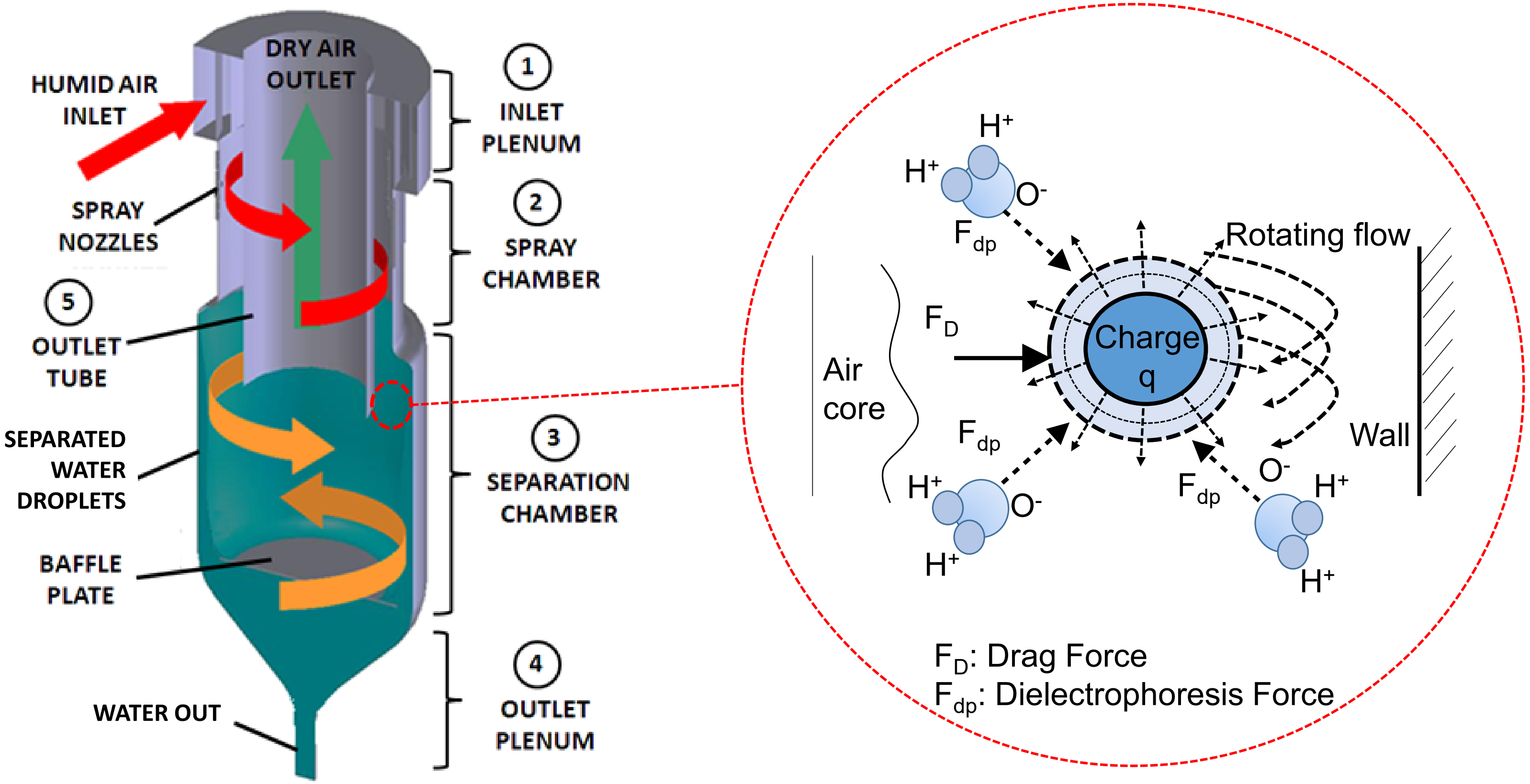
Separating Sensible and Latent Cooling with Electrically Charged Rotating Vortexes and Vapor Capturing Air Handler Technology



Auburn University
Advanced Cooling Technologies, Inc.
Johnson Control Inc.

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Project Summary

Timeline:

Start date: April 1, 2020

Planned end date: September 30, 2023

Key Milestones

1. Design electrospray Emitter, Sept. 2021
2. Proof-of-concept tests for 5 cfm; achieve 5% Dehumidification, Sept. 2022
3. Optimization and scale up to 200 cfm, Dec 2022
4. Technology Demo Unit, April 2023

Budget:

Total Project $ to Date:

- DOE: $563,093
- Cost Share: $141,581

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.

Team

AU – University; wind tunnel testing facility, computer cluster

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

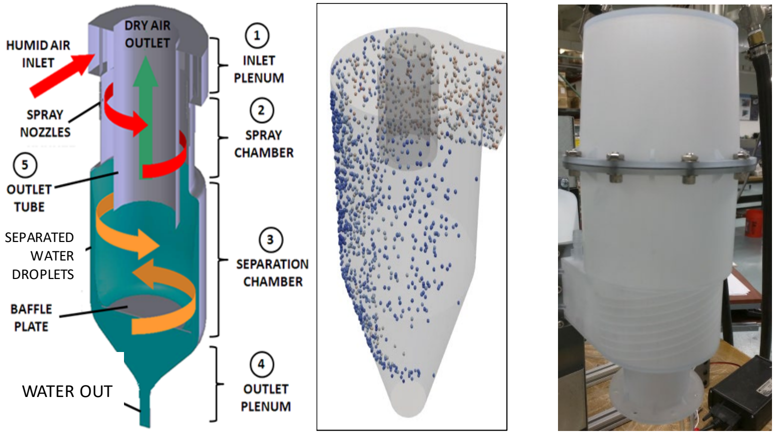
JCI – Large business; Manufacture 155,000 light commercial and residential air-conditioning and heat pump units per year

Team Track Record (previous work):

