Separating Sensible and Latent Cooling with Electrically Charged Rotating Vortexes and Vapor Capturing Air Handler Technology

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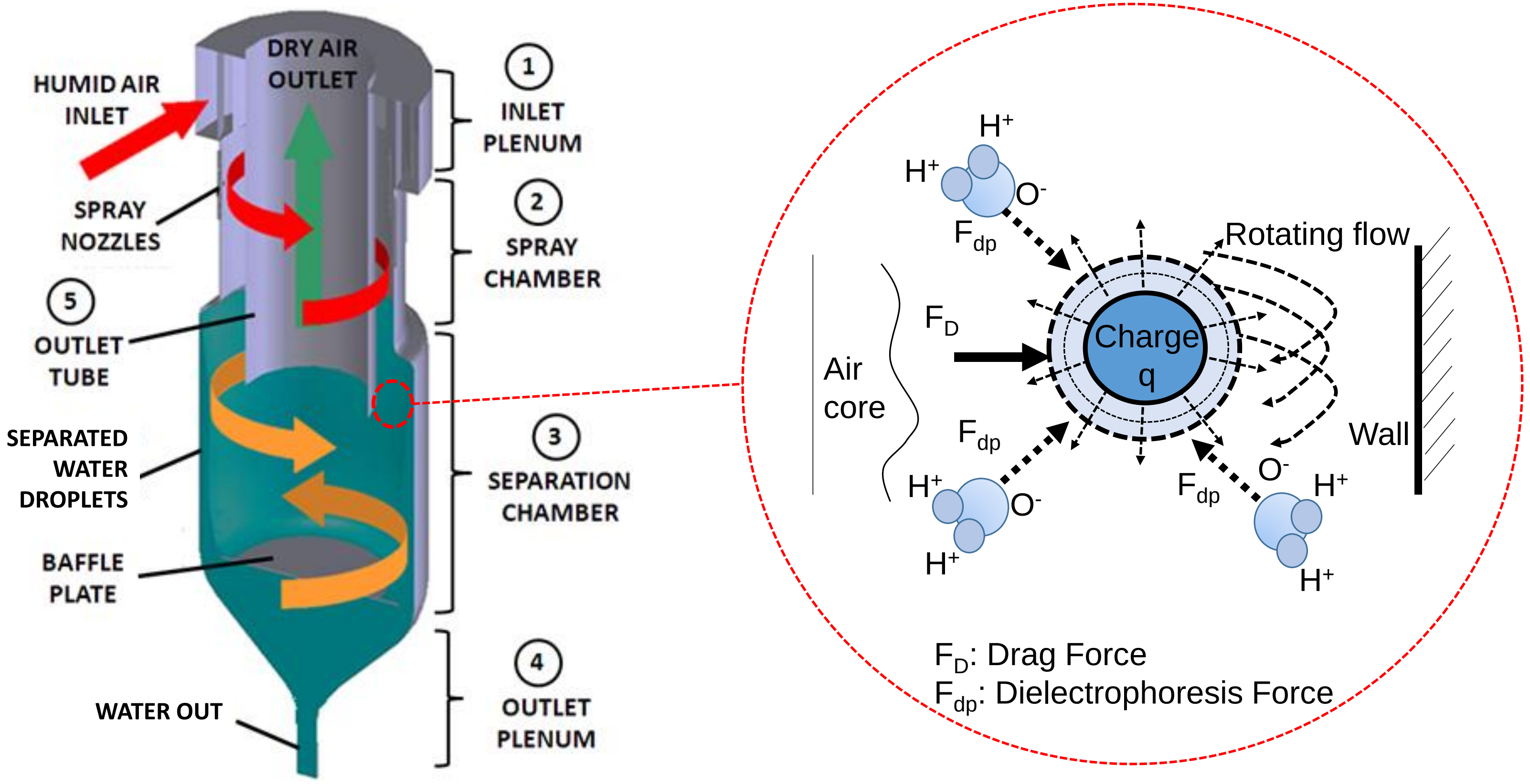


Project Summary

Timeline:

Start date: April 1, 2020

Planned end date: September 30, 2023

Key Milestones

1. Design electrospray Emitter, March 2021
2. Proof-of-concept tests for 5 cfm; achieve 5% Dehumidification, March 2023
3. Optimization and scale up to 200 cfm, Dec 2023
4. Technology Demo Unit, April 2024

Budget:

Total Project $ to Date:

- DOE: $1,015,126
- Cost Share: $259,030

Total Project $:

- DOE: $1,457,470
- Cost Share: $372,479

Key Partners:

Advanced Cooling Technologies, Inc.
Johnson Control Inc.

Project Outcome:

To develop and test Electrospray Vortical Flow eXchanger (EVFX) capable of flow rates of ≥200 cubic feet per minute (cfm) and ≥10% relative humidity to enable water vapor separation systems for separating sensible and latent cooling in heating, ventilation, and air conditioning (HVAC) systems.

Problem

U.S. Residential and Light Commercial building sector → over 40 Quads of primary energy

HVAC ~ 40% of total energy consumption and 28% is for space cooling

Space cooling using conventional air-conditioning → sensible load and latent load

In warm and humid climates → need low AC system dew point

- Temp too low for thermal comfort (reheat might require)
- Low COP

Separate Sensible and Latent Cooling (SSLC) A/C systems, specifically technologies that have high performance under extreme conditions (i.e.,above 60% relative humidity) have potential to save 30% of energy when compared with a conventional baseline system.

Alignment and Impact

The Emerging Technology Program (ETP) has identified the goal of supporting the development of cost-effective technologies capable of reducing the energy use of typical buildings by 45% by 2030, relative to high-efficiency technologies available in 2010.

BTO is seeking transformational non-vapor compression HVAC technologies to move beyond refrigerants, including hybrid technologies that are not purely based on vapor compression technologies.

BTO is also interested in enhanced dehumidification capabilities that can operate at partial load or at lower cooling set points.

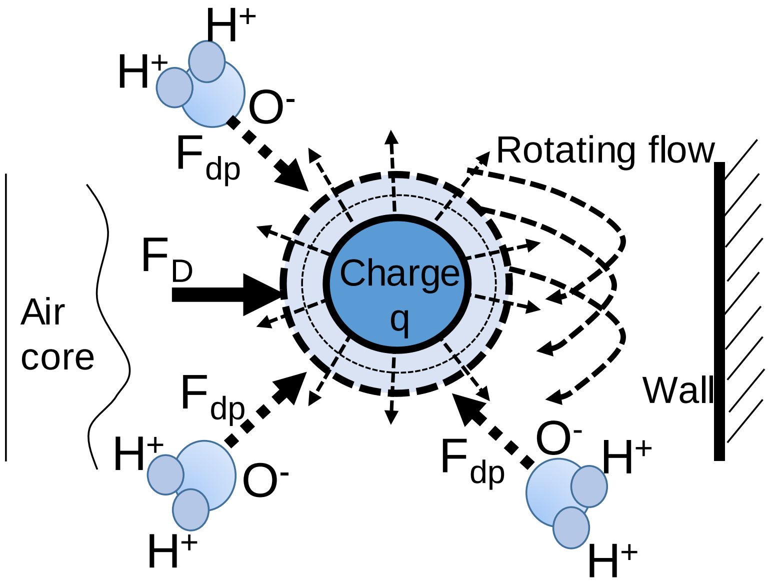
BTO identified system performance targets and desirable characteristics at part-load performance, including:

- Seasonal $COP_{cooling}$ = 12.3
- Net zero water consumption
- Reduced size and/or weight relative to today’s high efficiency units
- Readily available materials

Approach

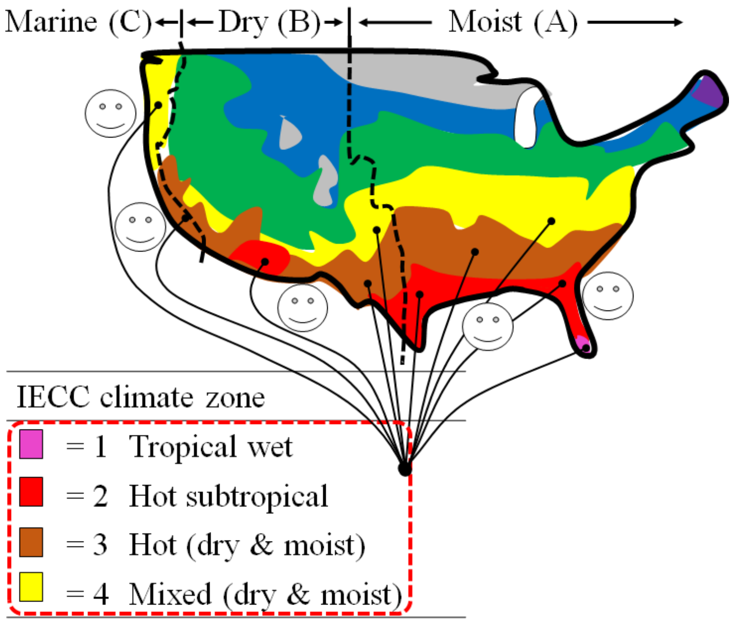
Our proposed EVFX is, in our opinion, an innovative separation technology that aligns well with ETP goal.

