cooling under desired sensible evaporation conditions with R-410A**

a)

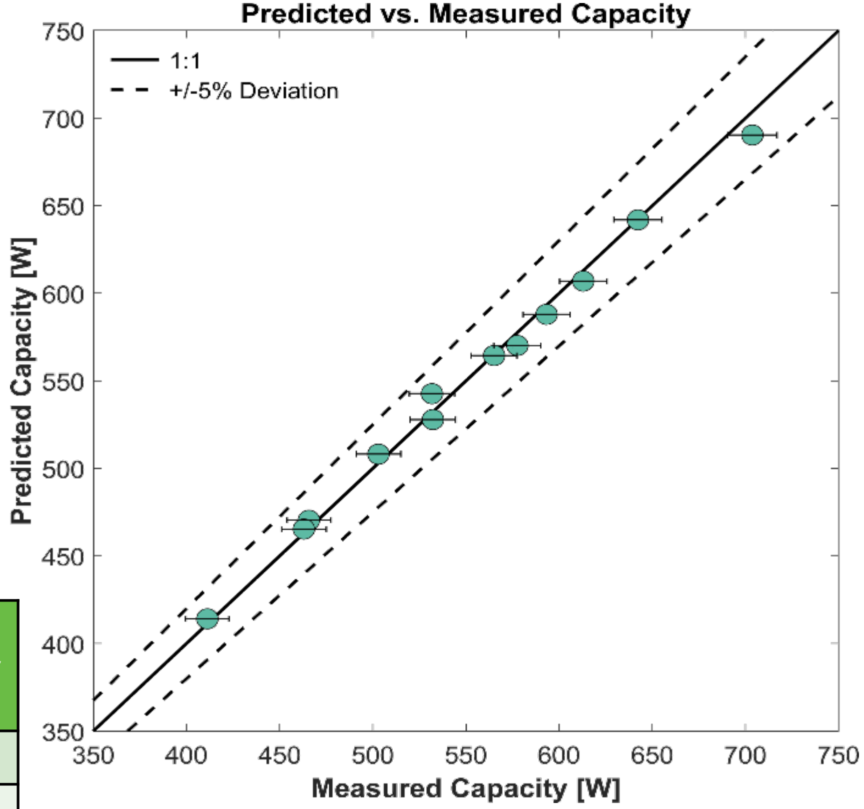


a) NTHX-001 3D-printed prototype

b)



b) NTHX-001 cross-section

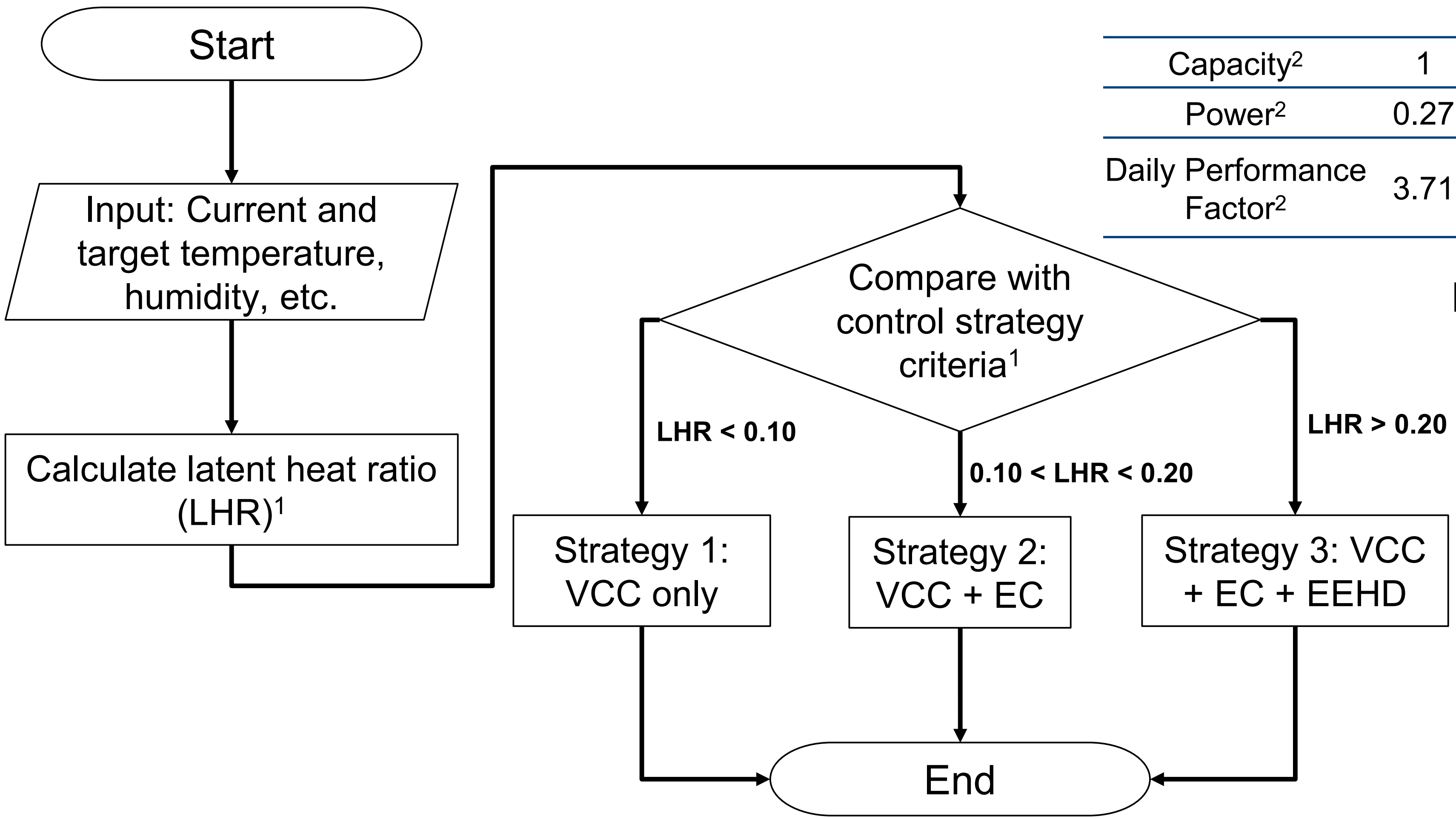


Capacity vs. Model Predictions

No	Air Inlet Temperature & Humidity[2]	Outlet Air Temperature	Ref. Inlet Temperature & Quality[3]	Inlet air V. [m/s]	Measured Airside Pressure Drop [Pa]	Measured Airside Capacity [W]
1	34.0°C / <20%	23.5°C	16.0°C / 0.33	3.7	66.3 ± 1.2	449.9 ± 11.5
2	34.0°C / <20%	22.7°C	14.0°C / 0.33	3.7	66.9 ± 1.2	493.9 ± 11.5
3	34.0°C / <20%	23.5°C	10.0°C / 0.30	6.4	157.4 ± 1.3	778.2 ± 19.7

Progress 5 - Control Logic Design

Flow Chart of the Control Strategy



Start

Input: Current and target temperature, humidity, etc.