(a) First-Principle Physic model

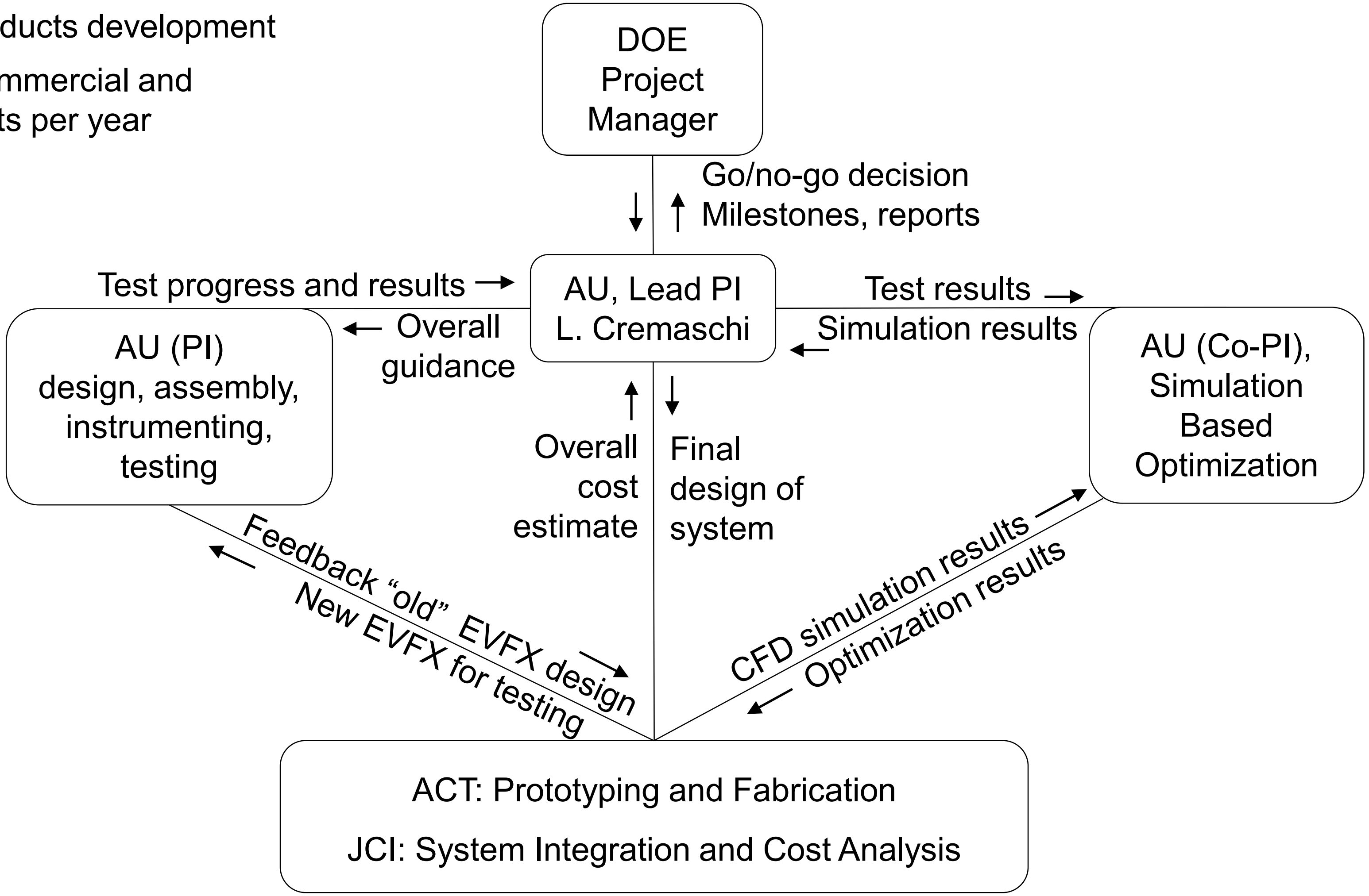
(b) CFD analysis (in OpenFoam)

(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

Test results →

← Simulation results

AU (PI) design, assembly, instrumenting, testing

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

Challenge

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.

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

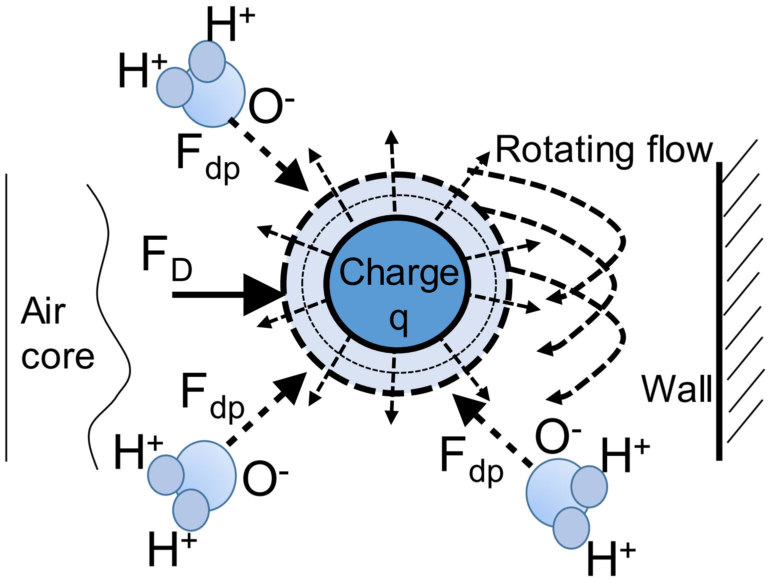
BTO identified system performance targets and desirable characteristics at part-load performance, including:

- 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

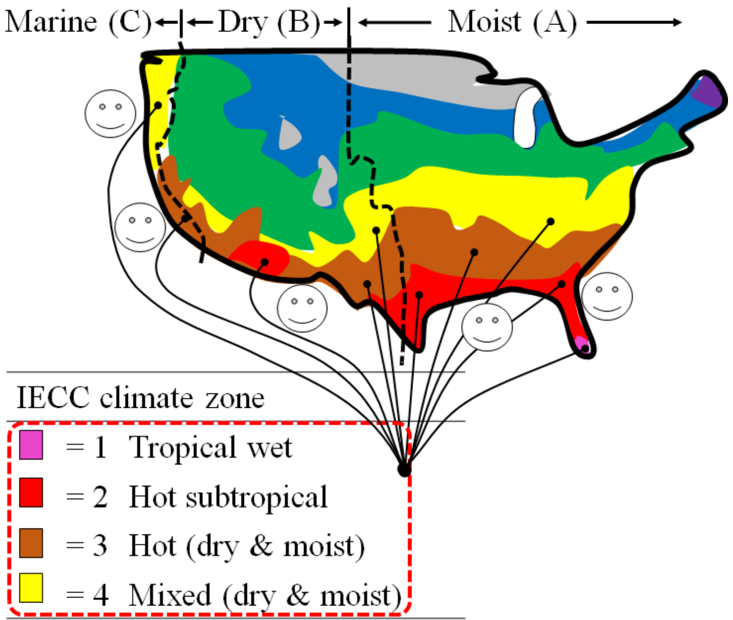
Our proposed EVFX is, in our opinion, an innovative separation technology that aligns well with ETP goal.