It separates and converts latent loads into sensible loads by using electrostatic energy and centrifugal force.



Electrospray Vortical Flow eXchanger (EVFX) consists of small electrically charged water droplets released inside air vortexes. The charged droplets attract water vapor molecules, effectively wiping out the humidity from the air. As the vapor molecules collapse on the droplets surface, the droplets initial electrical charge decreases with time due to the neutralization of the ions. Large droplets are collected at the outer wall of the vortexes and then they are re-utilized in the electrosprays.

It works well in:



This is a low TRL, high risk, and disruptive technology.

This project moves from the current TRL-2 (i.e., technology concept and application formulated) to TRL-5 (i.e., laboratory scale, similar system validation in relevant environment)

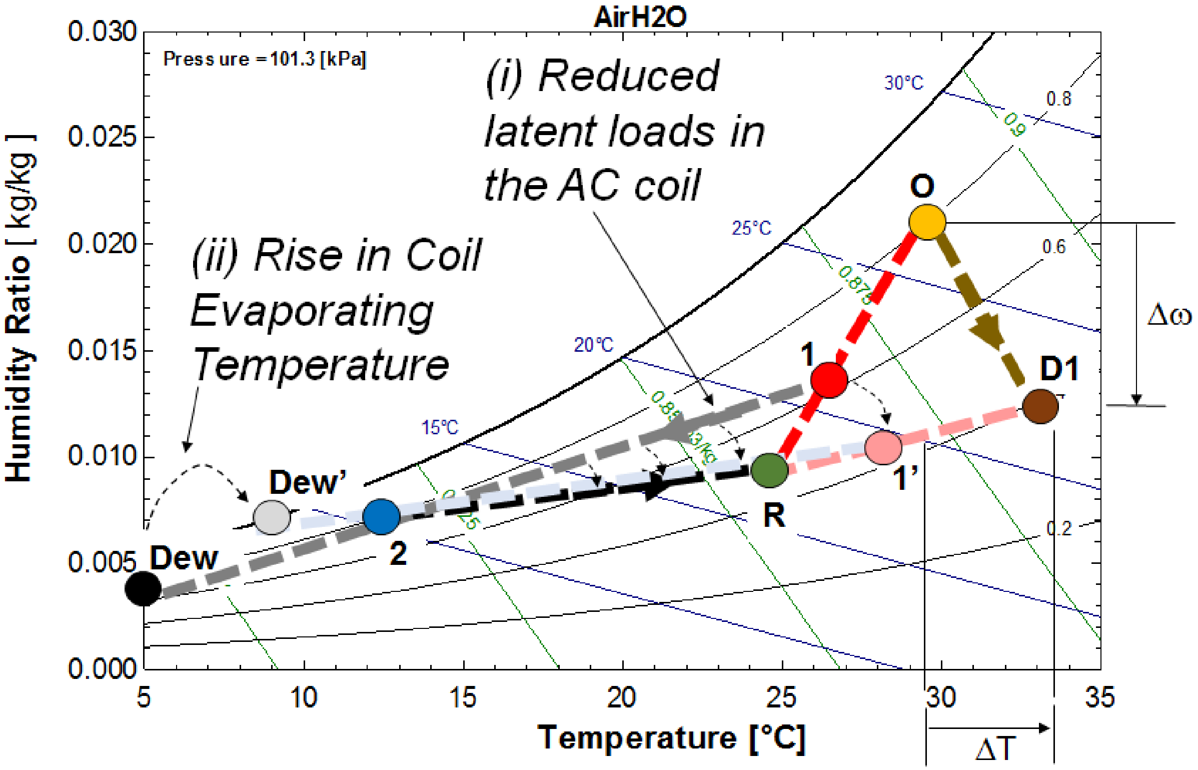
Impact

Technology Impact:

- “Not-In-Kind” AC dehumidification
- No toxic, no corrosive, no water consumption
- Integrate well with existing HVAC air handler
- Unit energy savings ranging from 15% to 39% as a result of (i) reduced latent load on evaporator coil and (ii) higher evaporating temperature
- Technical energy savings potential of 0.6 Quads
- For consumers, reduction in the annual cost of AC and improved air quality (clean dust, smoke, odors).

In addition:

- EVFX made of plastic and steel inserts
- Smaller/lighter evaporator coils
- Nozzles are readily available in the market



Metric Description	EVFX Metric
Primary Energy Savings	576 TBtu
Seasonal Coeff. of Performance (COP) $_{\text{Cooling}}$ $^{(2)}$	≥12.3
Installed cost $^{(1)(3)}$	≤ $2,500/unit
Installed cost per cooling unit $^{(1)}$	≤ $12/kBtu/h

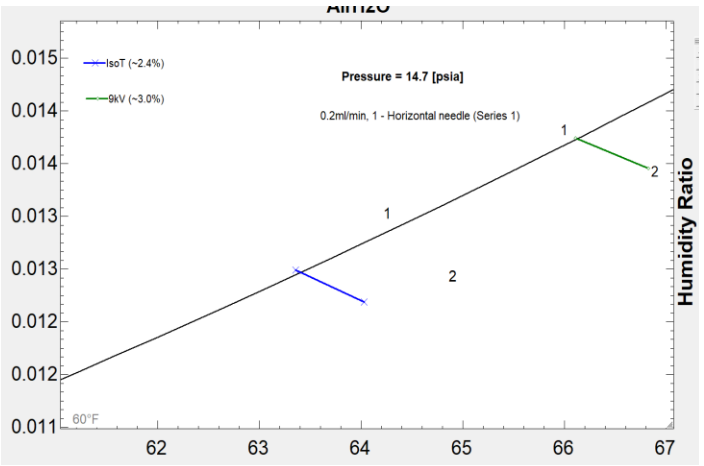
Note $^{(1)}$: Measured in 2019$
Note $^{(2)}$: Average across 57.5^{o}F to 100.4^{o}F in Climate zone 3A
Note $^{(3)}$: Average between residential ($6K) and commercial

Project Status

Three Phases / Three Budget Periods (BPs)

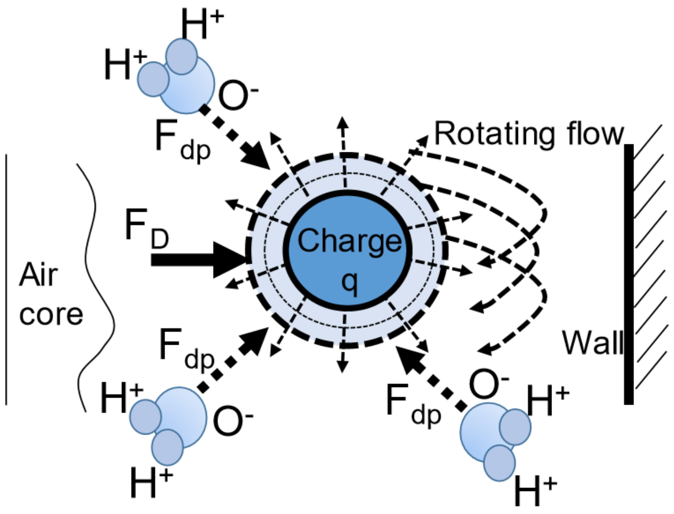
BP 1: Develop New Electrospray Emitter
BP 2: Test First EVFX Prototype and Optimization
BP 3: Develop EVFX Technology Demo Unit