Calculate latent heat ratio (LHR)[1]

Compare with control strategy criteria[1]

LHR < 0.10

0.10 < LHR < 0.20

LHR > 0.20

Strategy 1: VCC only

Strategy 2: VCC + EC

Strategy 3: VCC + EC + EEHD

End

Index	VCC	Proposed system (always on)	Proposed system (w/ control)
Capacity[2]	1	1	1
Power[2]	0.27	0.22	0.21
Daily Performance Factor[2]	3.71	4.50	4.73

Performance Comparison[3]

- **At least 5% improvements on the system performance with preliminary study on the control strategy.**
- **Will be validated with integrated EHDECD + sensible evaporator facility**

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1. LHR is one example for demonstration purposes. Alternatives can be temperature, time and combinations

2. First order analysis only with simplified assumptions as follows: a). All system fulfill same capacity, normalized as 1. b) Daily demands with low, medium and high LHR at 2/4/4 split; c). VCC COP at 4, 3.8 and 3.5 for different LHR, VCC + EC COP at 5.5, VCC + EC + EHD COP at 5.0

3. Based on first order analysis

Stakeholder Engagement

- **Team Partner (Early-stage):**
  - Dr. Piao from DAIKIN US having 26 years of industrial research experience in the field of building energy efficient technologies has involved in and reviewed our accomplishments and provided research feedbacks.

- **Team Partner (Mid-stage):**
  - We are cooperating with the University Delaware and SKYRE for membrane development and commercialization.

- **Industrial Partners Meeting (IPM) (Late-stage):**
  - Goal is ensuing our project to be a competitive novel technology based on feedbacks from industrial partners and potential further development and commercial deployment of the technology.
  - First IPM was held on March 9, 2021 with following participants: Daikin, Emerson, GE, HMC, Johnson Controls, LGE and Sanhua.
  - Planning to host the second IPM on Sep. 13, 2021

Remaining Project Work

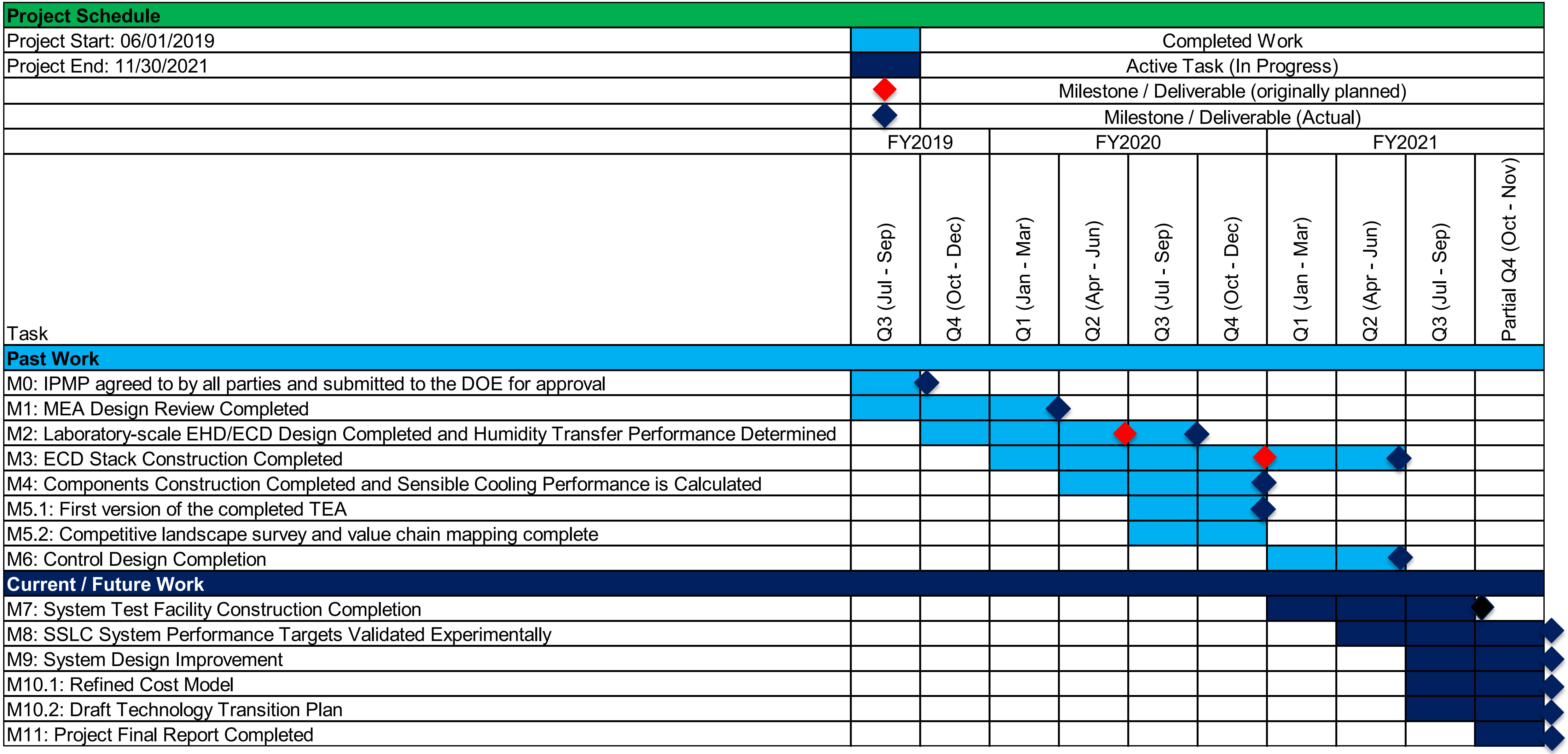
- **Task 7: SSLC test facility construction (In progress, 20%)**
  - A SSLC test facility that integrates existing EHD-ECD test facility, sensible evaporator prototype with newly constructed air loops
  - Expect full completion by late Sep. 2021
- **Task 8: Experiment evaluation of the novel SSLC system**
  - Comprehensive performance evaluations under various design conditions
  - Expect full completion by early Nov. 2021
- **Task 9: Improvement of the system**
  - Analysis and approaches for potentially a scaled up system
  - Expect full completion by late Nov. 2021
- **Task 10: Market transformation plan (In progress, 30%)**
  - Refined cost model and technology transition plan
  - Expect full completion by late Nov. 2021
- **Task 11: Final report:**
  - Submission by Nov. 2021

Project Budget

Project Budget: DOE 1,000,000, Costshare: 250,000
Variances: We made six-month no cost extension due to COVID-19 closures in 2020.
Cost to Date: DOE 1,000,000, Costshare: 250,000
Additional Funding: None.