It separates and converts latent loads into sensible loads by using electrostatic energy and centripetal 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)

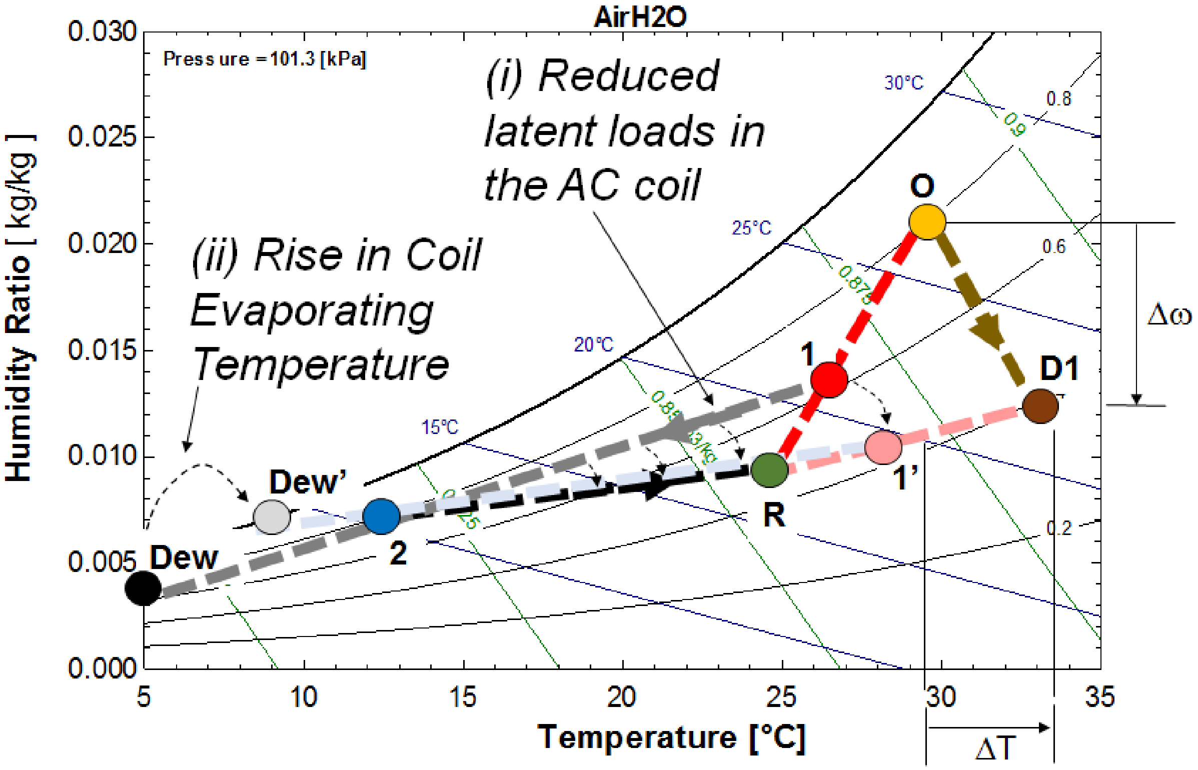
Impact

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

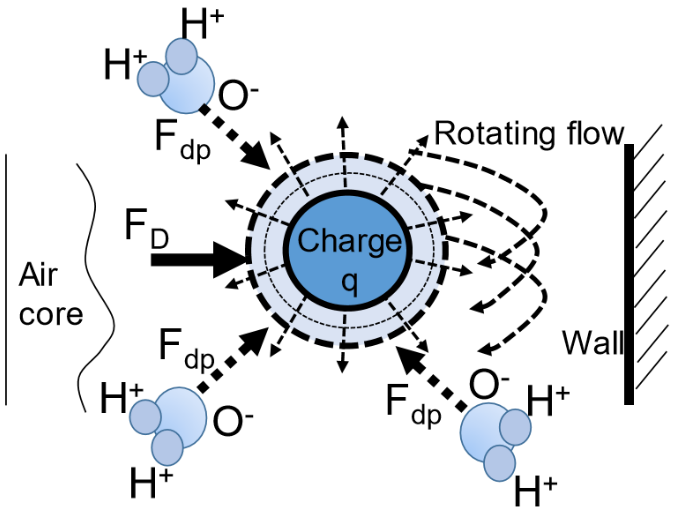


Metric Description	EVFX Metric
Primary Energy Savings	576 TBtu
Seasonal Coeff. of Performance (COP) $_{\text{Cooling}}$ (2)	≥12.3
Installed cost (1)(3)	≤ $2,500/unit
Installed cost per cooling unit (1)	≤ $12/kBtu/h

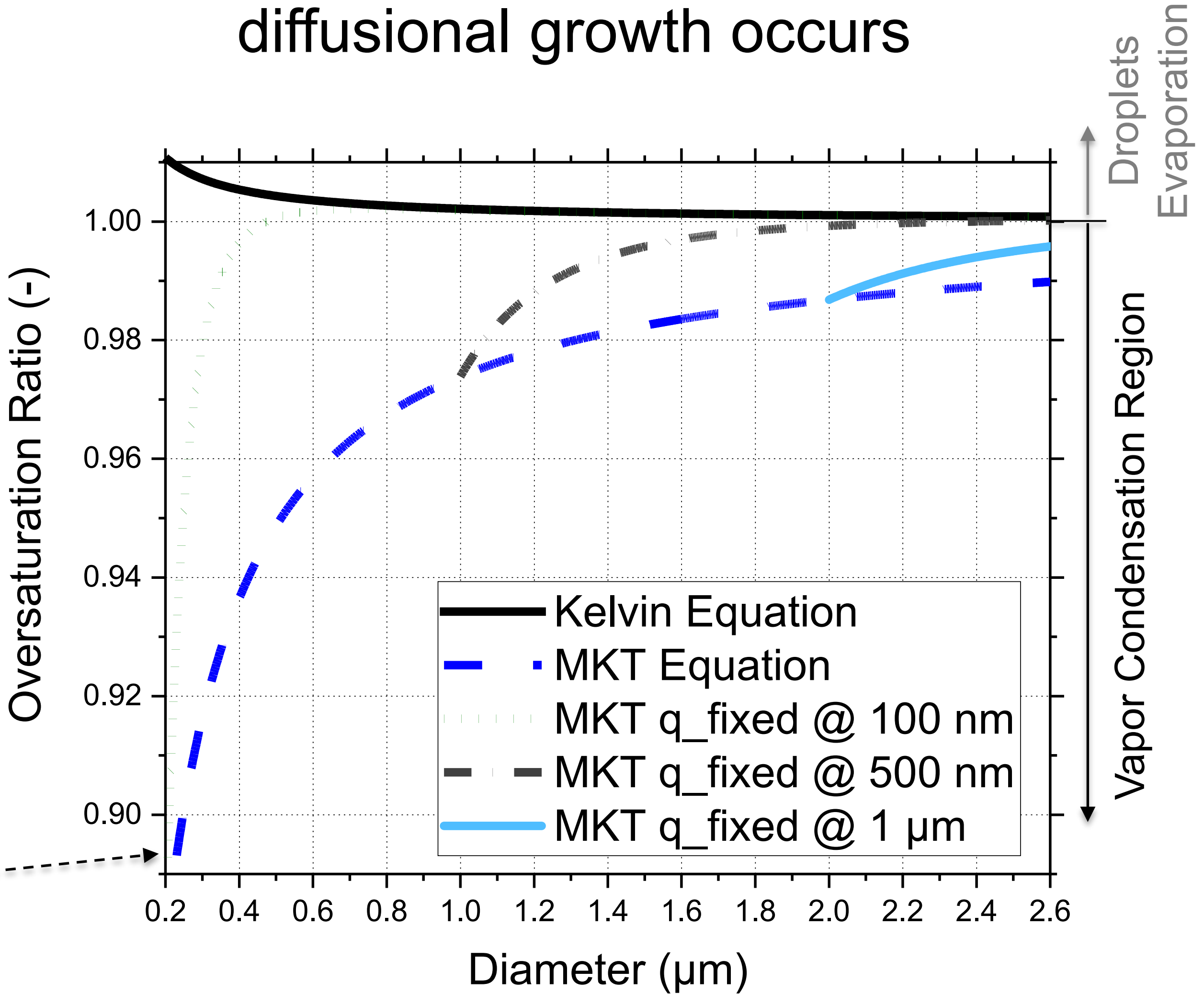
Note (1): Measured in 2019$
Note (2): Average across 57.5°F to 100.4°F in Climate zone 3A
Note (3): Average between residential ($6K) and commercial