- ✓ Modeled vapor capturing process by electrostatic water droplets
- ✓ Designing proof-of-concept EVFX prototype for low air flow rates (5 cfm)
- ✓ Manufacturing of EVFX prototype and assembly of the new electrospray
- ✓ Instrumentation of EVFX prototype and calibration
- ✓ Proof-of-concept tests for 5 cfm;
- ✓ Achieve measurable (> 2%) Dehumidification; (desirable target would be 5%).
- • Optimization and scale up to 200 cfm
- • Technology Demo Unit
- • Scale-up analysis and integration with air handlers for commercial building applications

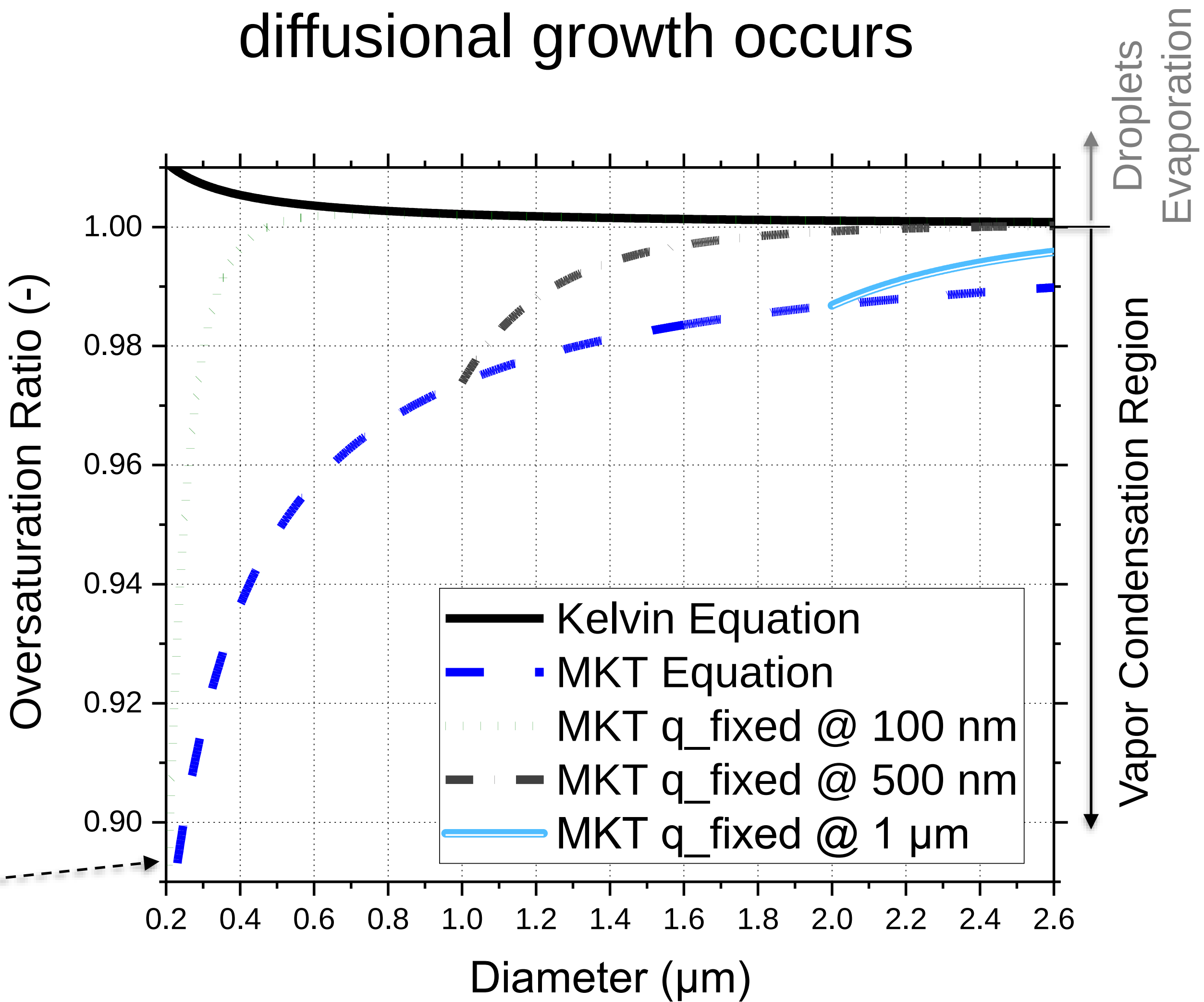


Progress – Vapor Condensation Thermodynamic Model

$P_{equilibrium\ @\ droplet\ surface}$ evaluated by the Modified Kelvin-Thomson (MKT) equation