Budget History					
06/2020 - FY 2020 (past)		FY 2021 (01-06) (current)		FY 2021 – 11/2021 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
710,430	163,046	1,000,000	250,000	1,000,000	250,000

Project Plan and Schedule



Project Schedule

Project Start: 06/01/2019

Project End: 11/30/2021

🟦	Completed Work
■	Active Task (In Progress)
♦	Milestone / Deliverable (originally planned)
◆	Milestone / Deliverable (Actual)

	FY2019		FY2020				FY2021			
Task	Q3 (Jul - Sep)	Q4 (Oct - Dec)	Q1 (Jan - Mar)	Q2 (Apr - Jun)	Q3 (Jul - Sep)	Q4 (Oct - Dec)	Q1 (Jan - Mar)	Q2 (Apr - Jun)	Q3 (Jul - Sep)	Partial Q4 (Oct - Nov)
Past Work										
M0: IPMP agreed to by all parties and submitted to the DOE for approval	🟦 ◆									
M1: MEA Design Review Completed	🟦	🟦	🟦 ◆							
M2: Laboratory-scale EHD/ECD Design Completed and Humidity Transfer Performance Determined		🟦	🟦	🟦 ♦	🟦 ◆					
M3: ECD Stack Construction Completed			🟦	🟦	🟦	🟦 ♦	🟦	🟦 ◆		
M4: Components Construction Completed and Sensible Cooling Performance is Calculated				🟦	🟦	🟦 ◆				
M5.1: First version of the completed TEA					🟦	🟦 ◆				
M5.2: Competitive landscape survey and value chain mapping complete					🟦	🟦				
M6: Control Design Completion							🟦	🟦 ◆		
Current / Future Work										
M7: System Test Facility Construction Completion							■	■	■ ◆	
M8: SSLC System Performance Targets Validated Experimentally								■	■	■ ◆
M9: System Design Improvement									■	■ ◆
M10.1: Refined Cost Model									■	■ ◆
M10.2: Draft Technology Transition Plan									■	■ ◆
M11: Project Final Report Completed										■ ◆

Thank You

Performing Organization(s): University of Maryland, College Park, Daikin U.S.
PI Name and Title: Yunho Hwang, Research Professor
PI Tel and/or Email:3014055247, yhhwang@umd.edu

REFERENCE SLIDES

Approach 1 - Water Vapor Transport Processes

- **Water moves through the membrane in three ways:**
  - Electrolysis (from chemical reactions)
  - Electroosmotic drag (dragging of water molecules from dipole forces)
  - Diffusion (physical diffusion)
- **Diffusion may work against direction of water transfer if outlet humidity is high**

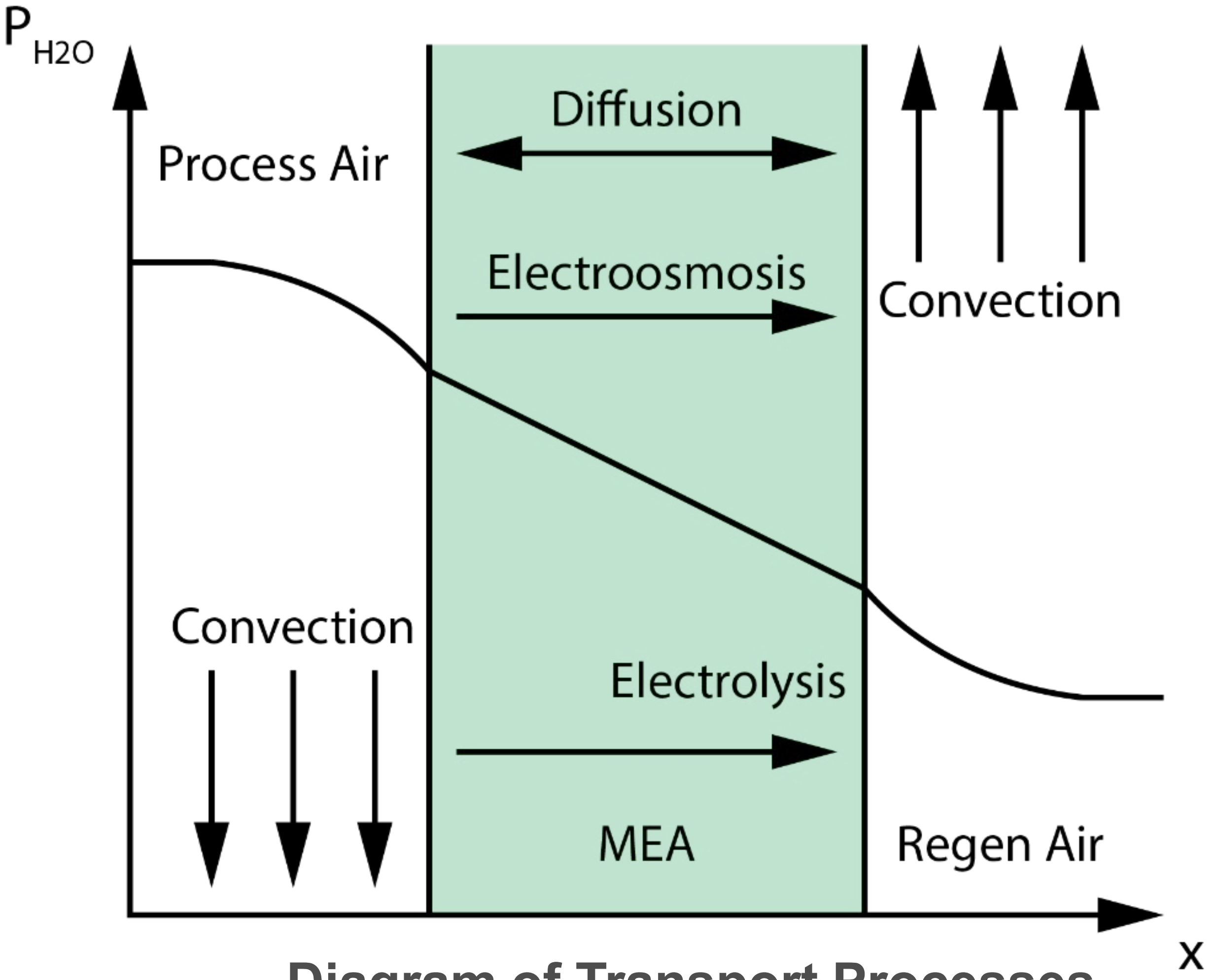
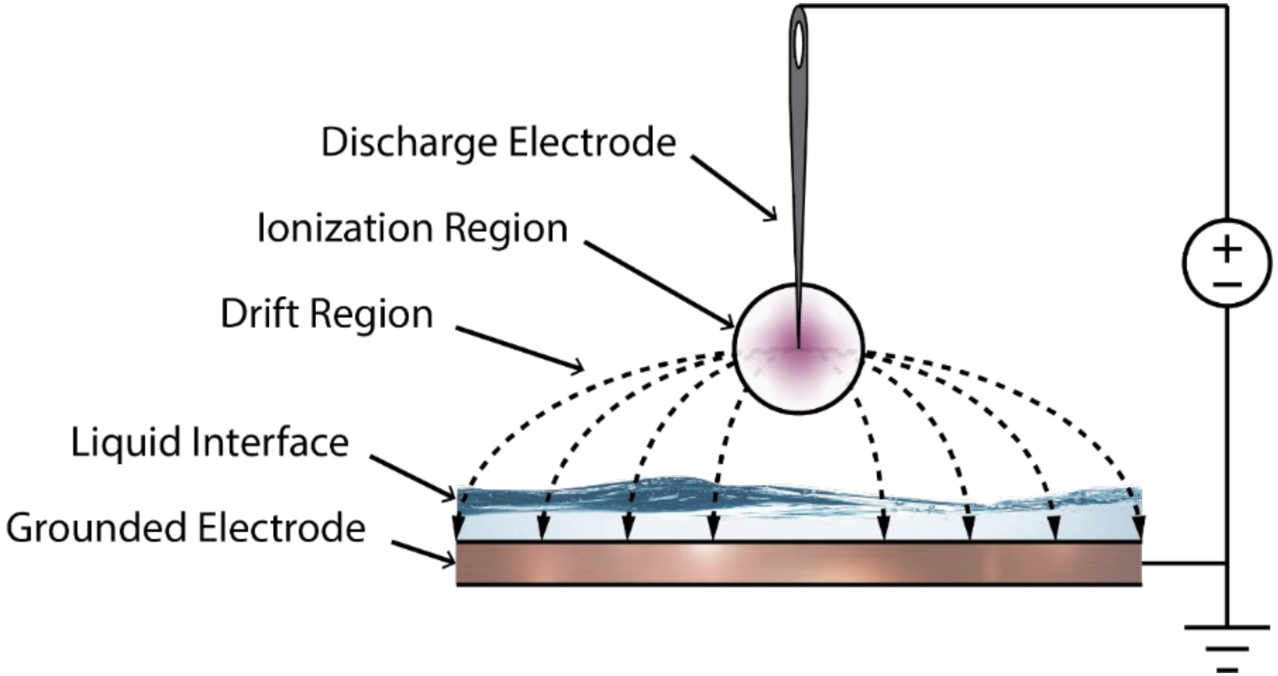