Progress – Vapor Condensation Thermodynamic Model

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

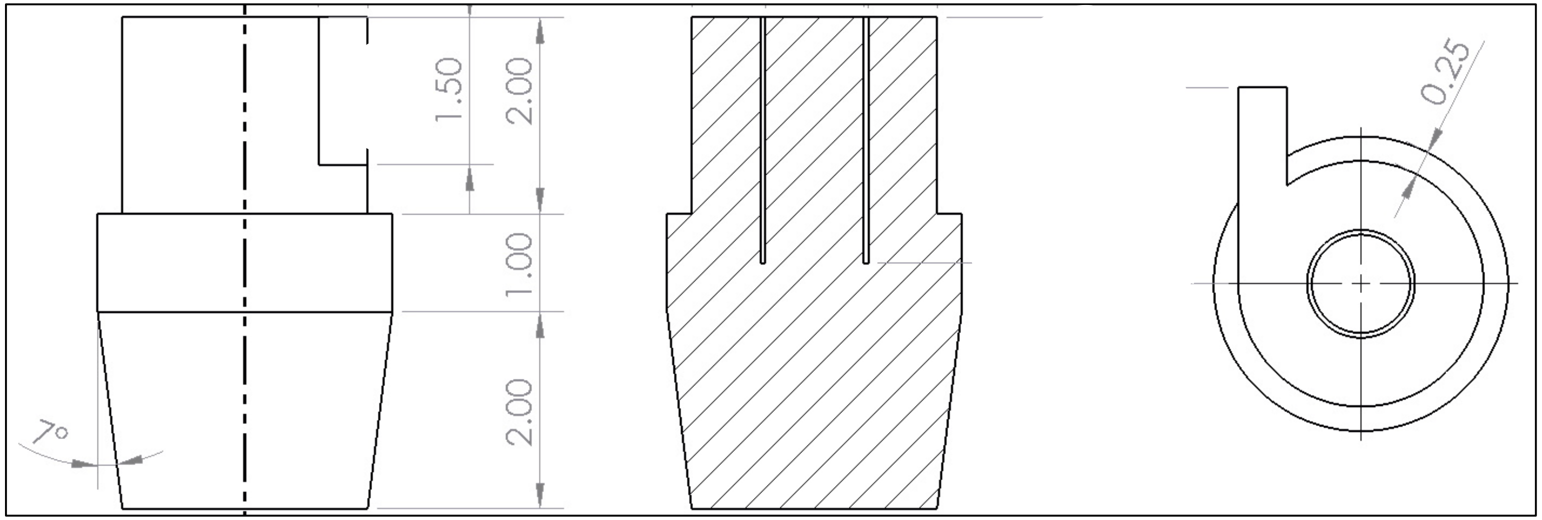


If $P_{bulk,air} > P_{equilibrium\ @\ droplet\ surface}$ diffusional growth occurs

