Assessment of Contrail Formation via Combustion of SAF
Project 102

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Project manager: Prem Lobo, FAA

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Assessment of Contrail Formation via Combustion of SAF

University of Illinois at Urbana-Champaign

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PM: Prem Lobo

Cost Share Partner(s): Convergent Sciences

Objective:

Develop a laser/optical experimental platform to
(1) Understand the physics of contrail formation
(2) Investigate contrail formation for fuels with varying composition
(3) Integrate test data with modeling and flight-based experiments

The project will allow us to study the fundamental physics of contrail formation at the molecular level in a completely-controllable environment design to mimic various atmosphere conditions.

Project Benefits:

This project would help to create a scientific foundation for contrail formation by studying the impact of fuel composition. It will complement and inform chase-plane tests. The data will help-to improve environmental models to better optimize flight paths to mitigate contrails.

Research Approach:

Establish a standard method of studying contrail physics to (1) allow consistent prediction of the effect of fuel composition on contrail production, (2) improve radiative forcing models by characterizing ice-crystal formation sizes and scattering, (3) provide the ability to corroborate data from other laboratory experiments, flight tests, and environmental models, and (4) to provide an additional experimental platform for testing novel laser/optical diagnostic methods for soot and contrail analysis.

Major Accomplishments (to date):

- Design and development of the altitude chamber.
- Identification of the laser/optical diagnostic methods
- Development of the control systems for humidity, temperature, and pressure
- Determination of the combustor requirements and methods
- Characterization of combustor soot
- Set up collaborations with Sandia, NASA, and NREL

Future Work / Schedule:

- Sourcing of diagnostic and control systems
- Shakedown of experimental platform plumbing
- Integration and characterization of diagnostic techniques
- Characterization of the chamber

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Introduction

Motivation

- Increased interest in understanding fuel composition impacts on contrail formation

Research Objectives

- **Develop altitude chamber** that can mimic relevant atmospheric conditions
- **Analyze ice nucleation** and growth around soot produced through the combustion of SAF
- **Analyze scattering** from ice crystals and aerosols for various wavelengths
- **Assemble experimental data** to better inform current climate models and to predict contrail production

Schedule and Status

Schedule

- December 2025 – complete characterization of combustor soot properties (size, chemistry, porosity) at lean, stoichiometric, and rich burn conditions
- February 2026 – environmental characterization of larger UIUC chamber
- March-April 2026 – expected completion of mini UIUC chamber
- April 2026 – complete shakedown of spectroscopy and DAQ setup
- June 2026 – analysis of soot within UIUC chamber
- July 2026 – initial analysis of contrail ice crystals and soot nucleation

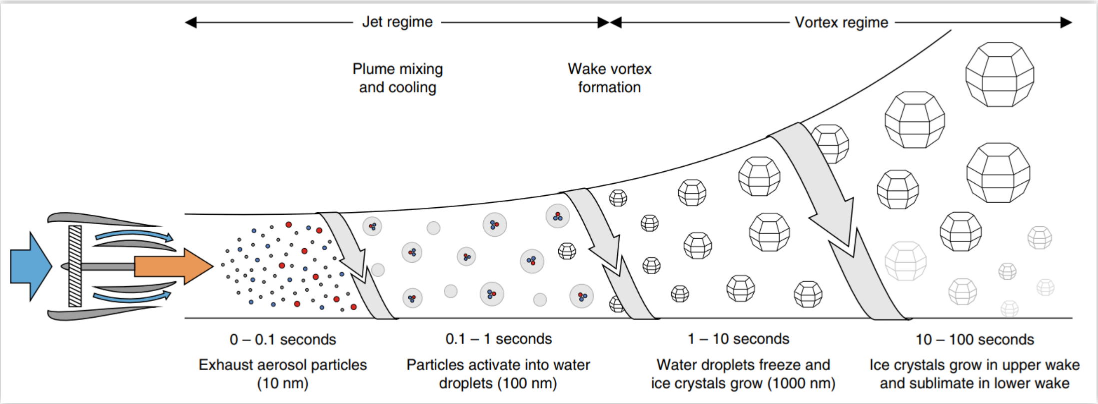
Status

- Combustor development completed
- Analysis of primary particle diameters actively being completed
- Analysis of elemental/organic carbon ratio actively being completed