Diagram of Transport Processes

Approach 2 - Electrohydrodynamic (EHD) Force

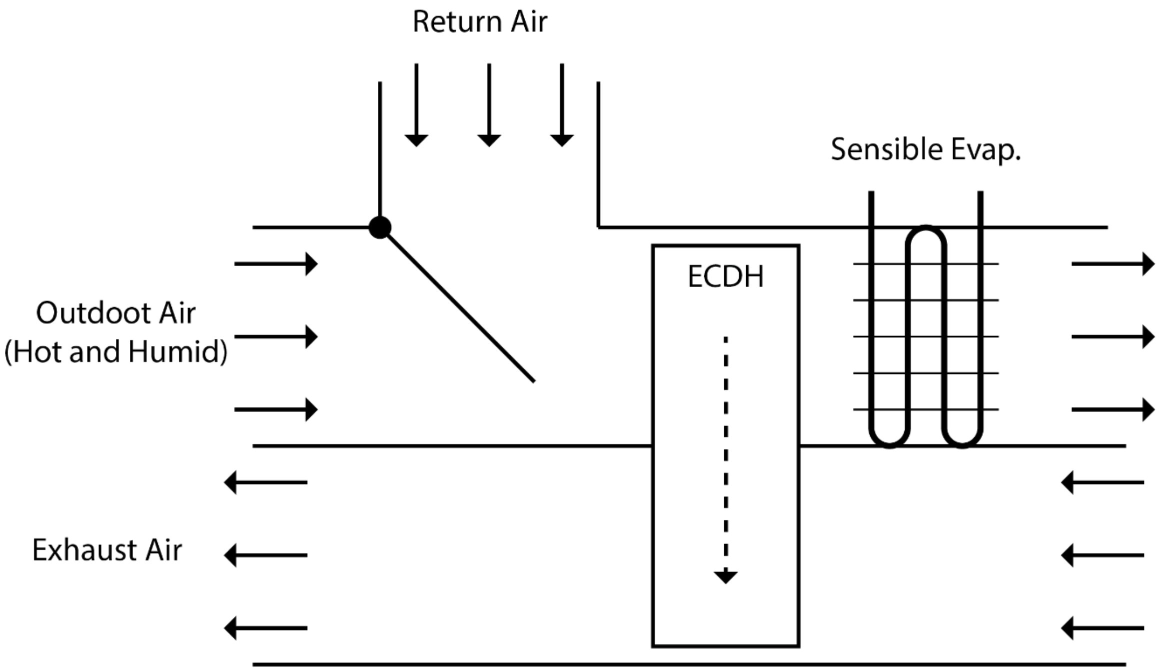
- High voltage source ionizes air molecules
- Ions collide with neutral particles, generating EHD flow
- Reactive gas flow is known as ionic wind
- EHD interactions affect rate of water evaporation