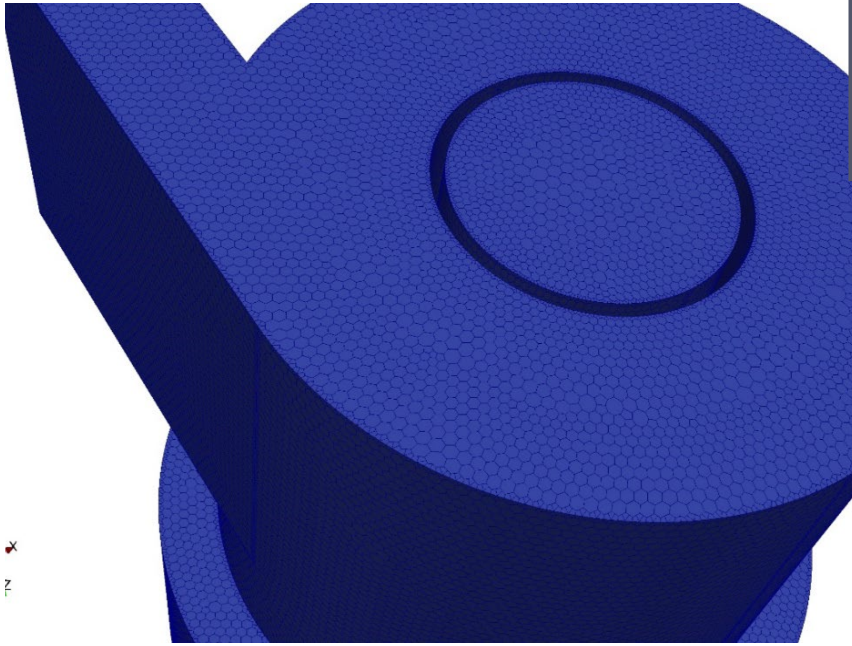


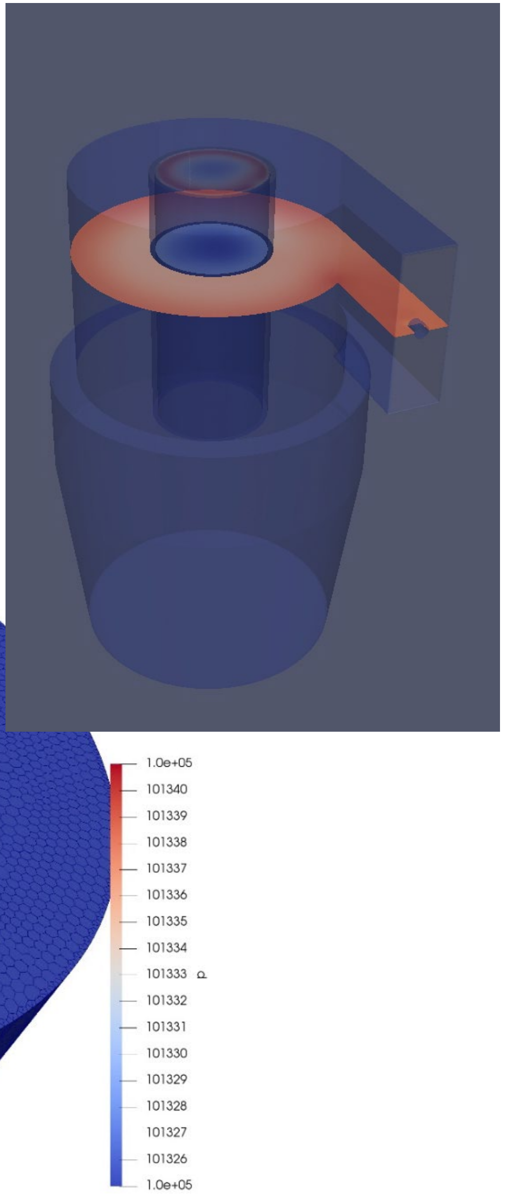
Maximum electric charge dictated by the Rayleigh limit: $q_{Rayleigh} = 8\pi\sqrt{\varepsilon_0 \sigma R^3}$

Progress – CFD Numerical Multi-Phase Flow Model



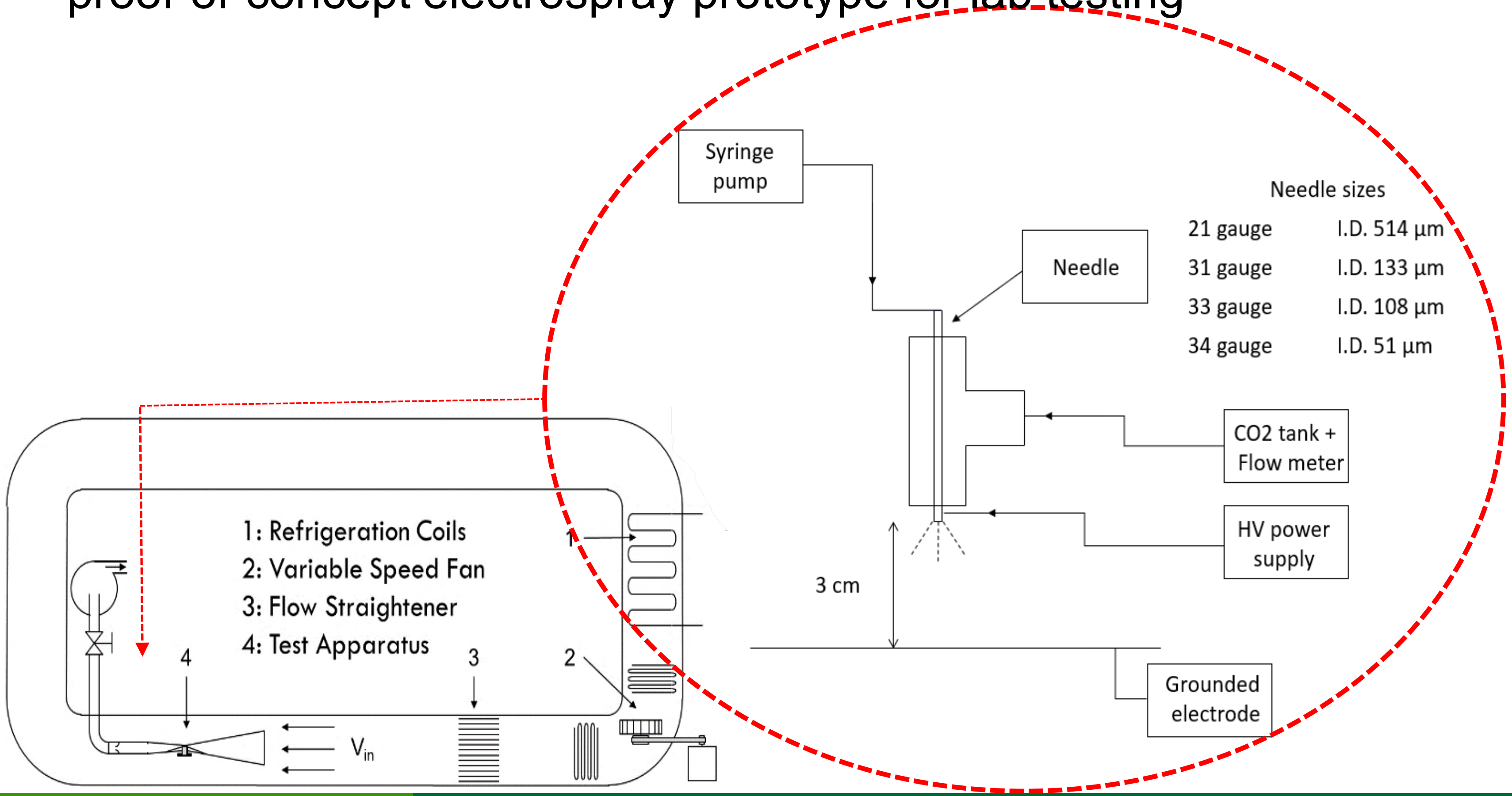
- CFD model developed in OpenFoam
- Electrically charged droplets sprayed in the air flow.
- Droplets grow and then move in the vortex tube where they are separated from the air





Progress – CFD Numerical Model Experimental Validation

Low installed cost and readily available materials;
electrosprays have been used for decades in spray painting and fuel (diesel engine) atomization and injection. Using off-the-shelf components from these areas, we recently successfully built a proof-of-concept electrospray prototype for lab testing



Needle sizes

21 gauge	I.D. 514 µm
31 gauge	I.D. 133 µm
33 gauge	I.D. 108 µm
34 gauge	I.D. 51 µm

