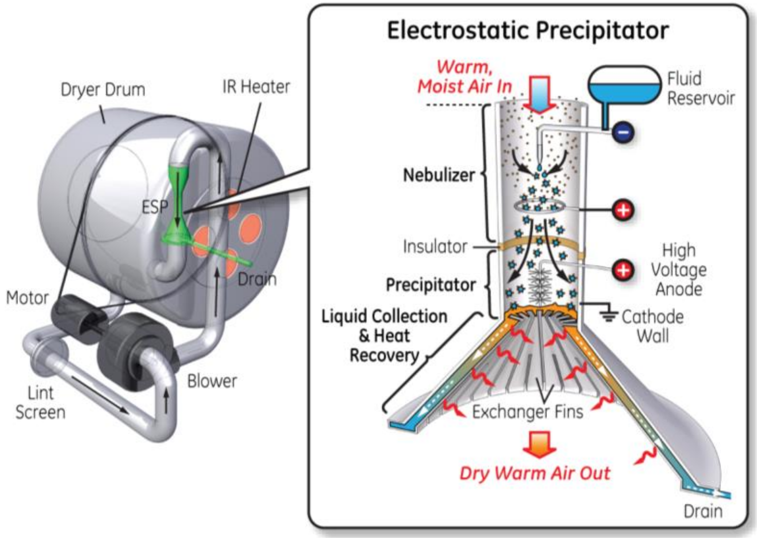
Energy Efficient Clothes Dryer with IR Heating and Electrostatic Precipitator

2016 Building Technologies Office Peer Review

Project team members left to right Tom Stecher, Stan Weaver, Ralf Lenigk, Martin Vysohlid, Arin Cross, Francisco Moraga, absent from photo Nannan Chen.

Program Objective: *Demonstrate a Ventless Residential Dryer with a EF >4.04*



Technical Approach

- Ventless closed loop system
- Advanced IR heating
- Modulated heater drying cycle
- Electrostatic Precipitator (ESP) for humidity removal

Technical Challenges

- Lint fouling in exchanger
- Efficient heat spreading in drum
- IR heater/ESP optimization
- ESP efficiency near end of cycle

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Project Summary

Timeline:

Start date: 10/1/2014

Planned end date: 6/30/2017

Key Milestones

Milestone 1: Demonstration of an ESP exchanger operating at 40% efficiency; 6/30/2016

Milestone 2: Demonstrate Integrated dryer operating at an EF goal of >4.04; 6/30/2017

Key Partners: NA

Budget:

Total Project $ to Date:

- DOE: $536,217
- Cost Share: $134,054

Total Project $:

- DOE: $1,040,040
- Cost Share: $260,001

Project Outcome:

The goal of the program is to design, build, and demonstrate a residential ventless dryer with an energy factor (EF) of >4.04.

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Purpose and Objectives

Problem Statement: Current residential dryer EF's (lbs/kWh) are ~3.73. DOE MYPP target is an EF of 6.0 by 2020 at a payback of less than 5 years.

- **Target Market and Audience**: Target market is the US residential clothes dryer market, consisting of ~ 84 million dryers, consuming ~64 billion kWh per year.

Impact of Project: A residential ventless dryer with an EF of 4.8 translating to energy savings 50.8 billion kWh (appliance and make up air savings). The planned EF is concurrent with DOE 2020 goals of 6.0.

a. Near-term outcomes (during or up to 1yr after project)? – Licensing of the proposed technology.
b. Intermediate outcomes (1-3yr after project) – Commercialization of the proposed dryer and realization of energy savings.
c. Long-term outcomes(3yr.+ after project)? Technology insertion broadening into other applications; i.e. industrial drying and smoke stack and exhaust effluent remediation.

Approach

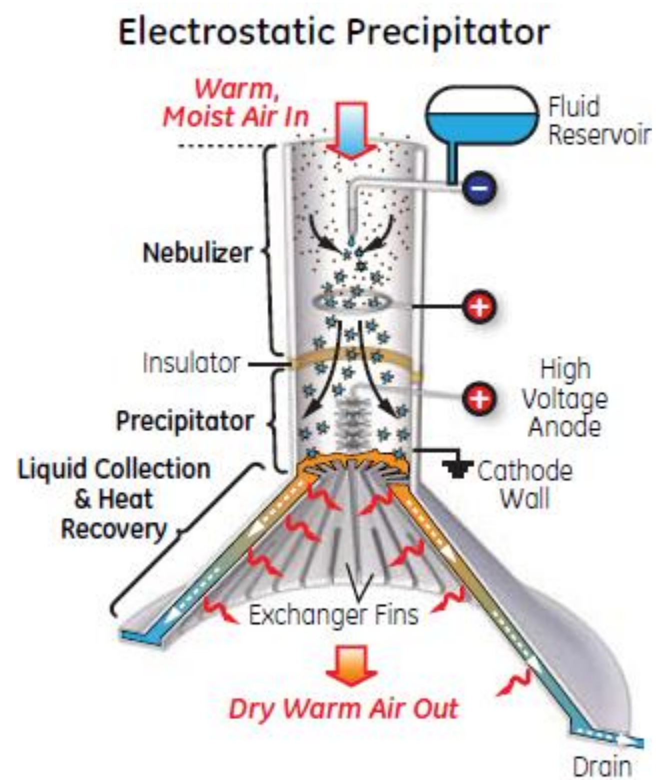
Approach: Development of next generation technology prototypes.