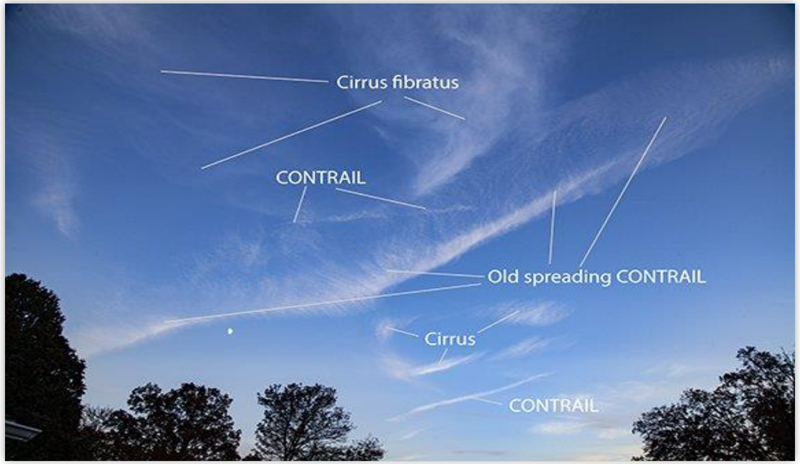
CONTRAIL PROPERTIES

Condensation Trails

- Condensation trails (contrails) are clouds produced by water vapor and soot found in engine exhaust
- Soot particles act as nuclei for water condensation, leading to ice crystal formation



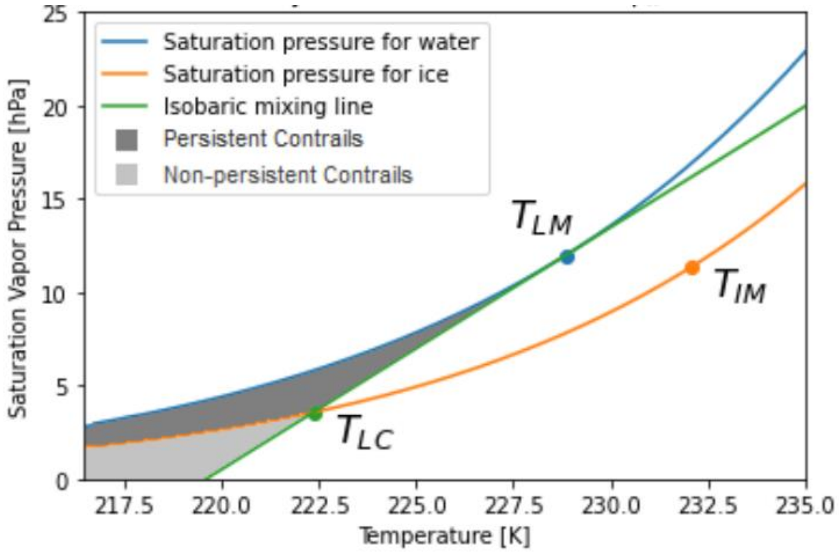
Kärcher 2018



https://www.weatherbriefing.com/weather-blog/2022/11/2/clouds-of-the-day-cirrus-fibratus-and-contrails

Schmidt-Appleman Criterion (SAC)

- Formation depends on ambient pressure, humidity, and the ratio of water and heat released
- Contrails generally form at cruising altitudes at temperatures < -40 ℃
- $T_c = T_m - \frac{1}{G}(e_{sat}(T_m) - U_{amb}e_{sat}(T_c))$

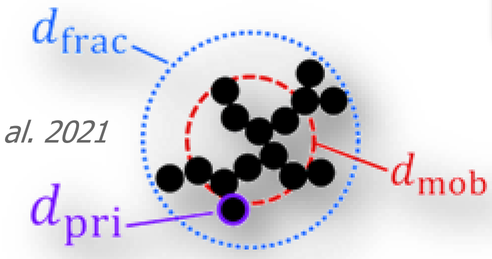


Roosenbrand et al. 2022

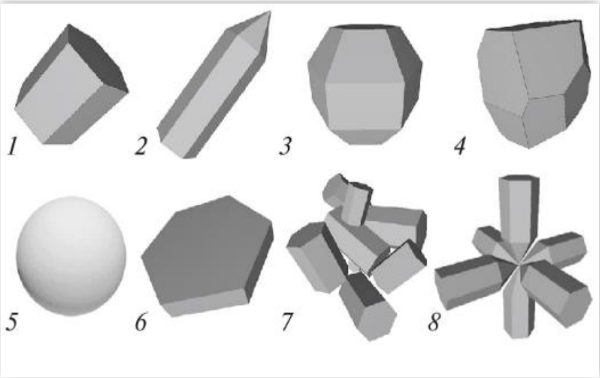
Nucleation and Soot Parameters

Particulate Matter

- Non-volatile particulate matter (nvPM)
  - Elemental carbon (black carbon)
- Volatile particulate matter (vPM)
  - Engine lube oil
  - Unburnt hydrocarbons
  - NOx
  - SOx