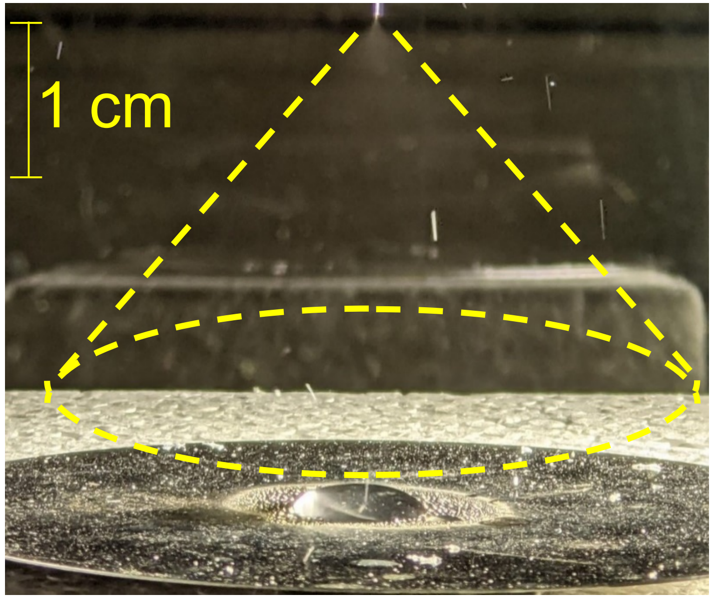


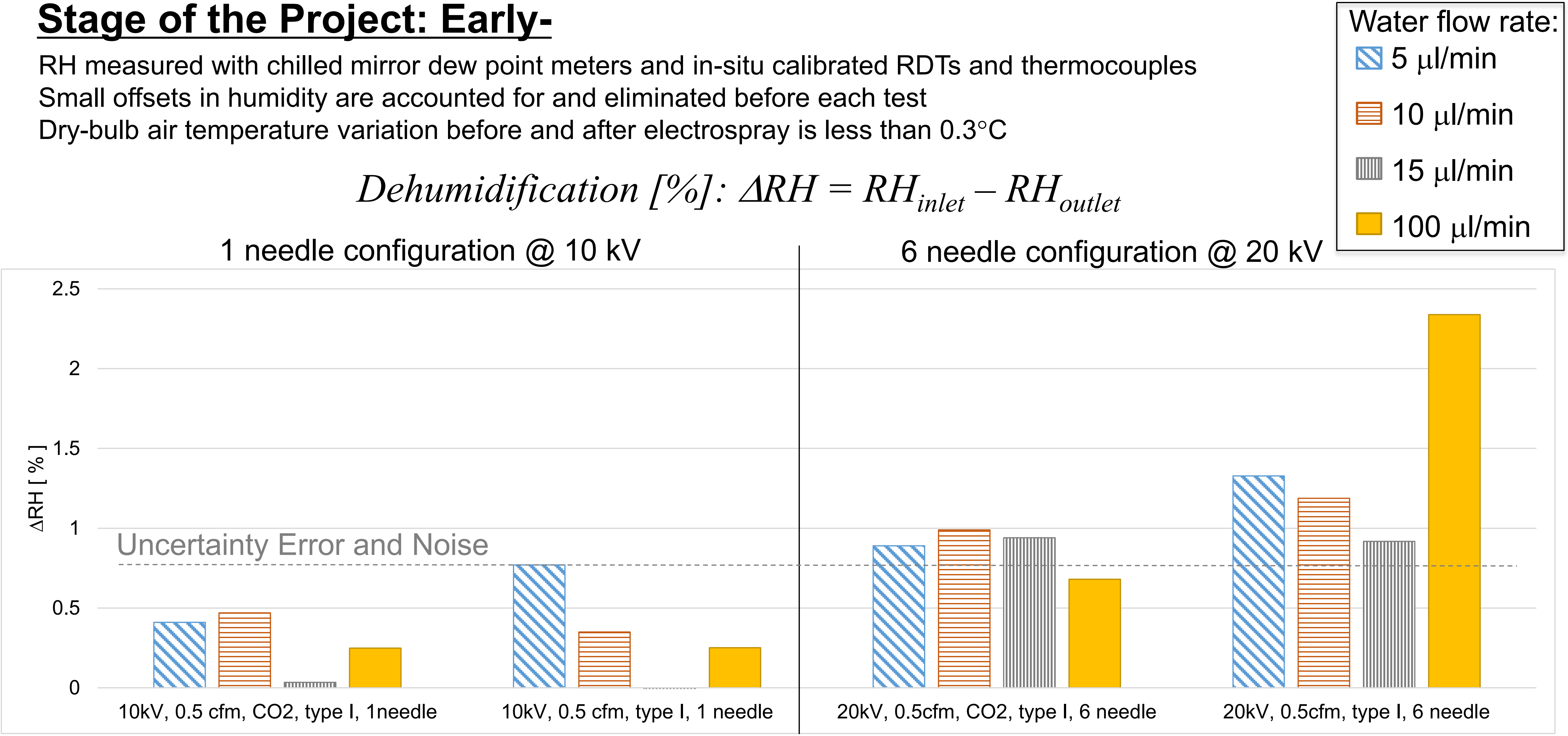
Image of the electrospray in the cone-jet operational mode
(34 gauge needle,
10 µl/min, 11 kV)

Progress – Data for CFD Model Experimental Validation

Stage of the Project: Early-

RH measured with chilled mirror dew point meters and in-situ calibrated RDTs and thermocouples
Small offsets in humidity are accounted for and eliminated before each test
Dry-bulb air temperature variation before and after electrospray is less than 0.3°C

$$Dehumidification\ [\%]:\ \Delta RH = RH_{inlet} - RH_{outlet}$$



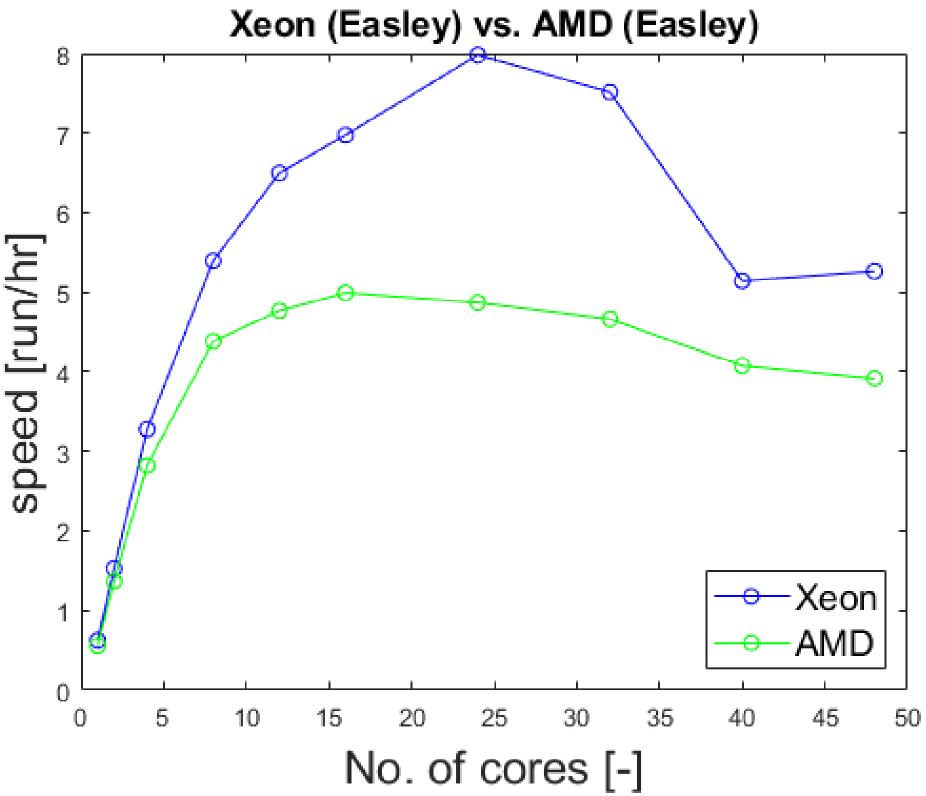
Progress – CFD Model Computational Challenges

Number of sub-domains	Simulation runtime	Solution reconstruction runtime	With Script to extract only key metrics (seconds)
4	14 minutes	15 minutes	
8	8 minutes	1 hour	
16	6 minutes	1.6 hour	7 minutes

- Massive amount of simulation outputs
  - data management, transfer, storage, archive
- Computational time and costs
  - Reduce to few hours without compromising the accuracy and key information needed
- CFD based optimization framework for super-computing cluster
  - Sensitivity analysis
  - Optimization of prototype

CPU spec.