- Construction of a “variable” dryer output simulator
- Model, design, testing, optimization and demonstration of key technologies
  - ESP/Exchanger and IR heaters
- Integration of key technologies into working prototypes meeting program goals

Key Issues: Low efficiency of ESP/Exchanger, 13% vs 40% needed. Arcing in ESP.

Distinctive Characteristics: High EF, non vented dryer with <5yr payback.

- Combined Nebulizer/ESP for water extraction and recycling of latent heat
- IR heating system tuned (~3um) for optimum heat transfer to water



Progress and Accomplishments

Accomplishments: Reduction of theory to practice through demonstration of water extraction using the proposed technology.

Market Impact: Broad and far reaching. Program infancy makes impact unclear.

Awards/Recognition: Invention disclosure submitted.

Lessons Learned:

- Significant unforeseen issues were encountered while making in system droplet growth measurements using laser diffraction. Insufficient vapor densities were the main issue. Progress has been made making offline nebulizer drop measurements.
- Preventing arcing in the wet electrostatic precipitator turned out to be a much larger effort than anticipated, requiring architecture and material redesign.
- Attaining submicron, “Rayleigh limit”, charged droplets at the desired density requires innovation in electrospray head design

Droplet Growth Modeling

Matching k_E to experiments of Arif-UZ-Zaman et al.

At steady state the diffusive flux has to cancel the electrostatic one.

$$\dot{m} = \underbrace{\frac{k_E(\epsilon_v - 1)}{\epsilon_0}\varphi_v v_v \nabla E}_{\text{Electrostatic flux}} - \underbrace{D_m Sh \frac{M_v}{M_a}\left(\left(\frac{p_v}{p}\right)_D - \left(\frac{p_v}{p}\right)_\infty\right)}_{\text{Diffusive flux}}$$

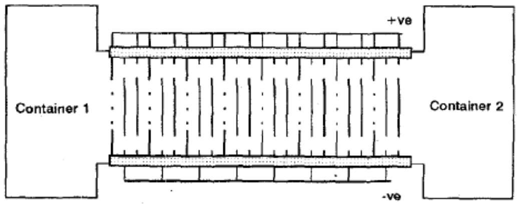


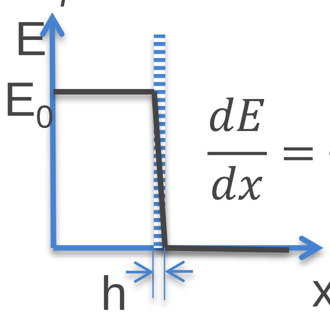
Fig. 8. Cross-sectional view of the array of electric plates with porous plate connected to positive potential.

Arif-UZ-Zaman et al. 1996

Constant, k_E is analogous to other transport properties like thermal conductivity, diffusion coefficient, etc.

Authors did not measure ∇E but estimate it with bias toward ∇E overestimation (k_E underestimation):

h=vapor molecule size



$$\frac{dE}{dx} = \frac{E_0}{h}$$

Table	K_e (mol s/m^3)	ΔRH Measured (%)	ΔRH Computed (%)	Mass flux (kg/s/m^2)
1	7.0e-11	2.4	2.4	4300
2	9.3e-11	3.2	2.98	7631
mean	8.15e-11			

1st complete continuum mechanics analysis for electrostatic droplet growth.