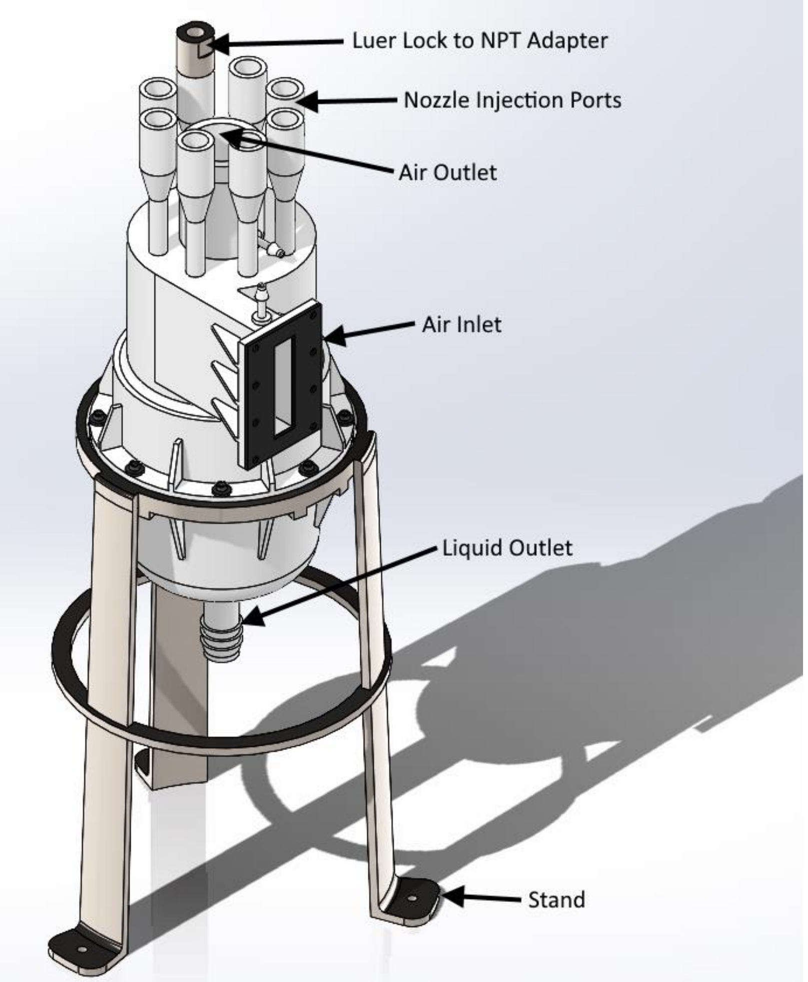


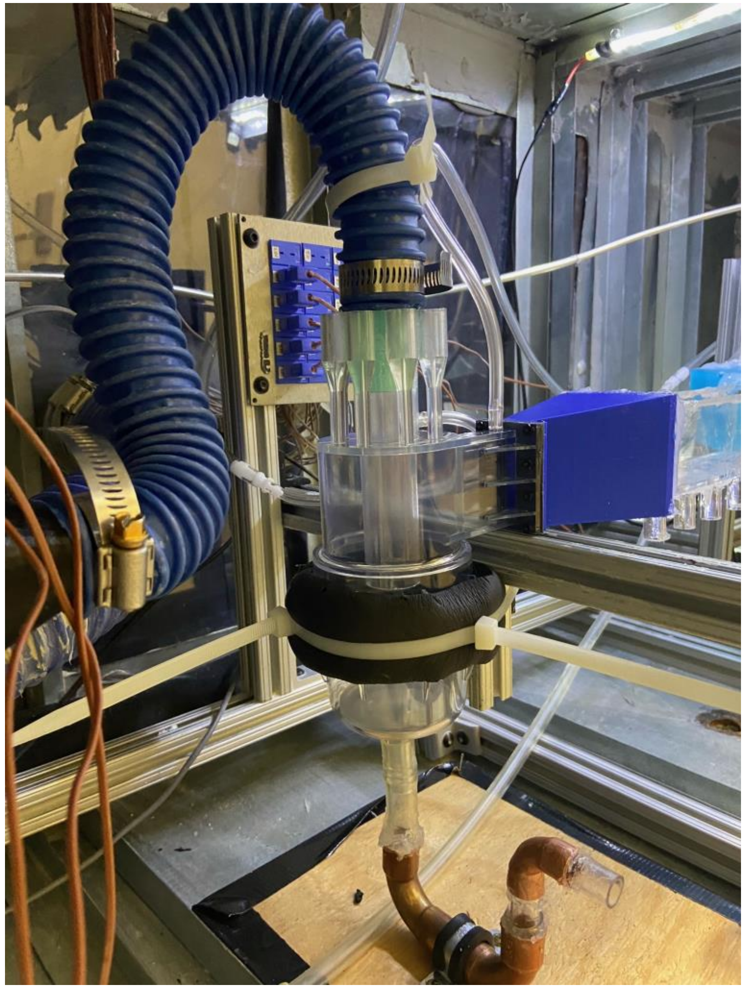
If $P_{bulk,air} > P_{equilibrium\ @\ droplet\ surface}$ diffusional growth occurs



Maximum electric charge dictated by the Rayleigh limit: $q_{Rayleigh} = 8\pi\sqrt{\varepsilon_0 \sigma R^3}$

Project Status – Prototype and Electrospray Emitter





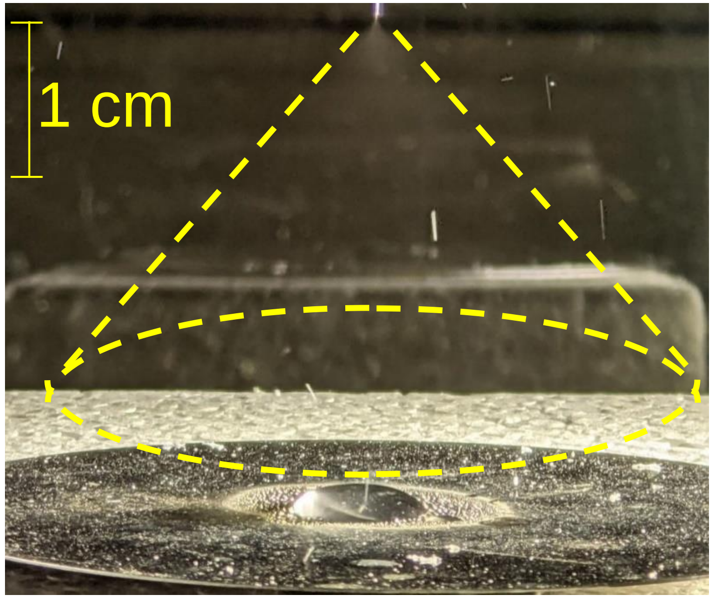
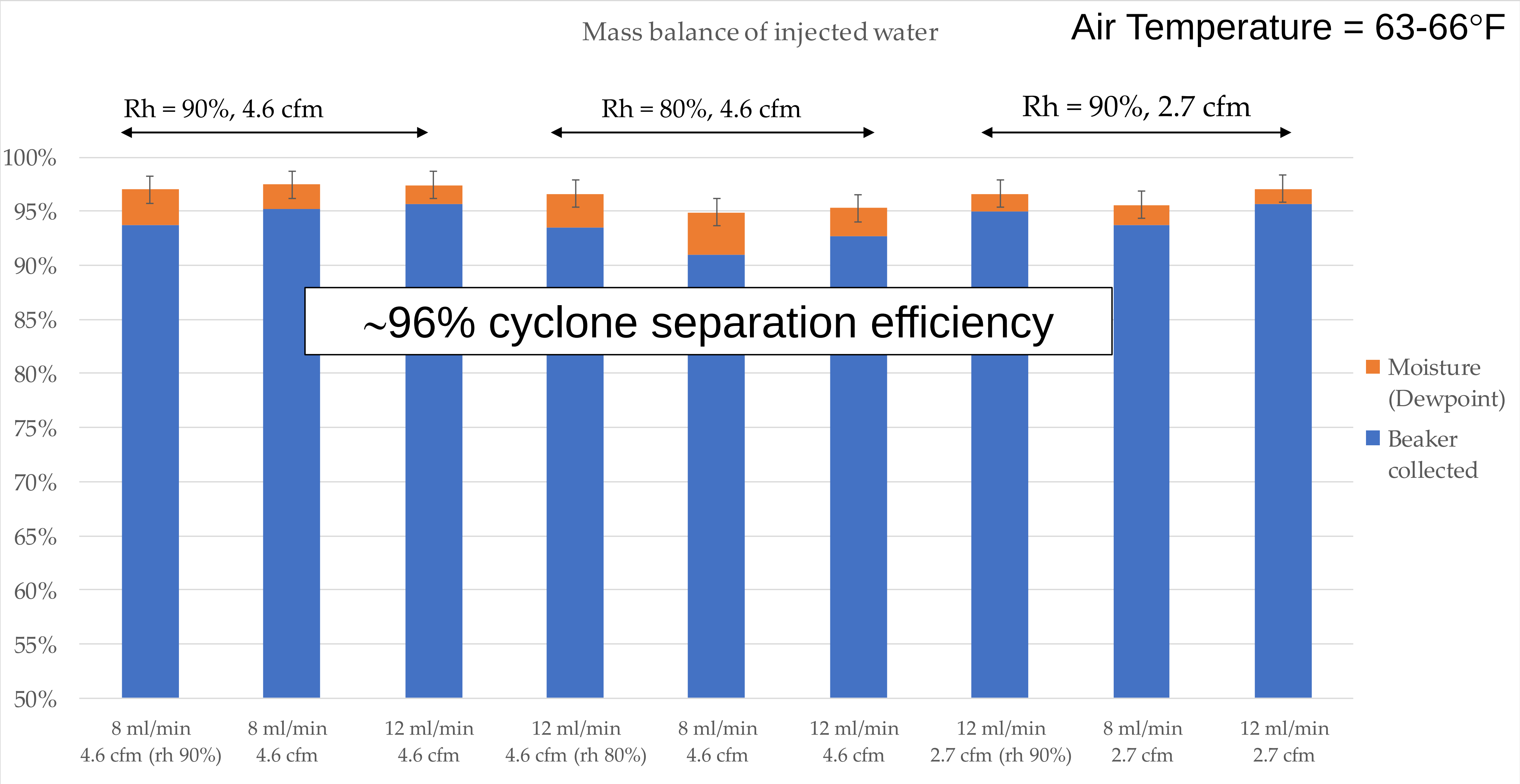
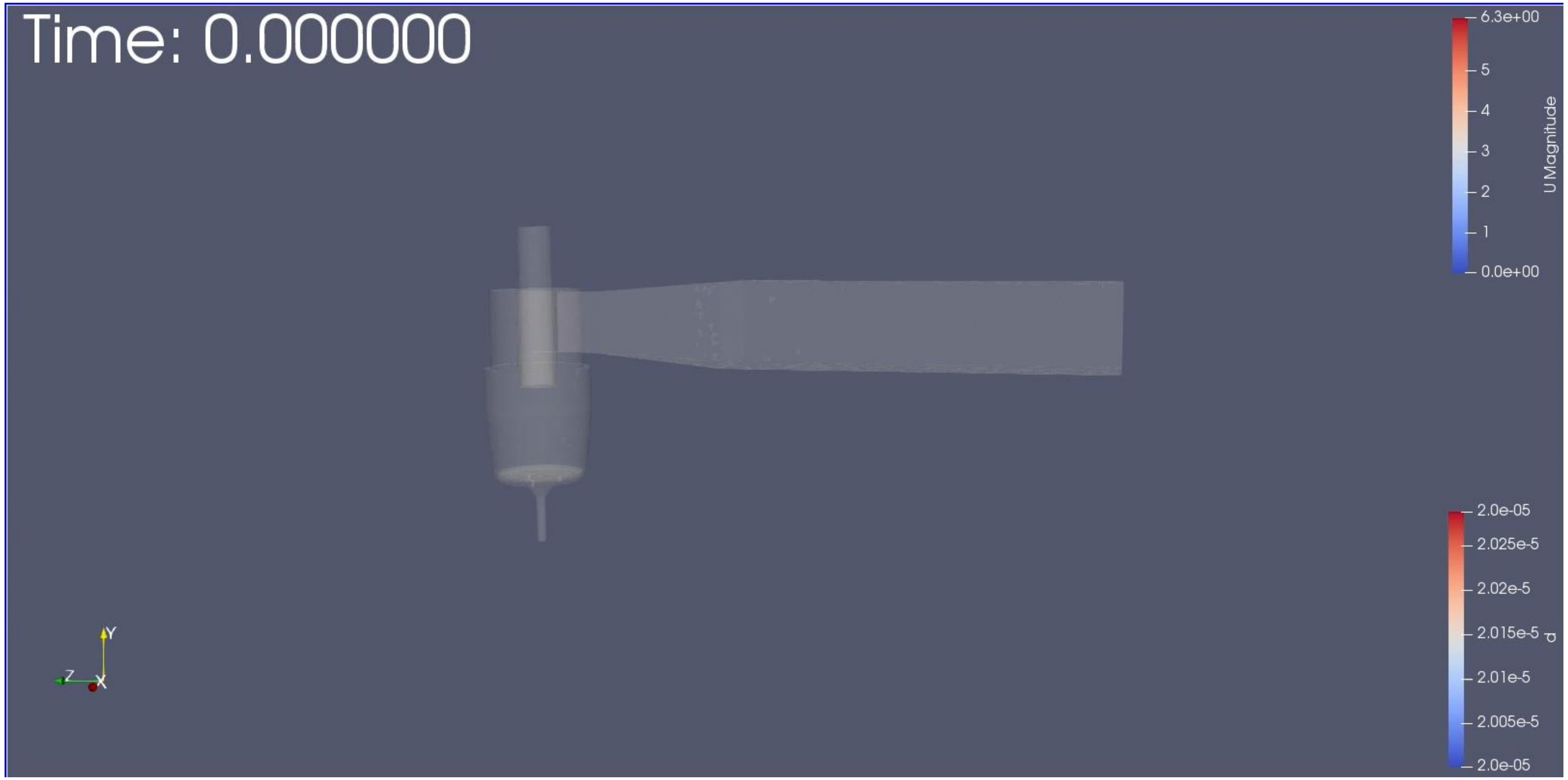