	Xeon	AMD
Processors	48/Node	128/Node
CPU MHz	3700	1996



Stakeholder Engagement

- EVFX works better in high humidity air ➔ EVFX used on the outside air flows ➔ dedicated outdoor air systems (DOAS) and exhaust recovery ventilators (ERV) are expected to be the immediate systems in which the proposed technology will be placed.
- Commercial buildings are well suited because
  i. the level of technical expertise required for installing and servicing this potentially new technology are often already available for larger air handler systems
  ii. even small percentages of energy savings by not adding any notable space are well received by the commercial buildings HVAC market.
- ACT is located in a 1,300,000 ft^2 business park that affords with plenty of space and infrastructure to expand as necessary. **ACT recently expanded into an additional 10,000 ft^2 to support energy recovery and enclosure cooling product line**
- JCI has already high voltage amplifiers for UV air quality control in their air handlers.
- It is likely that this new technology will be manufactured at JCI air handling systems facility. The new facility, named the "**JCI Airside Center of Excellence** (JCI-ACE)" is located in York, Pennsylvania and it includes 40,000-square-feet of office space and **a 285,000-square-foot manufacturing area where standard and custom air-handling units are manufactured.** It is also a training and support center for JCI air handling products and currently hold 530 employees.
- Once the performances are validated, there are not any laws of physics that prevent scaling up further the technology for commercial building applications. There is no need to synthetize new materials or develop large stacks of membranes for larger systems.
- At any rate, ACT assesses manufacturability at scale, and JCI investigate system integration in existing air handlers and market penetration

  Example of this type of assessment during current FY period:

  for large flow rates, the millions of electro-needles could be replace by hundreds electro-nozzles and without using carbon dioxide in the electrospray.

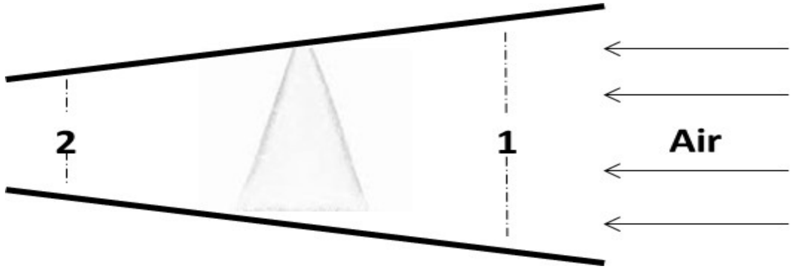
Stakeholder Engagement

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

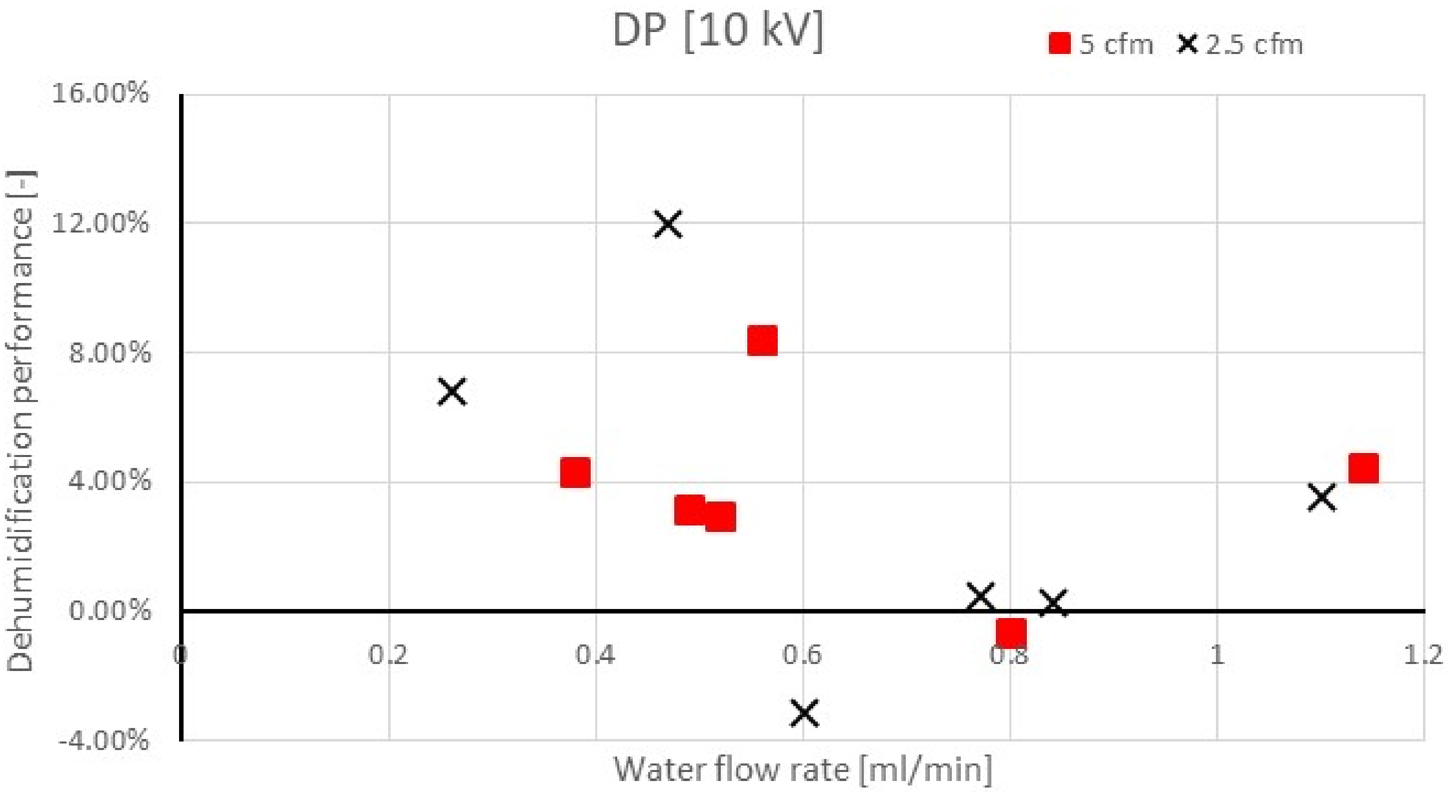
Dehumidification performance [DP]

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

Preliminary Results at 10 kV



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



Remaining Project Work

Stage of the Project: Early-

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

Year 2: Test First EVFX Prototype and Optimization

Year 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 (Summer 2022)

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

Thank You

Auburn University
Lorenzo Cremaschi
Email: lzc0047@auburn.edu

REFERENCE SLIDES

Conference Papers

1. 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
2. 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 Application

2020, Electrospray Vortical Flow Exchanger, US Patent App. 17/034344 (Serial number for the Patent Cooperation Treaty case is PCT/US2020/53038).
Inventor: Cremaschi L.