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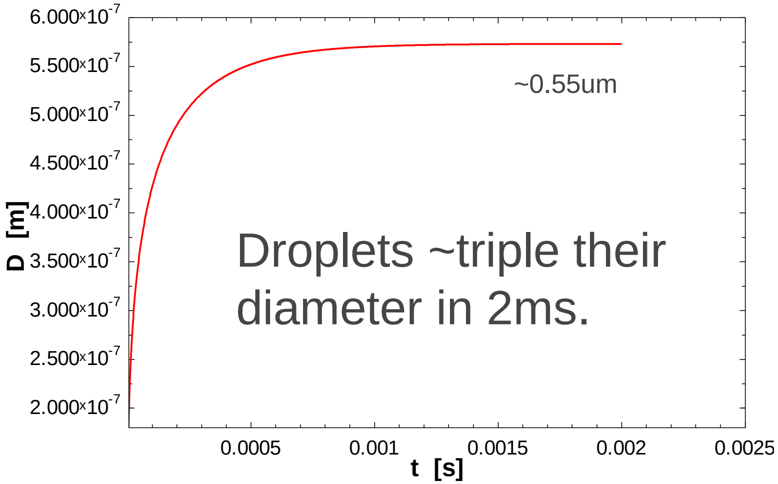
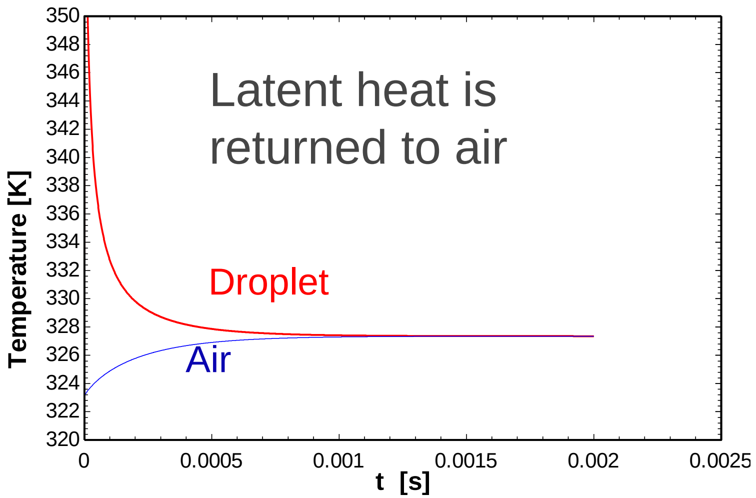
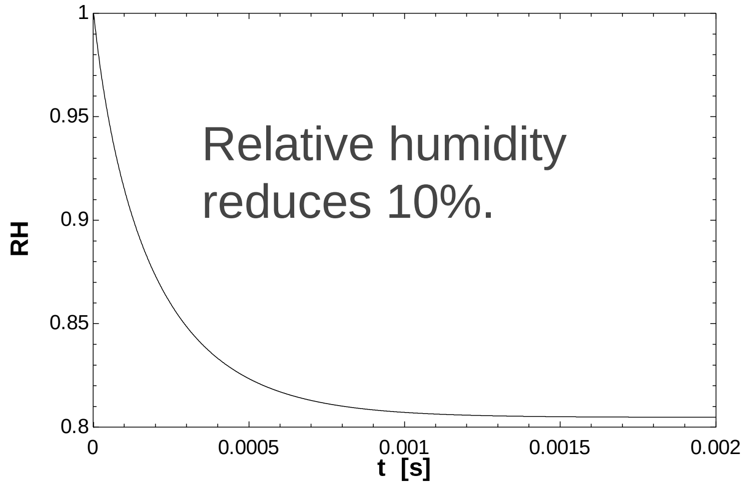
Droplet Growth Modeling Continued



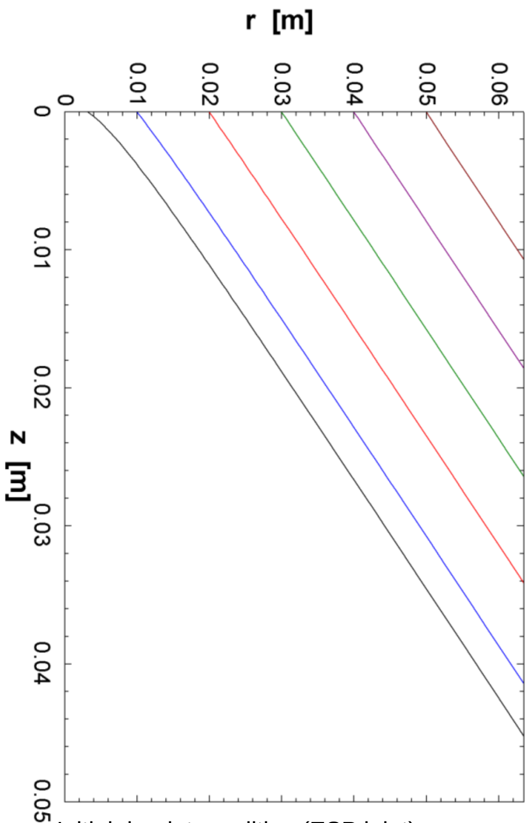




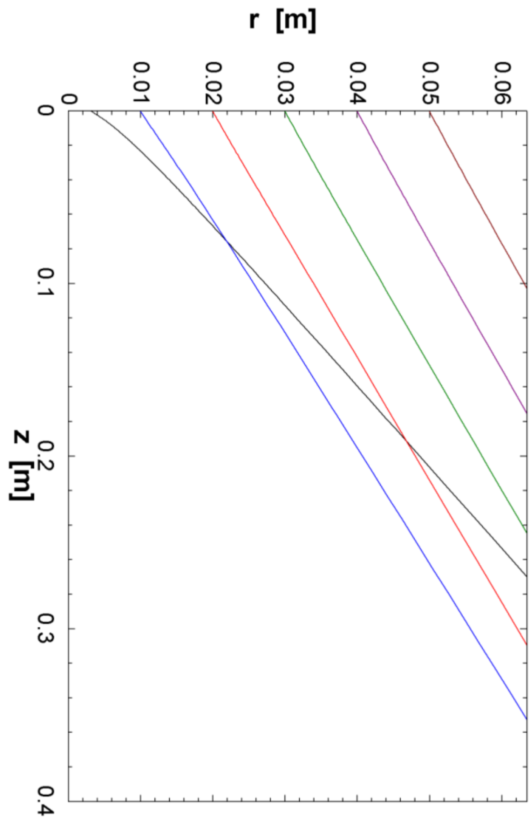
- Data shown for a magnitude increase of k_E
- It is conceivable that k_E is even larger.
- Numerical problem becomes stiffer as k_E gets larger.