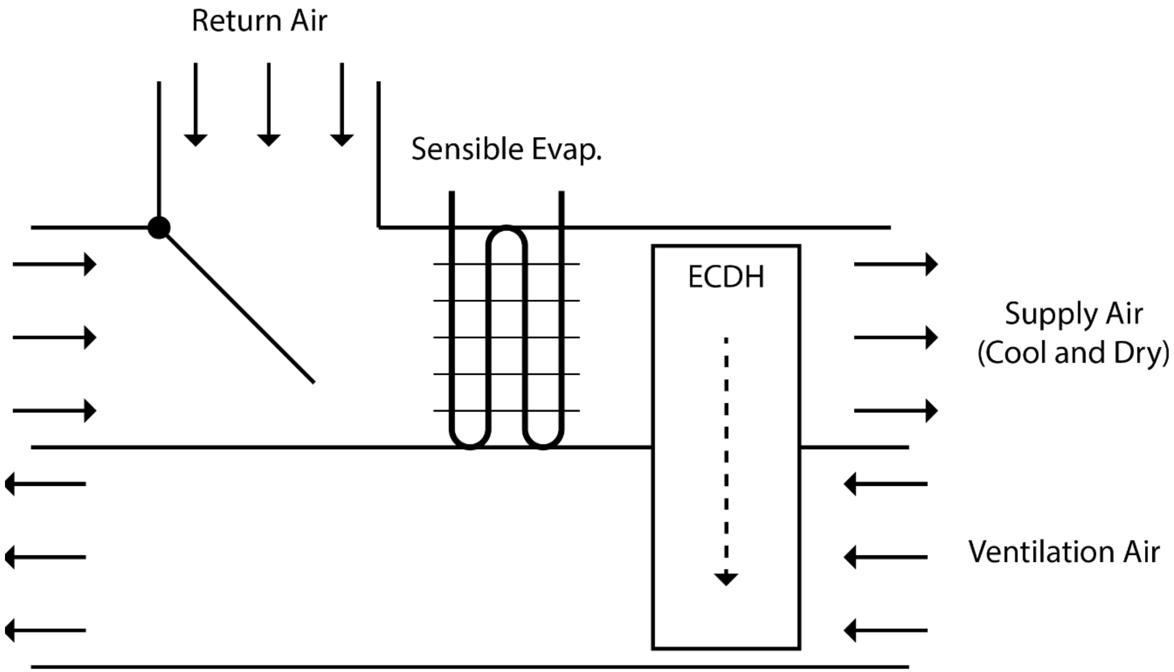
EHD Flow Generation
Point-to-plane EHD drying at the liquid-vapor interface

Approach 3 - System Integration (ECD + EHD + Sensible HX)

- **ECD performance affected by the location of the sensible evaporator**
- **Different amounts of outdoor air require different rates of dehumidification**



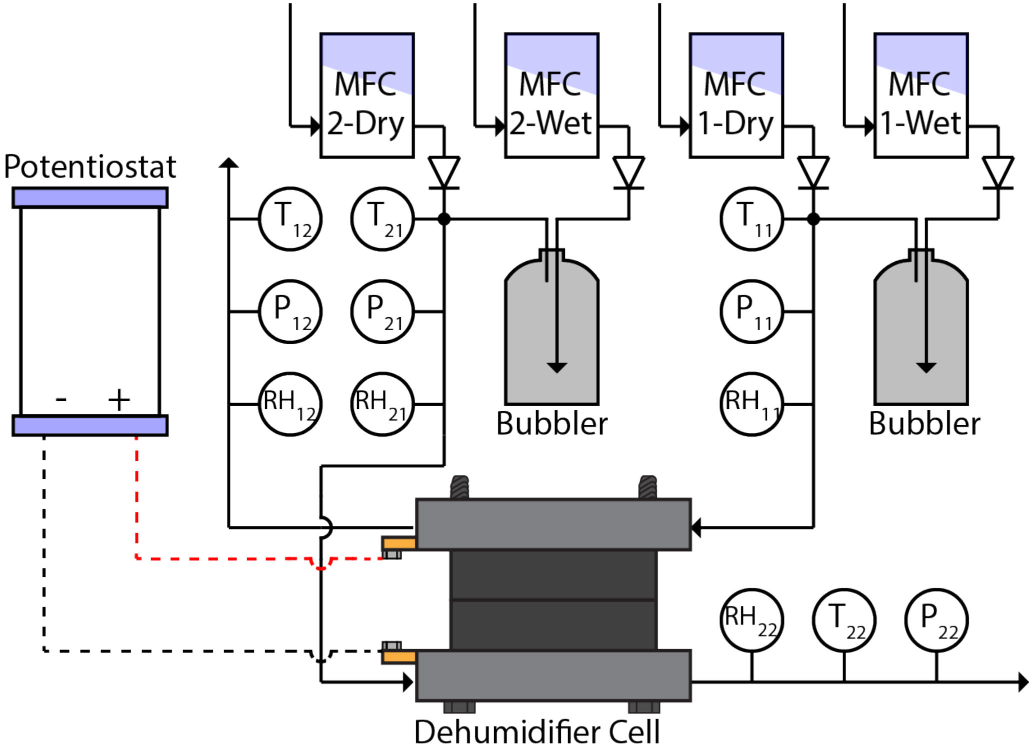
ECD used as latent evaporator, before sensible evaporator



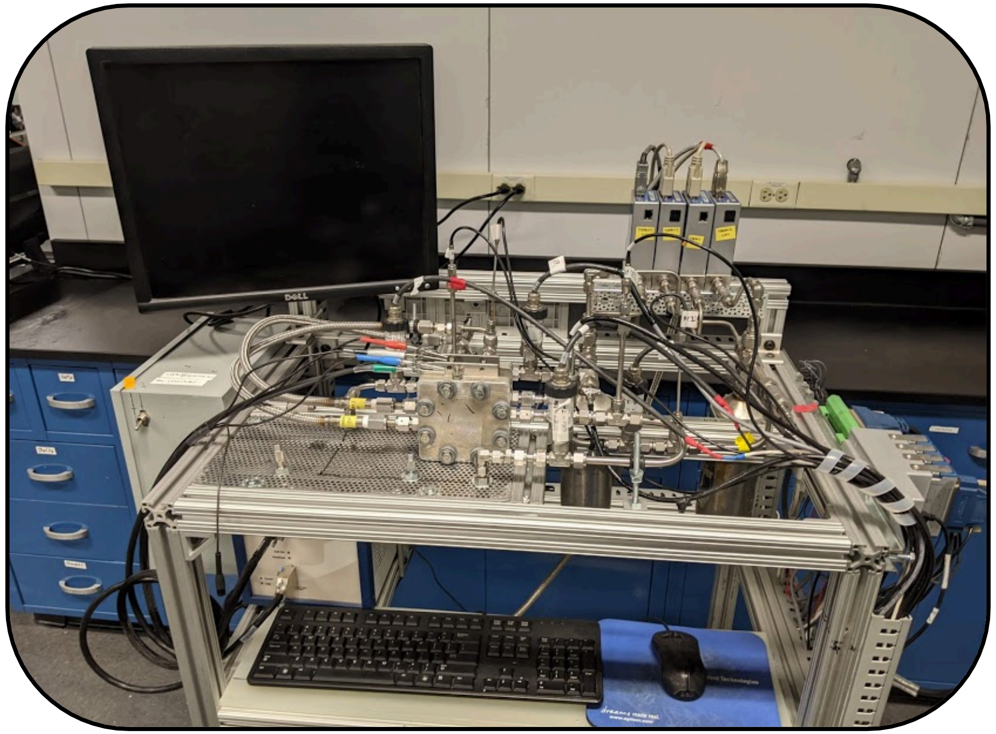
ECD used as latent evaporator, after sensible evaporator