Project Budget

Project Budget:

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

Variances: 6-months no-cost time extension was approved, resulting on the project budget period year 1 from April 1, 2020 to September 30, 2021.

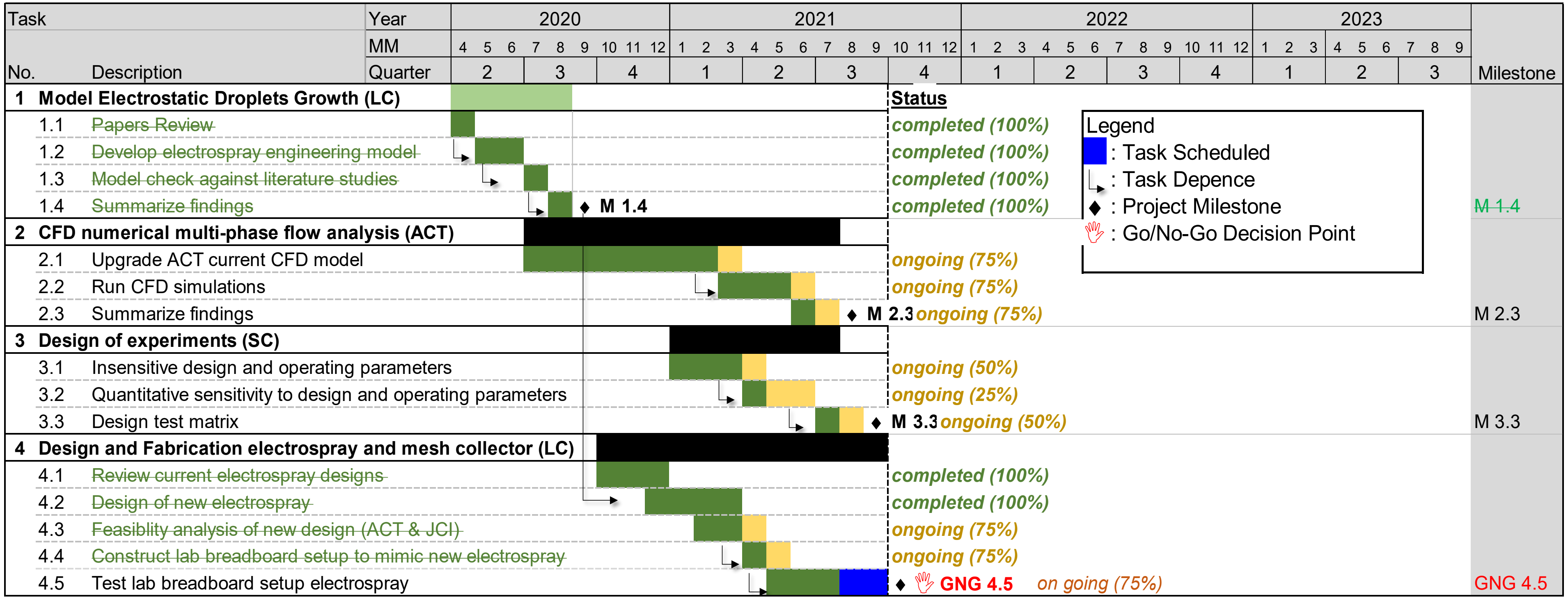
Cost to Date: 30% of Project Budget ($441,002) has been expended to date (as of July 15, 2021)

Additional Funding: Not needed at this time.

Budget History

April 20, 2020 FY 2020 (past)		FY 2021 end Sept. 30 2021 (current)		FY 2022 end Sept. 30 2022 (planned)		FY 2023 end Sep. 30 2023 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
NA	NA	$563,093	$141,581	$452,033	$117,449	$442,344	$113,449

Project Plan and Schedule



No.	Description	Status	Milestone
1	**Model Electrostatic Droplets Growth (LC)**		
1.1	~~Papers Review~~	*completed (100%)*	
1.2	~~Develop electrospray engineering model~~	*completed (100%)*	
1.3	~~Model check against literature studies~~	*completed (100%)*	
1.4	~~Summarize findings~~	◆ **M 1.4** *completed (100%)*	~~M 1.4~~
2	**CFD numerical multi-phase flow analysis (ACT)**		
2.1	Upgrade ACT current CFD model	*ongoing (75%)*	
2.2	Run CFD simulations	*ongoing (75%)*	
2.3	Summarize findings	◆ **M 2.3** *ongoing (75%)*	M 2.3
3	**Design of experiments (SC)**		
3.1	Insensitive design and operating parameters	*ongoing (50%)*	
3.2	Quantitative sensitivity to design and operating parameters	*ongoing (25%)*	
3.3	Design test matrix	◆ **M 3.3** *ongoing (50%)*	M 3.3
4	**Design and Fabrication electrospray and mesh collector (LC)**		
4.1	~~Review current electrospray designs~~	*completed (100%)*	
4.2	~~Design of new electrospray~~	*completed (100%)*	
4.3	~~Feasiblity analysis of new design (ACT & JCI)~~	*ongoing (75%)*	
4.4	~~Construct lab breadboard setup to mimic new electrospray~~	*ongoing (75%)*	
4.5	Test lab breadboard setup electrospray	◆ ✋ **GNG 4.5** *on going (75%)*	GNG 4.5

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

Future work

No.	Description		Milestone
5	**Revision of the Design**		
5.1	Revision of the electrospray and mesh collector design		
5.2	Summarize findings and Write interim report		
6	**3D Printing of first lab setup for up to 5 cfm (ACT)**		
6.1	3D printing first lab set up		
6.2	Integrate new electrospray emitter		
6.3	Test for hydrodynamic performance and at ambient conditions		
6.4	Summarize findings	◆ **M 6.4**	M 6.4
7	**Proof-of-concept Tests at 5 cfm flow rate (LC)**		
7.1	Update test rig		
7.2	Proof-of-concept tests at high and medium humidity, low/medium/high voltage		
7.3	Data analysis and repeat tests		
7.4	Summarize findings and Write interim report	◆ **M 7.4**	M 7.4