Experimental calibration of k_E to be determined

Precipitator Modeling



Initial droplet condition (ESP inlet):
charge = Rayleigh limit for 250 nm diameter
drop diameter = **0.4 um**
(R1=1/8in, R2=2.5in, V=50kV, I = 4mA, u=8 m/s)



Initial droplet condition (ESP inlet):
charge = Rayleigh limit for 250 nm diameter
diameter = **4 um**
(R1=1/8in, R2=2.5in, V=50kV, I = 4mA, u=8 m/s)

Downward view into GE precipitator while energized. Top photo 25KV, bottom photo 27.5KV

<u>Small droplet diameter example</u>
No charging in ESP
Droplets keep initial charge
Initial charge important for capture

<u>Large droplet diameter example :</u>
More charging in ESP
Larger drag
Initial charge not so important

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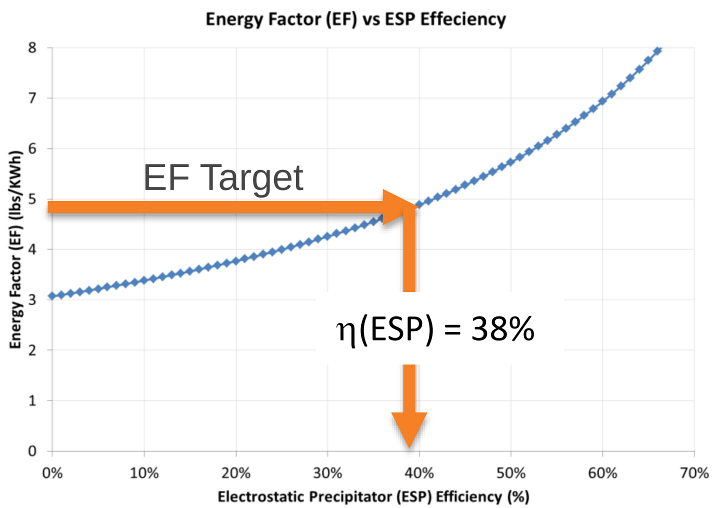
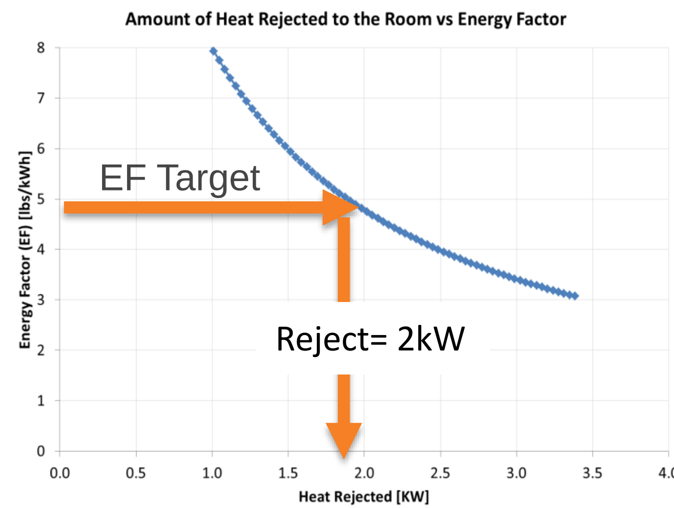
System Modeling





A target EF of 4.8 lbs/kWh can be achieved with an ESP efficiency of less than 40% and ~2 kW rejected to the room for the duration of the cycle

Stage	Time		Conventional		Ventless ESP		Ventless ESP with IR	
	[mins]	[hrs]	[kWh]	[kW]	[kWh]	[kW]	[kWh]	[kW]
Bulk Drying	23	0.38	1.99	5.19	0.968	2.53	0.678	1.77
High Heat	30	0.50	0.91	1.81	0.907	1.81	0.635	1.27
Total	**53**	**0.88**	**2.90**	**7.01**	**1.875**	**4.34**	**1.313**	**3.04**