Progress 1 – ECD Experimental Facility

- Built a test facility to measure EC membrane performance
- Control inlet flow rate and humidity



Schematic of ECD Test Bench



Photographs of Test Facility

Progress 1 - ECD Test Conditions

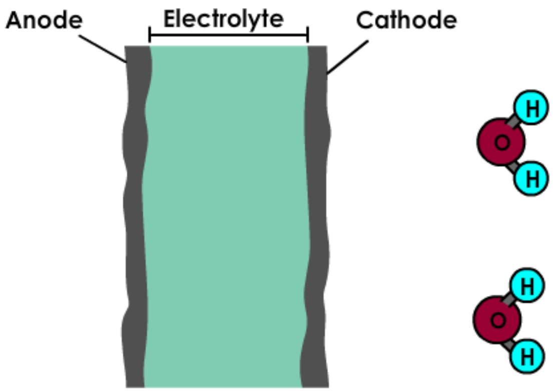
- **Evaluating the effects of several variables:**
  - Cathode humidity
  - Anode humidity
  - Cathode/Anode flow rate
- **Ambient temperature**
- **Slightly increased pressure to facilitate water transfer**

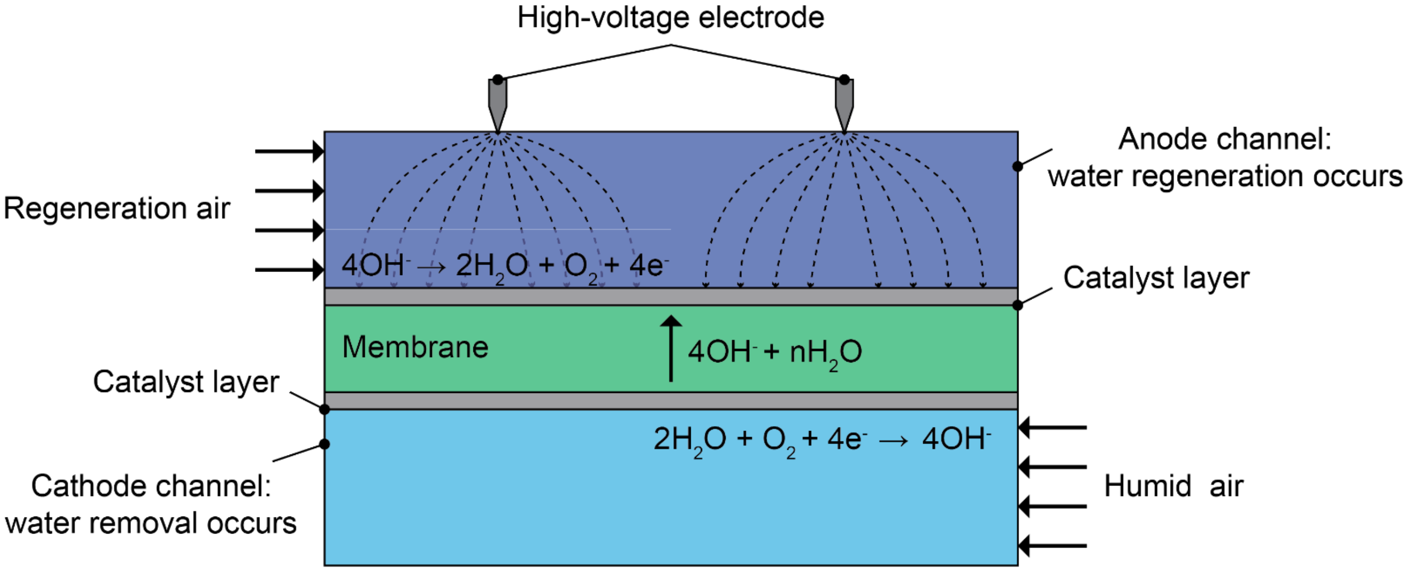
EC Dehumidifier Test Matrix

Cathode RH (%RH)	Anode RH (%RH)	Cathode Flow (sccm)	Anode Flow (sccm)	Temp. (°C)	Pressure (kPa)
80	40	100	100	25	125
60	60	100	100	25	125
40	80	100	100	25	125
80	40	200	200	25	125
60	60	200	200	25	125
40	80	200	200	25	125
80	40	400	400	25	125
60	60	400	400	25	125
40	80	400	400	25	125
80	40	800	800	25	125
60	60	800	800	25	125
40	80	800	800	25	125

Progress 2 - Dehumidification Enhancement by EHD

- EC water transport may be inhibited by mass transfer resistance
- Possible to improve via Electrohydrodynamic (EHD) enhancement
- High voltage field creating “electric wind” increases mass transfer