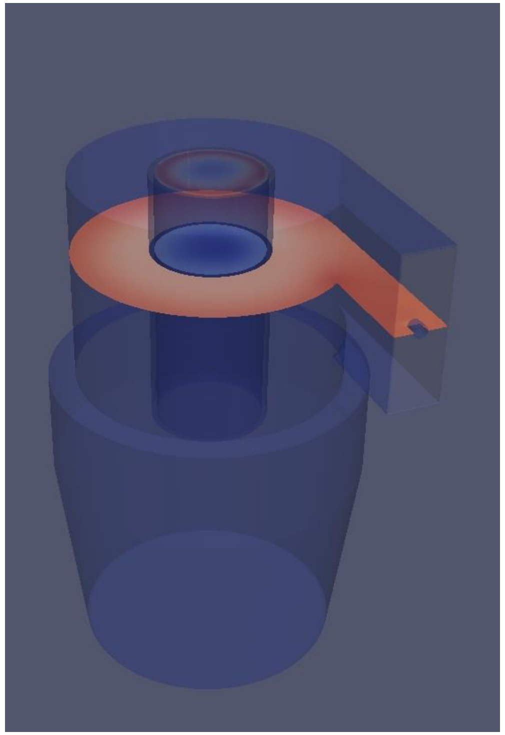
Image of the electrospray in the cone-jet operational mode (34 gauge needle, 10 μl/min, 11 kV)

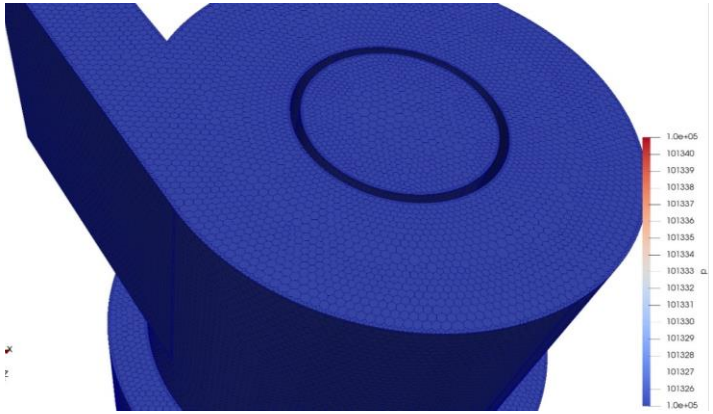
Project Status – Droplet Separation Efficiency



Progress – CFD Numerical Multi-Phase Flow Model

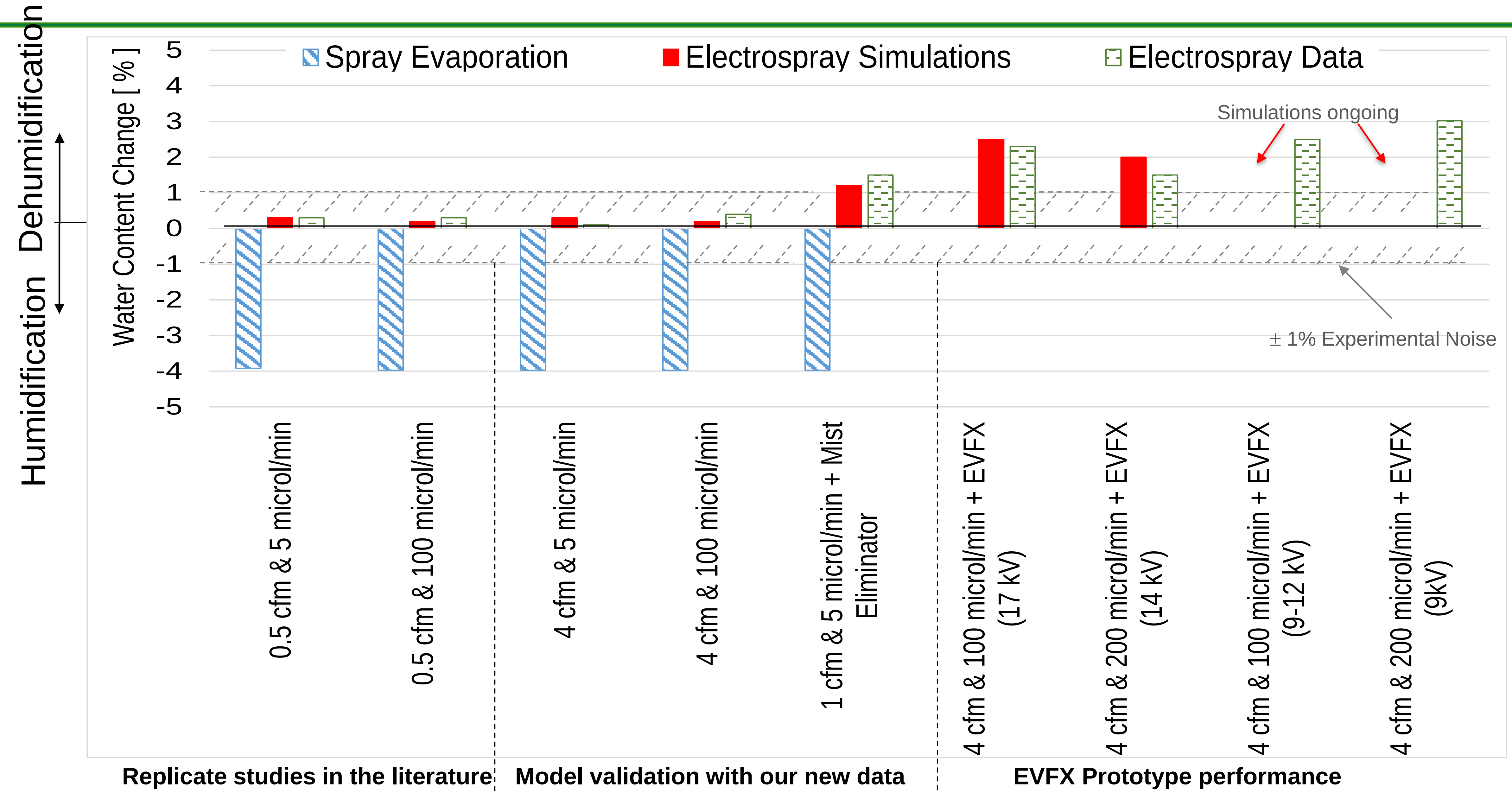






- CFD model developed in OpenFoam
- Electrically charged droplets sprayed in the air flow.
- Droplets grow and then move in the vortex tube where they are separated from the air