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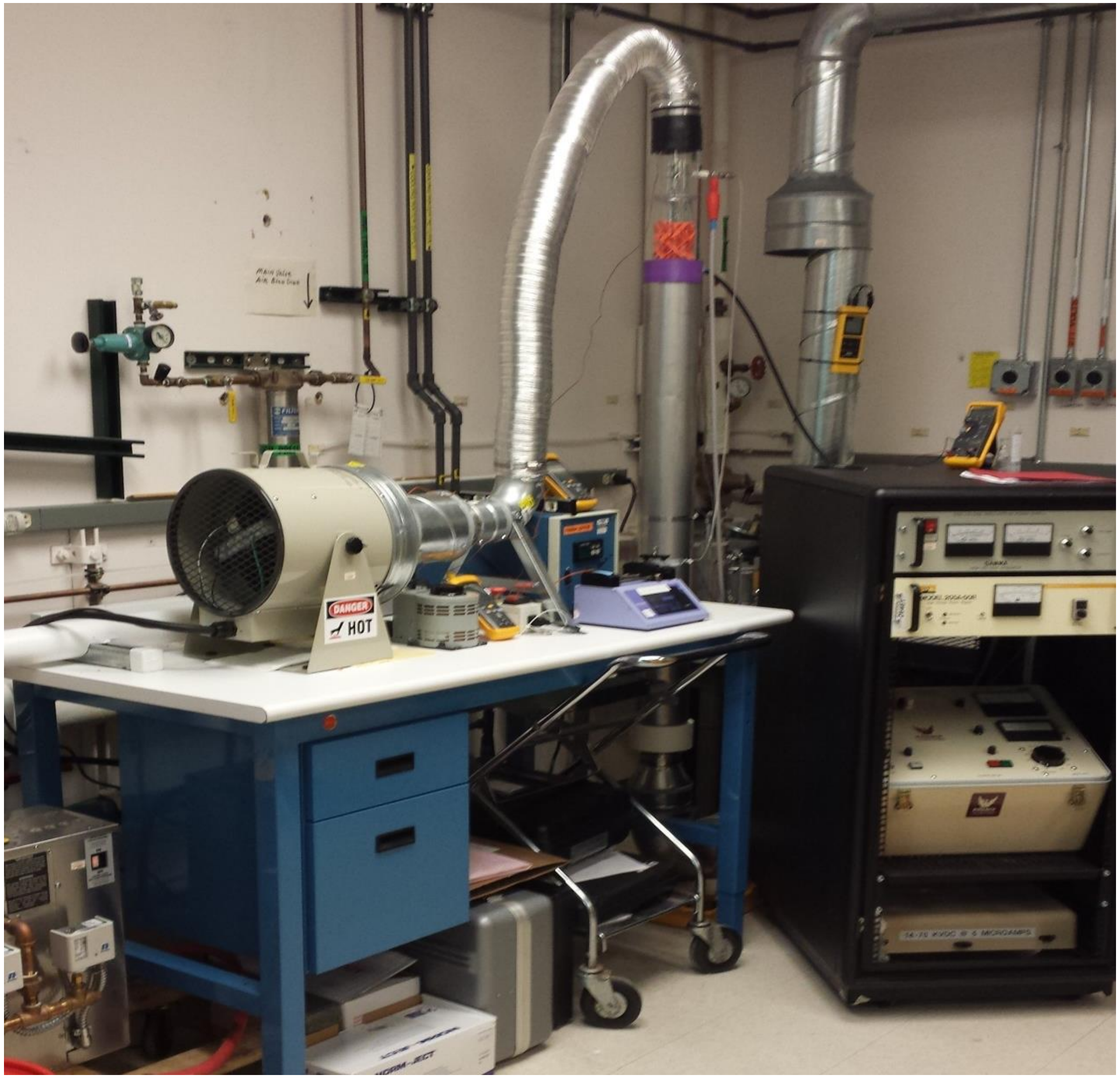
Dryer Simulator Test System Design



Dryer Simulator test system

Controls for:

- Steam Input/Humidity level
- Variable speed fan
- Heat Input
- Variable speed fan control
- Syringe pump for Nebulizer feed
- High voltage for Nebulizer
- High Voltage for Precipitator

Instrumentation for:

- Totalized water input to steam generator
- Temperature – multiple points
- Humidity – multiple points
- Pressure – multiple points
- Air Speed
- Total collected water

Air speed monitoring

Nebulizer Design

Nebulizer Design/Components
- Hypodermic needle 27-33 gauge
  - Single and multi nozzle designs
- High voltage supply 12-25KV
- Supply fluid, counter electrode design

Key Design Considerations
- Produce submicron droplets
- Highest charge transfer
- Least spray contact with counter electrode
- Must supply a volume flow >1ml/min

Functionality Measurements

Charge Transfer

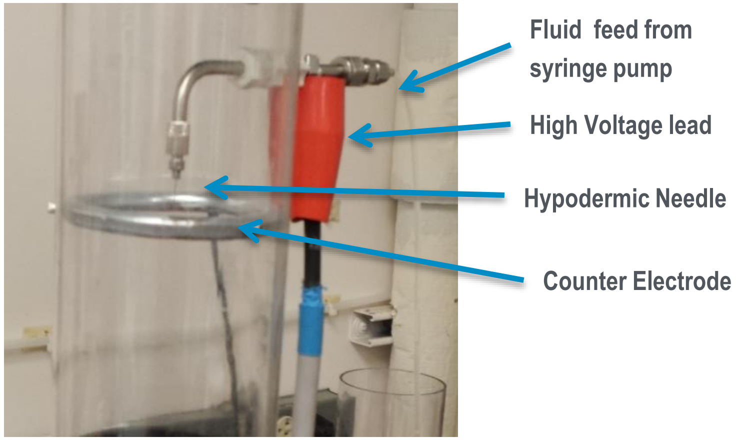
Commercial Charge Plate Monitor Utilized