Lao et al. 2021



Shishko et al. 2022

Soot Size Parameters

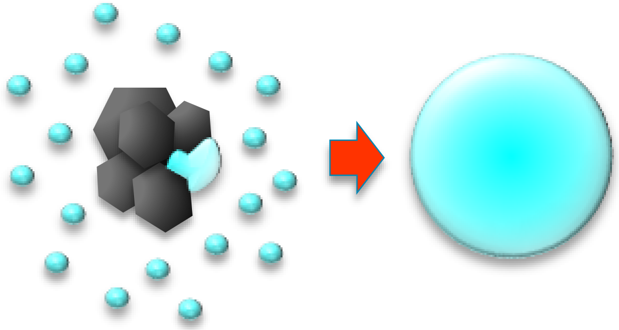
- Primary particle diameter
- Mobility diameter
  - Cross-sectional area perpendicular to motion
  - Determines drag and electrical mobility
- Fractal diameter
  - Measure of complexity and therefore light scattering efficiency

Ice Crystal Parameters

- Effective size (equivalent diameters)
- Shape/Roughness
- Mass transfer and droplet growth
  - Vapor Deposition
  - Riming
  - Aggregation
- Sublimation efficiency within wake
- Ice crystal distribution
- Ice water content

Homogeneous vs Heterogeneous Freezing

- Homogeneous freezing of water-activated PM is the primary mechanism for contrail formation
- Homogeneous
  - Spontaneous
  - Defined by SAC
  - Does not require external particles
- Heterogeneous
  - Caused by external particles (nuclei) with porous forms
  - Results in freezing at higher-than-expected temperatures
  - Dependent on particulate shape, porosity, and outer chemical nature



Contrails generally form heterogeneously within nucleation sites of soot (nvPM)

TEST CHAMBER METHODS

UIUC Chamber Design

- Based on Sandia National Laboratories (Livermore) Chamber
- Double-walled chamber cooled by TMC HFE-347E Fluoro-Solvent
- 4 double-paned rectangular optical windows (21.75" x 1.75") with internal vacuum
  - Corning 7980 fused silica
  - TSC-3 fused quartz
- 12 large and 8 small conflat ports for specialty optical windows and sensors
- Top cap with 2 ports for sensors and one central exhaust port
- Bottom cap with 6 tubes for cooled Air/N2 co-flow mixture
- Central sample tube for soot particles

Mini-chamber Design

Temperature controlled, vacuum chamber with optical access

UIUC Experimental Platform

Edwards nES220 Rotary Pump

- Pumping speed 105-125 cfm
- Ultimate vacuum 0.08 mbar

TEMPCO Circulation Heater

- Temperature range 15C to 121C
- 6000W with 48W/sq in
- Protects pumps from cold exhaust

Soot Analysis

- Transmission Electron Microscope (TEM) for primary particle size
- Sunset Lab EC/OC Scanner for elemental/organic carbon ratio
- TSI SMPS for mobility diameter
- ASAP 2020 for specific surface area and porosity

Vacuum Exhaust Panel

- Used to open chamber to vacuum system
- Controls rate of exhaust leaving the chamber

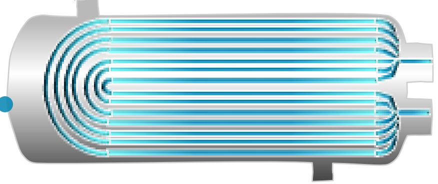
Air and Nitrogen

Co-flow Panel

- Air and/or nitrogen sent through cooling system to chill chamber and provide controlled environment

Water Cooled Thermonics Process Chiller

- Temperature range -80C o 25C
- 1800W cooling at 6GPM

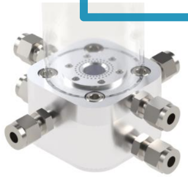


Heat Exchanger

- Transfers heat from air/nitrogen to coolant fluid
- Provides coolant to chamber walls