Project Status – CFD Simulation and Data



Stakeholder Engagement

- EVFX works better in high humidity air

  ➔ EVFX used on the outside air flows ➔ dedicated outdoor air systems (DOAS)

  ➔ Exhaust Recovery Ventilators (ERV)

- Commercial buildings are well suited because
  1. the level of technical expertise required for installing and servicing this potentially new technology are often already available for larger air handler systems
  2. even small percentages of energy savings by not adding any notable space are well received by the commercial buildings HVAC market.

JCI Isoclean Unit

Envirco IsoClean® Portable HEPA Filtration System

- Creates Negative Pressure Isolation Environments

- Ideal solution for hospitals, nursing homes, and dorms hotels.

Future Work

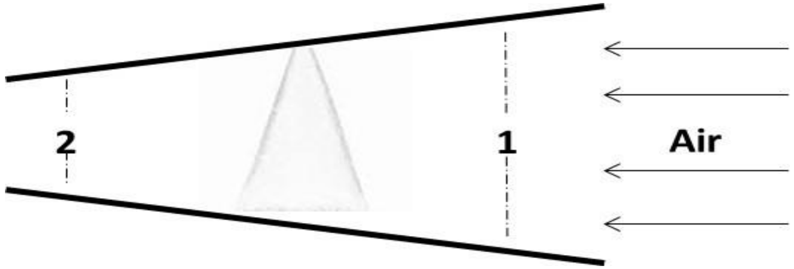
Feasibility Tests of a commercially available nozzle converted to an **electro-nozzle**

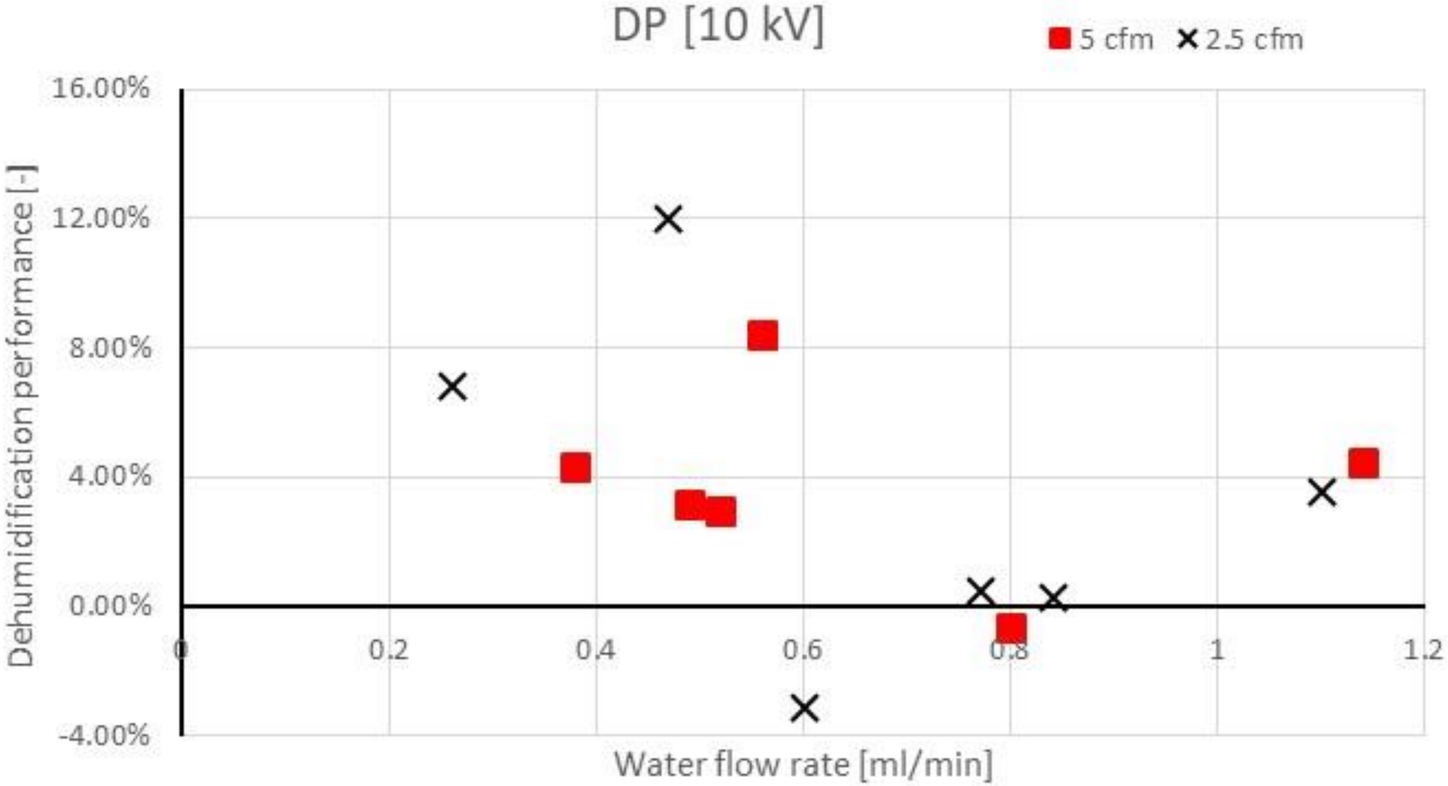
Dehumidification performance [DP]

$$DP = \frac{w_2 - w_2^*}{w_2 - w_1}$$

- An air atomizing-nozzle is placed in a strong electrical field.

Preliminary Results at 10 kV





Thank You

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REFERENCE SLIDES

Conference Papers (6)

2022

1. Young, D., Shoji, Y., Yel Mahi, M., Cremaschi, S., Cremaschi, L., and Ellis, M., 2022, Sensitivity Analysis of an Electrospray Dehumidification System, Process System Engineering (PSE) Conference 2021+, Kyoto, Japan, June 19-23, 2022, Paper Identifier 518.
2. Muteba, G., and Cremaschi, L., 2022, Experimental Investigation of the effect of atomizing electrospray nozzles on the cooling and reduced humidification of air, *Proceedings of the 19th International Refrigeration and Air Conditioning Conference at Purdue University,* West Lafayette, IN (USA), July 11-14, 2022, Pages 1-10.
3. Yel Mahi, M., Young, D., Shoji, Y., Cremaschi, L., and Cremaschi, S., 2022, Numerical Investigation of Air Dehumidification through Water Droplets Dielectrophoresis, *Proc. of the 7th Thermal and Fluids Engineering Conference of the American Society of Thermal and Fluid Engineers* (ASTFE), Las Vegas, NV, USA, and virtual, May 16-18, 2022

2021

4. Mahi Yel, M, Young, D., Shoji, Y., Cremaschi, S., and Cremaschi, L., 2021, Numerical Investigation of Enhanced Dehumidification Processes By Using Dielectrophoresis Principles in Moist Airflows, AIChE Annual Meeting 2021, Boston, MA, USA, Nov. 10, Paper Identifier 498h. Link: https://aiche.confex.com/aiche/2021/meetingapp.cgi/Paper/627553
5. Morcelli, S., and Cremaschi, L., 2021, Modeling of Enhanced Air Dehumidification through Electrically Charged Vapor Capturing Electrostatic Droplets, *Proc. of the 5-6th Thermal and Fluids Engineering Conference of the American Society of Thermal and Fluid Engineers* (ASTFE), New Orleans, LA, USA, now virtual, May 26-28, 2021
6. Morcelli, S., and Cremaschi, L., 2021, Analysis of New Data of Electro-static Assisted Air Dehumidification Processes, *Proc. of the 18th International Air Conditioning and Refrigeration Conference*, Purdue University, West Lafayette, IN, USA, now virtual conference, May 23-27, 2021

Patent

2022, Cremaschi L., Electrospray Vortical Flow Exchanger, US Patent No. US 11,358,094. Publication Date June 14, 2022.