Variables examined
- Needle size
- Flow
- Electrospray Voltage
- Counter Electrode Configurations
- DI, City, and Surfactant spiked DI water

Optimum Conditions exist when:
- Minimum droplet size achieved
- Uniform cone spray observed
- Fastest charge/discharge times achieved

Droplet Size Measurement
- Laser Diffraction
  - Bench top and in system
- High speed imaging

Basic Nebulizer Setup



Various Counter Electrode Designs

Commercial Charge Plate Monitor

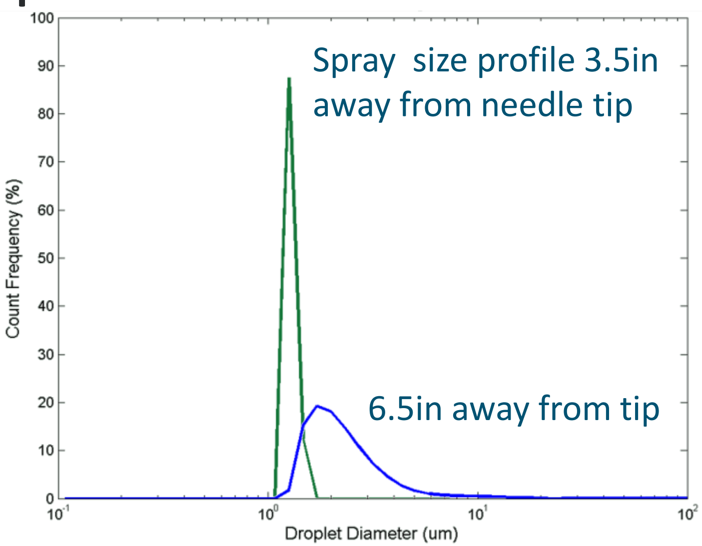
Image of Electrospray from needle tip

Droplet Size Measurement

2015: Data from System

Electrospray "Kink-type" instabilities agree with mode descriptions in literature

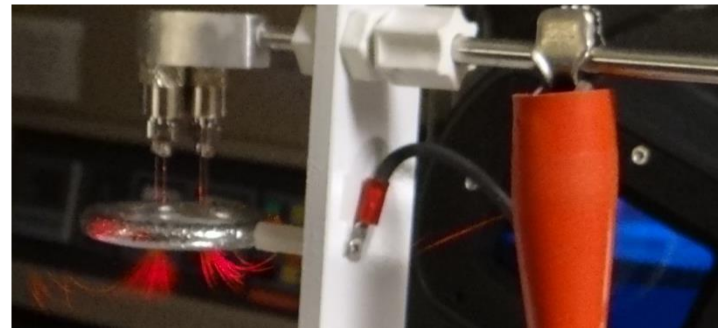
Droplets measured with laser diffraction



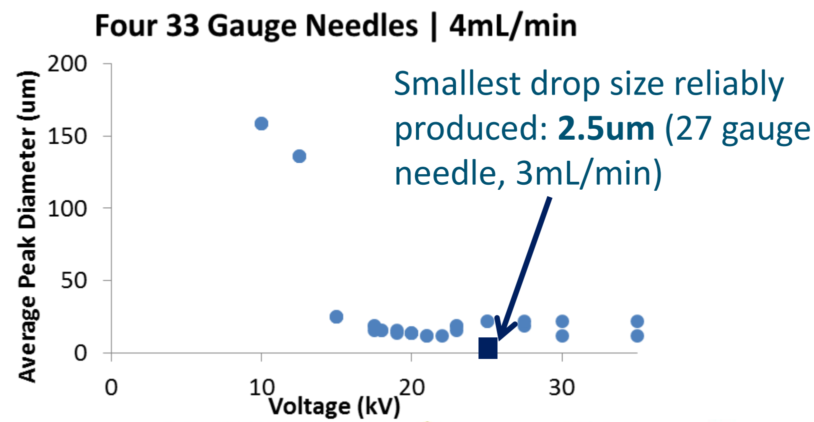
- Goal: measure droplet growth in steam
- Low spray density, window obscuration, and steam cycles led to poor repeatability

2016: Data from Benchtop

Spray duplicated on benchtop to improve measurement conditions



- High spray density produces highly repeatable data
- Reduce drop size by optimizing voltage, flow rate, nozzle geometry, and ground distance