Combustor

- Designed to provide soot at variable but consistent sizes
- Burns liquid fuel



Diffusion Dryer

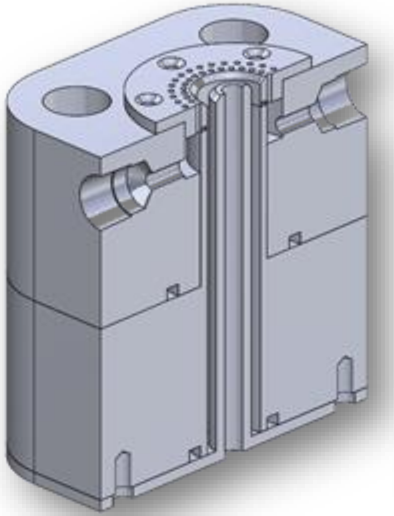
- Removes moisture from soot samples for instrument analysis

SOOT PRODUCTION

Combustor Design Iteration

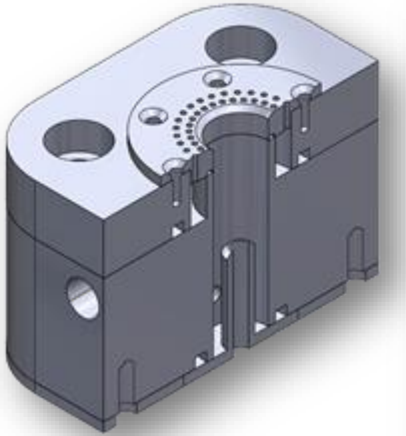
Version 1

- Oxygen & Methane pilot flame
- Evaporated fuel mixes with nitrogen and is injected axially
- **Extremely unstable and "sooty" flame**



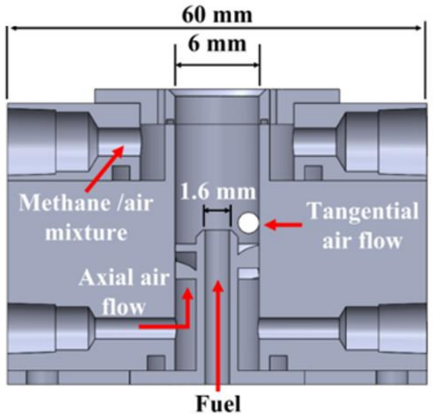
Version 2

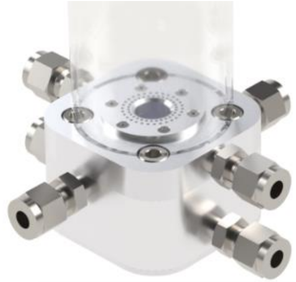
- Inner cavity for mixing is added
- Axial air flow added
- Tangential off-center air is added to increase swirl inside body
- **Relatively stable flame with "sooty" center and blue-stoichiometric base**

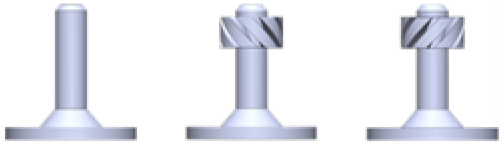


Version 3

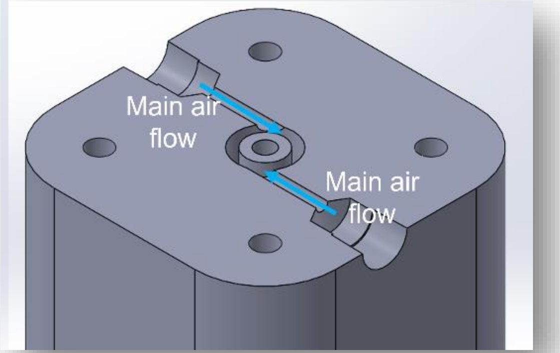
- Inner swirling body added to increase mixing
- Inline heaters added to air flows to match evaporated fuel temp to prevent condensation within body
- **Stable swirl flame with a well mixed blue color**
- Other inner bodies can now be used to produce controlled level of soot production along with fuel ratio