Project Budget

Project Budget:

- **Total DOE: $1,457,470**
- **Total Cost Share: $372,479**

Cost to Date: 66% of Project Budget ($978k) has been expended to date (as of Jan 31, 2023)

Additional Funding: Not needed at this time.

Budget History

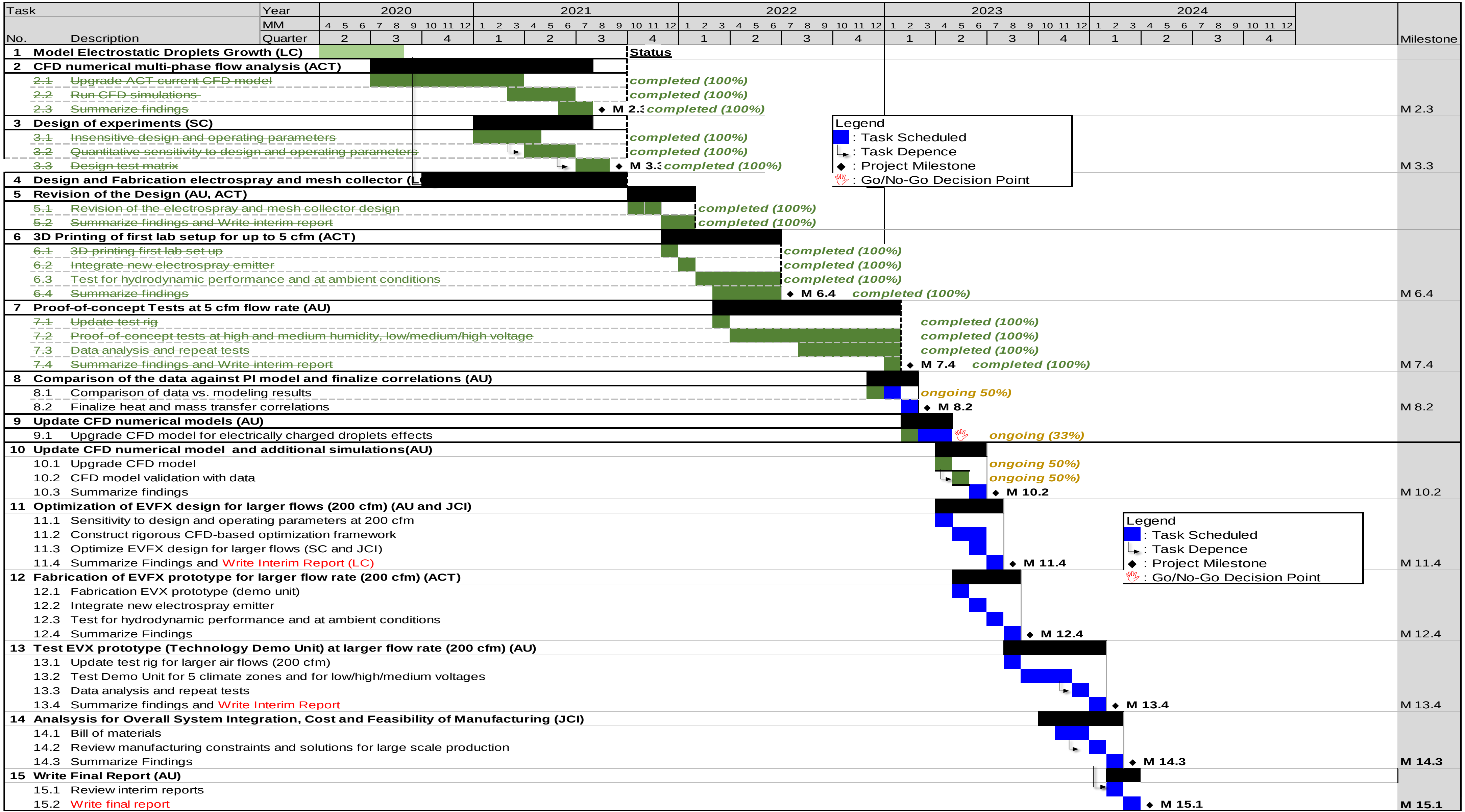
FY 2021 end Sept. 30 2021 (past)		FY 2022-23 end March 31 2023 (past)		FY 2024 end March 31 2024 (current)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$563,093	$141,581	$452,033	$117,449	$442,344	$113,449

Project Plan and Schedule

Past work

Current work

Future work



No.	Task Description	Status	Milestone
1	**Model Electrostatic Droplets Growth (LC)**		
2	**CFD numerical multi-phase flow analysis (ACT)**		
~~2.1~~	~~Upgrade ACT current CFD model~~	*completed (100%)*	
~~2.2~~	~~Run CFD simulations~~	*completed (100%)*	
~~2.3~~	~~Summarize findings~~	◆ M 2.3 *completed (100%)*	M 2.3
3	**Design of experiments (SC)**		
~~3.1~~	~~Insensitive design and operating parameters~~	*completed (100%)*	
~~3.2~~	~~Quantitative sensitivity to design and operating parameters~~	*completed (100%)*	
~~3.3~~	~~Design test matrix~~	◆ M 3.3 *completed (100%)*	M 3.3
4	**Design and Fabrication electrospray and mesh collector (L**		
5	**Revision of the Design (AU, ACT)**		
~~5.1~~	~~Revision of the electrospray and mesh collector design~~	*completed (100%)*	
~~5.2~~	~~Summarize findings and Write interim report~~	*completed (100%)*	
6	**3D Printing of first lab setup for up to 5 cfm (ACT)**		
~~6.1~~	~~3D printing first lab set up~~	*completed (100%)*	
~~6.2~~	~~Integrate new electrospray emitter~~	*completed (100%)*	
~~6.3~~	~~Test for hydrodynamic performance and at ambient conditions~~	*completed (100%)*	
~~6.4~~	~~Summarize findings~~	◆ M 6.4 *completed (100%)*	M 6.4
7	**Proof-of-concept Tests at 5 cfm flow rate (AU)**		
~~7.1~~	~~Update test rig~~	*completed (100%)*	
~~7.2~~	~~Proof-of-concept tests at high and medium humidity, low/medium/high voltage~~	*completed (100%)*	
~~7.3~~	~~Data analysis and repeat tests~~	*completed (100%)*	
~~7.4~~	~~Summarize findings and Write interim report~~	◆ M 7.4 *completed (100%)*	M 7.4
8	**Comparison of the data against PI model and finalize correlations (AU)**		
8.1	Comparison of data vs. modeling results	*ongoing 50%)*	
8.2	Finalize heat and mass transfer correlations	◆ M 8.2	M 8.2
9	**Update CFD numerical models (AU)**		
9.1	Upgrade CFD model for electrically charged droplets effects	*ongoing (33%)*	
10	**Update CFD numerical model and additional simulations(AU)**		
10.1	Upgrade CFD model	*ongoing 50%)*	
10.2	CFD model validation with data	*ongoing 50%)*	
10.3	Summarize findings	◆ M 10.2	M 10.2
11	**Optimization of EVFX design for larger flows (200 cfm) (AU and JCI)**		
11.1	Sensitivity to design and operating parameters at 200 cfm		
11.2	Construct rigorous CFD-based optimization framework		
11.3	Optimize EVFX design for larger flows (SC and JCI)		
11.4	Summarize Findings and Write Interim Report (LC)	◆ M 11.4	M 11.4
12	**Fabrication of EVFX prototype for larger flow rate (200 cfm) (ACT)**		
12.1	Fabrication EVX prototype (demo unit)		
12.2	Integrate new electrospray emitter		
12.3	Test for hydrodynamic performance and at ambient conditions		
12.4	Summarize Findings	◆ M 12.4	M 12.4
13	**Test EVX prototype (Technology Demo Unit) at larger flow rate (200 cfm) (AU)**		
13.1	Update test rig for larger air flows (200 cfm)		
13.2	Test Demo Unit for 5 climate zones and for low/high/medium voltages		
13.3	Data analysis and repeat tests		
13.4	Summarize findings and Write Interim Report	◆ M 13.4	M 13.4
14	**Analsysis for Overall System Integration, Cost and Feasibility of Manufacturing (JCI)**		
14.1	Bill of materials		
14.2	Review manufacturing constraints and solutions for large scale production		
14.3	Summarize Findings	◆ M 14.3	**M 14.3**
15	**Write Final Report (AU)**		
15.1	Review interim reports		
15.2	Write final report	◆ M 15.1	**M 15.1**