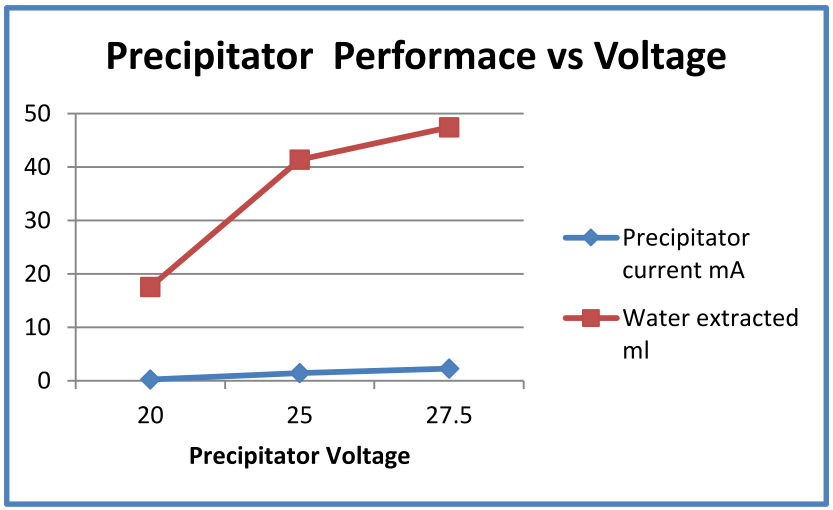
Precipitator Design and Performance

Precipitator Design

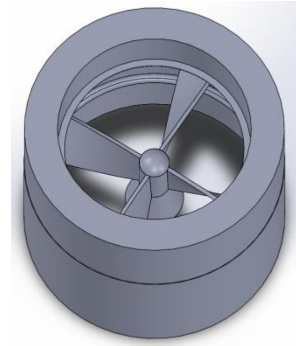
- Target Length > 0.8m
- Wet operating Voltage ~25KV
- Current >1mA

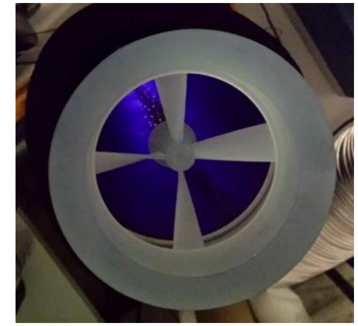
Modifications to Address Arcing

- Electrode top and bottom holders redesigned several times
- Several material types used
    - ABS, PLA, Watershed
- Overcoat materials examined
    - Epoxy, Acrylic, Urethane
- Use of hydrophobic coatings

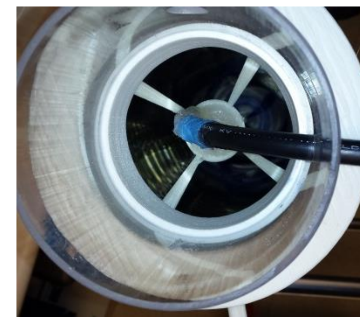


48" Precipitator



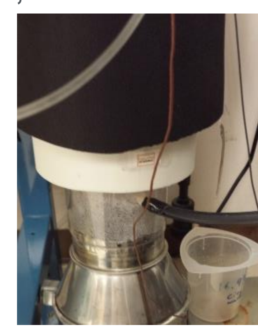


Rev 5 Top Electrode holder, model left actual right



Rev 2 Top Bottom electrode holder, model left actual right

Precipitator Electrode



Precipitator Extractor Section

Experimental results to Date

Adjusted Steam input ml	Nebulizer KV	Nebulizer I uA	Precipitator KV	Precipitator I mA	Water extracted ml	Efficiency %	Run type
742	0	0	0	0	0	0	Steam only
678	0	0	25	1.05	41.34	6	Precipitator only
652	15	30	0	0	18.4	3	Nebulizer only
681	15	30	25	1.03	88.86	13	Full system

*Tests shown demonstrate the best measured performance to date, for a 10 minute run, for each condition
*Data repeatability is +/-10%, largest variance is due to steam input fill cycling

- Best prior efficiency measured to date was 7.3% on 12/2015.
- Current best efficiency 13% (attribute this to precipitator improvements).
- Zero collection with "Steam only" shows no condensing in precipitator.
- Collection with "Precipitator only" suggests a population of larger droplets exists.
- Collection with Nebulizer only is due to injected charged droplets being attracted to the grounded precipitator walls.
- ~2X increase in collection with "Full System" operation suggests theory is working
- Need optimization of parameters to increase efficiency.

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Driving towards smaller droplets

Multi-nozzle Head Approach

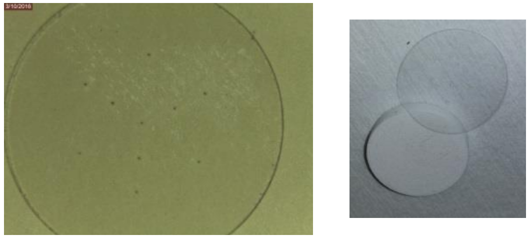
- Investigating <100u diameter nozzles
- Placing multiple nozzles in parallel
- Maintaining flows >1ml/min
- Aimed at driving droplet size to <1um

Gen 1 Multi-Nozzle design

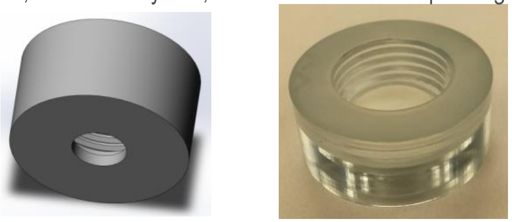
- Laser drilled/cut 170um thick glass
- 25um and 50um hole sizes
- Hole arrays of 3,5,8 and 10 holes
- 2.5um glass frit filter ahead of nozzle plate
- Droplet size and charge tests in progress
- System installation and testing to follow