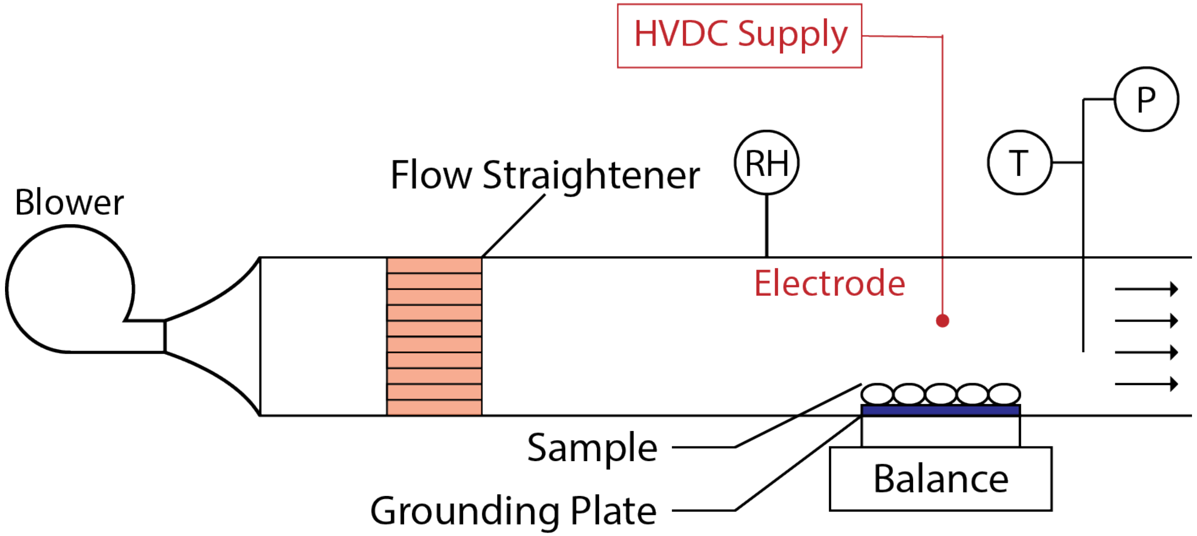




EHD Mass Transfer Enhancement

Progress 2 - EHD Mass Transfer Test Facility

- **Built a test facility to measure EHD performance**
- **Control inlet flow rate and humidity**



Schematic of EHD Test Section

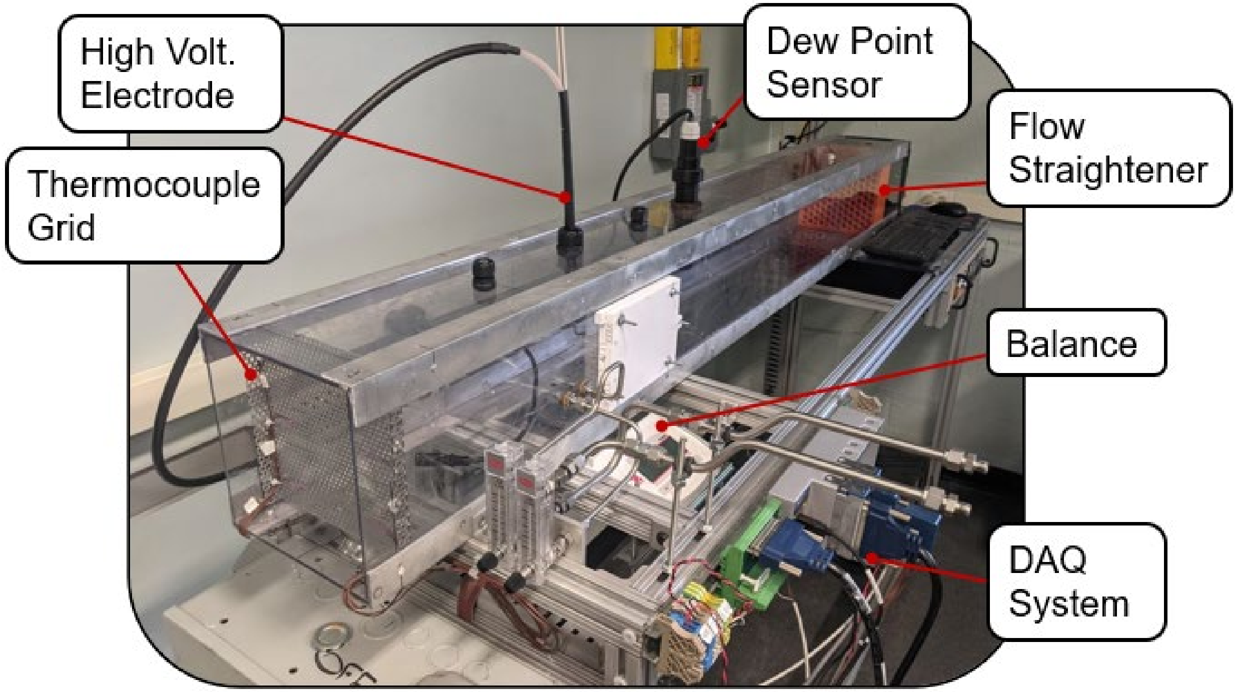
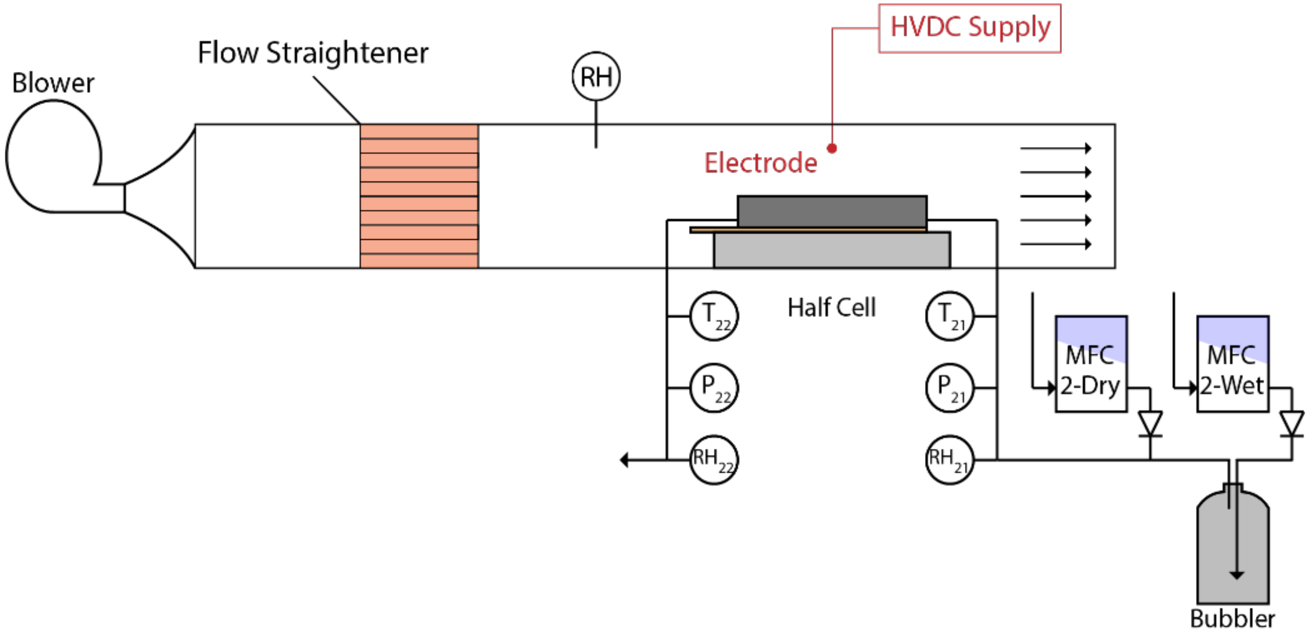