Legend
🟦 : Task Scheduled
↳ : Task Depence
◆ : Project Milestone
✋ : Go/No-Go Decision Point

Legend
🟦 : Task Scheduled
↳ : Task Depence
◆ : Project Milestone
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Remaining Project Work

Stage of the Project:

~~BP 1: Develop New Electrospray Emitter (completed)~~

~~BP 2: Test First EVFX Prototype and Optimization~~

BP 3: Develop EVFX Technology Demo Unit

Start Date: April 1, 2020

- ~~✓ Modeled vapor capturing process by electrostatic water droplets (completed)~~
- ~~✓ Designing proof-of-concept EVFX prototype for low air flow rates (5 cfm) (next month)~~

- ~~✓ Manufacturing of EVFX prototype and assembly of the new electrospray (by end-of-year)~~
- ~~✓ Instrumentation of EVFX prototype and calibration (Spring 2022)~~
- ~~✓ Proof-of-concept tests for 5 cfm; achieve 5% Dehumidification (Fall 2023)~~

- Optimization and scale up to 200 cfm (Fall 2023)
- Technology Demo Unit
- Scale up analysis and integration with air handlers for commercial building applications

Team

AU – University; wind tunnel testing facility, computer cluster

ACT – Small business; R&D prototyping and new products development

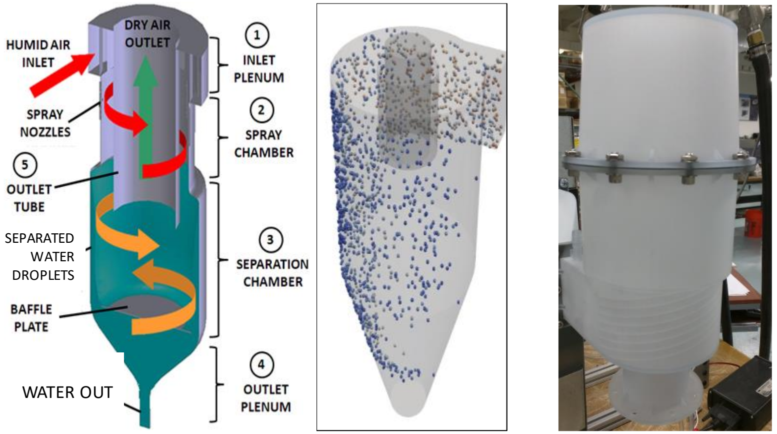
JCI – Large business; Manufacture 155,000 light commercial and residential air-conditioning and heat pump units per year

Team Track Record (previous work):

(a) First-Principle Physic model

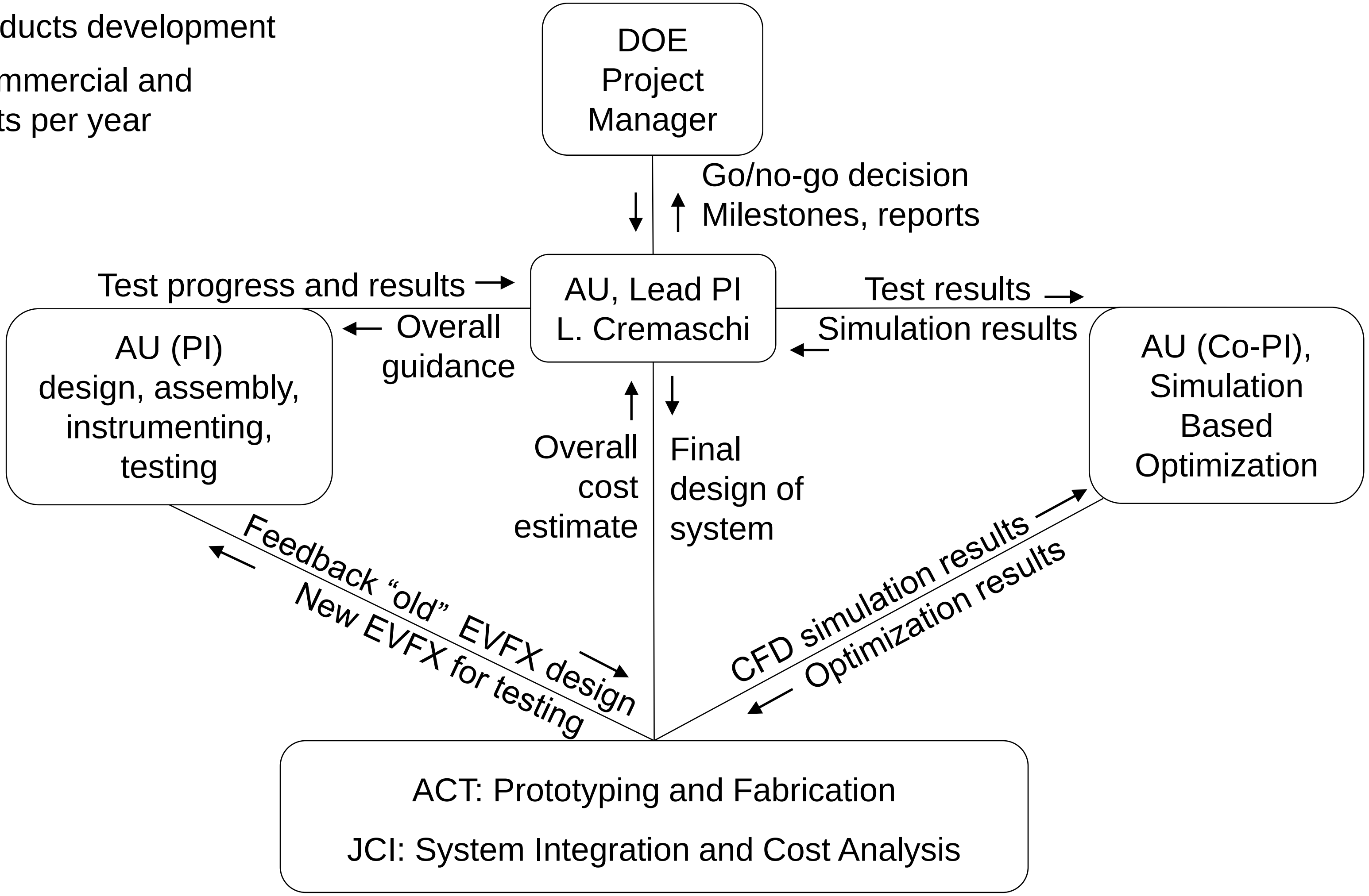
(b) CFD analysis (in OpenFoam)

(c) Prototype made by 3D AM of Vortical Flow Exchanger



(a) (b) (c)

Contribution of Each Team Members



DOE Project Manager

Go/no-go decision

Milestones, reports

AU, Lead PI L. Cremaschi

Test progress and results →

← Overall guidance

AU (PI) design, assembly, instrumenting, testing

Test results →

← Simulation results

AU (Co-PI), Simulation Based Optimization

Overall cost estimate

Final design of system

Feedback “old” EVFX design

New EVFX for testing

CFD simulation results

Optimization results

ACT: Prototyping and Fabrication

JCI: System Integration and Cost Analysis