Lower Cost multi-nozzle approaches

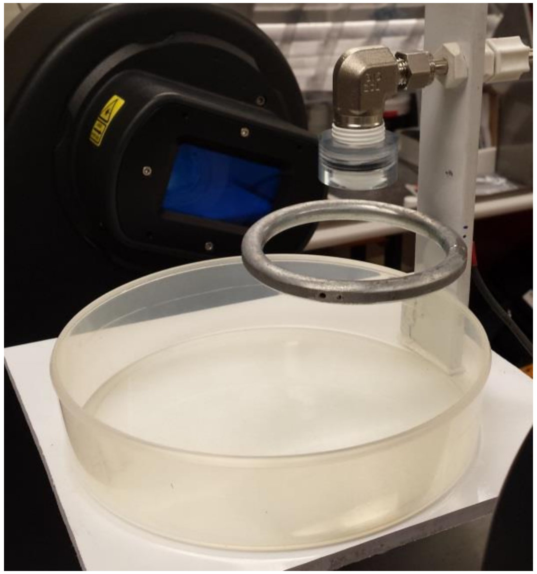
- Multi Lumen tubing
- Vendor- Zeus Inc.
- Materials PFA, FEP ,PTFE



50um, 10 hole array lefft, filter and 50um 5 hole plate right



Multi-nozzle spray head holder, model left actual right



Benchtop Multi-nozzle spray test setup

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Project Integration and Collaboration

Project Integration: The project staff routinely collaborates with internal "GE Experts" and BDM's to accelerate development.

Partners, Subcontractors, and Collaborators: DOE

Communications: NA to date. Research publications to follow.

Next Steps and Future Plans

Short term plans going forward:

- Increase efficiency to meet Phase 1 Milestones prior to 6/30/2016.
- Optimization of Nebulizer parameters
  - Droplet size <1.0um
  - Flow ml/min >1ml/min
  - Optimize Nebulizer parameters for system efficiency
  - Examine dryer exhaust flow regimes (laminar to turbulent)

REFERENCE SLIDES

Project Budget

Project Budget: DOE $1,040,040, Cost share $260,001
Variances: No cost extension for 6 months applied for 12/2015. Currently operating at risk.
Cost to Date: $670,271
Additional Funding: NA

Budget History					
Start Date –10/1/2014 (past)		FY 2016 (current)		FY 6/30/2017 –End Date (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
125,461	31,365	536,217	134,054	503,823	125,947

Project Plan and Schedule

- Project origination date 10/1/2014, Completion date 6/30/2017
- First Milestones 12/31/2015 – Demonstration of 40% extraction efficiency
- Milestone not met, 7.3% efficiency demonstrated
- 6 Month no cost extension requested, currently operating at risk.

Milestone summary table.

Recipient Name: GE Global Research Project Title: Energy Efficient Clothes dryer with IR Heating and ESP						
Task	**Milestone Type**	**Milestone Number**	**Milestone Description**	**Milestone Verification Process**	**Anticipated Date**	**Anticipated Quarter**
1.Dryer System Level Design	Milestone	M1.0	Report summarizing the dryer design and required subcomponent performances to exceed an EF of 4.04	Report submitted to DOE	3	1
2. Design and Testing of the ESP and Exchanger	Milestone	M2.1	Demonstration of an ESP meeting the system Subtask1.1 requirements	Measured results from ESP testing	12	4
2. Design and Testing of the ESP and Exchanger	Milestone	M2.2	Report summarizing the ESP design and performance	Report submitted to DOE	21	7
2. Design and Testing of the ESP and Exchanger	Go/No-Go 1 No-End Program	Go/No-Go 1	Measured efficiency of the ESP must meet system requirements from Subtask 1.1	Measured results from the ESP testing	21	7
3.Design and Testing of the IR heater system	Milestone	M3.1	Demonstration of IR dryer assembly meeting requirements of Subtask 1.2	Measured results from the IR dryer testing	27	9
3.Design and Testing of the IR heater system	Milestone	M3.2	Report summarizing the IR heater design and performance	Report submitted to DOE	27	9
4. Integration, testing and optimization of the IR/ESP clothes dryer	Milestone	M4.1	Demonstration of integrated dryer exceeding 4.04 EF	Measured results of integrated dryer testing	33	11
4. Integration, testing and optimization of the IR/ESP clothes dryer	Milestone	M4.2	Report summarizing the integrated dryer performance	Report submitted to DOE	33	11
5. Technology to Market Strategy Plan and Commercialization	Milestone	M5.1	1.Develop a detailed market strategy and commercialization plan with a market analysis of potential sales and an evaluation of potential US jobs created by commercialization. A target range for total system cost will be identified.	Report submitted to DOE	33	11
5. Technology to Market Strategy Plan and Commercialization	Milestone	M5.2	2.Identify potential US manufacturers of required system components.	Report submitted to DOE	33	11