Photo of the Test Section

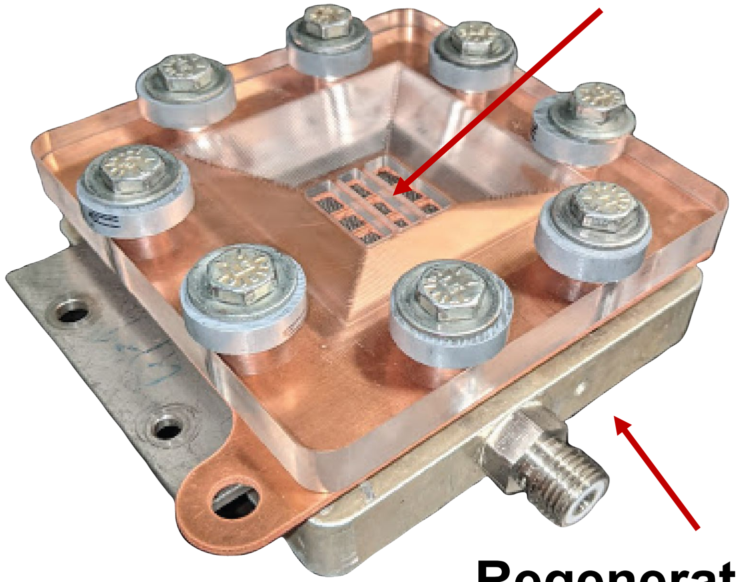
Progress 3 - EHD Integration with ECD

- Place open-air EC in EHD test facility
- Control air flow and humidity on both sides of membrane



Schematic of EHD Integrated ECD Device

Open air side



Regeneration side

Prototype of ECD Design

Progress 5 - Cost Modeling

- Determining cost of ECD-EHD system for air conditioning applications
- Depends on ECD performance
- Membrane area requirement depends on desired latent capacity
- Larger systems require more membrane area

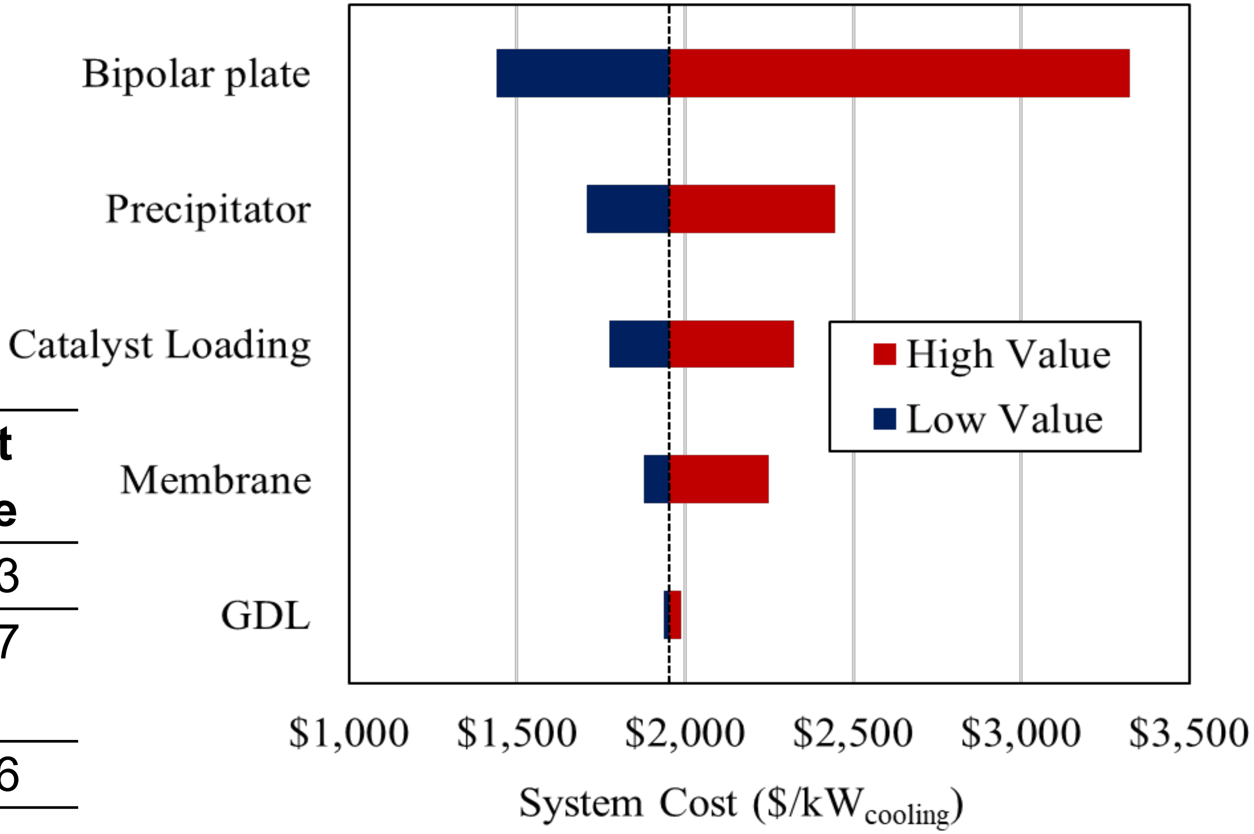
Cost Modeling Parameters

Characteristic	Unit	Base Value
Rate of Water Flux	$mg/m^2/s$	15
Bipolar Plate		
Bipolar plate density	kg/m^3	8000
Bipolar plate thickness	um	1000
Bipolar plate cost	$/kg	17.50
Catalyst		
Pt catalyst loading	mg/cm^2	0.125
Pt cost	$/g	49.66
Membrane		
Membrane cost	$\$/m^2$	15.90
GDL		
Woven Carbon	$\$/m^2$	5.91
Precipitator		
System cost	$/unit	493.99

Progress 5 - Parametric Cost Analysis

- Determine most significant parameter determining system cost

Parameter	**Unit**	**Worse Case**	**Base**	**Best Case**
Water Flux	$g/m^2/s$	0.015	0.009	0.023
Bipolar Plate	Cost Multiplier	1	1.5	0.667
Pt Loading	mg/cm^2	0.125	0.144	0.106
Membrane	Cost Multiplier	1	2	0.5
GDL	$\$/m^2$	5.91	6.7965	5.0235
Precipitator	Cost Multiplier	1	2	0.5



Cost Sensitivity to Key Parameters