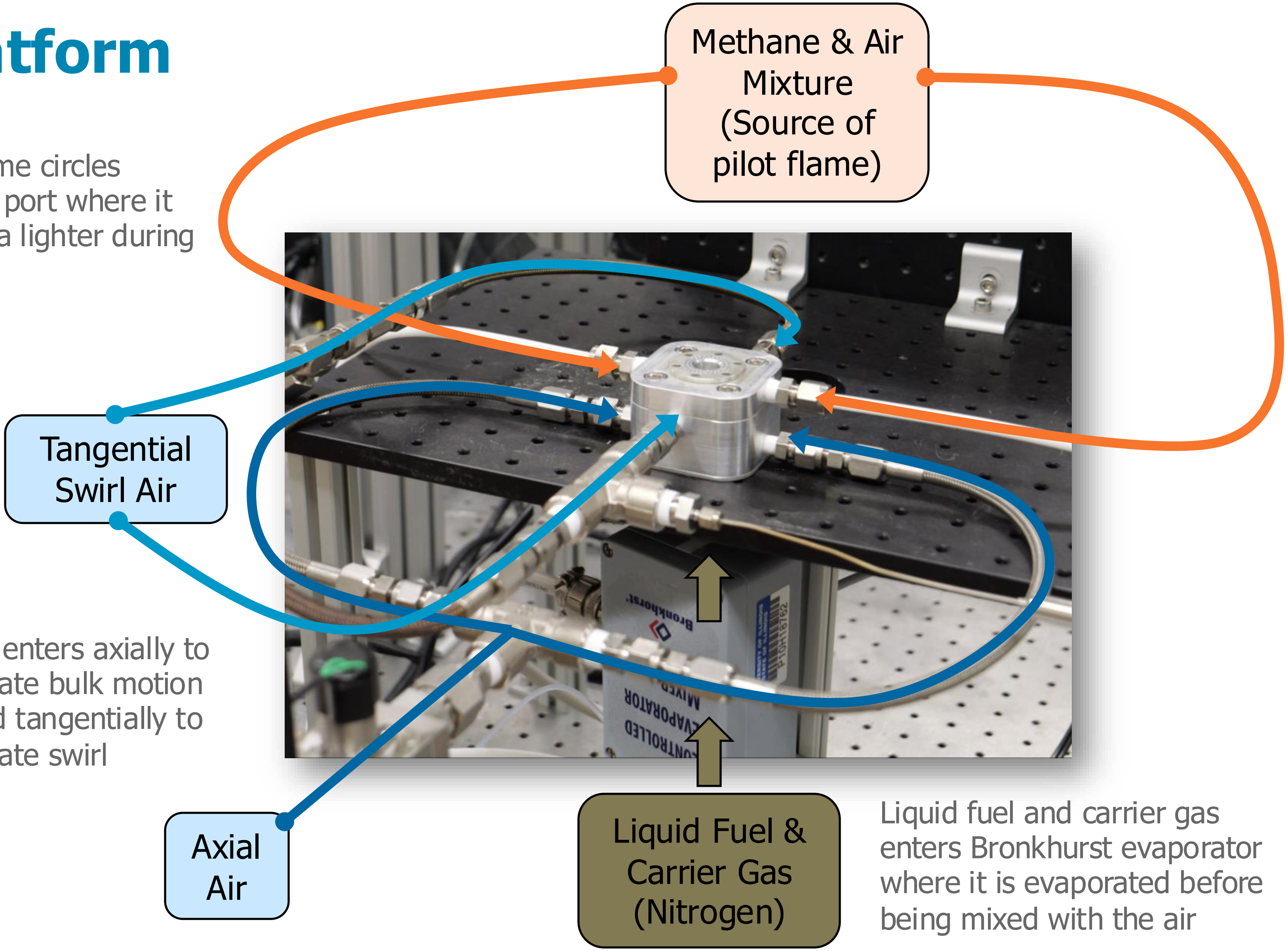


Soot Production Platform



Feature	Unit	Condition
Carrier gas (Nitrogen) flow rate	g/min	1.00
Tangential air flow rate	g/min	6.18
Axial/Swirl air flow rate	g/min	6.00
Fuel (Jet-A) flow rate	g/hr	30-50
Air temperature	K	413.15 - 453.15
Fuel (Jet-A) temperature	K	413.15 - 473.15
Methane flow rate (Pilot flame)	g/min	0.20
Air flow rate (Pilot flame)	g/min	3.42

Pilot flame circles exhaust port where it is lit by a lighter during a test

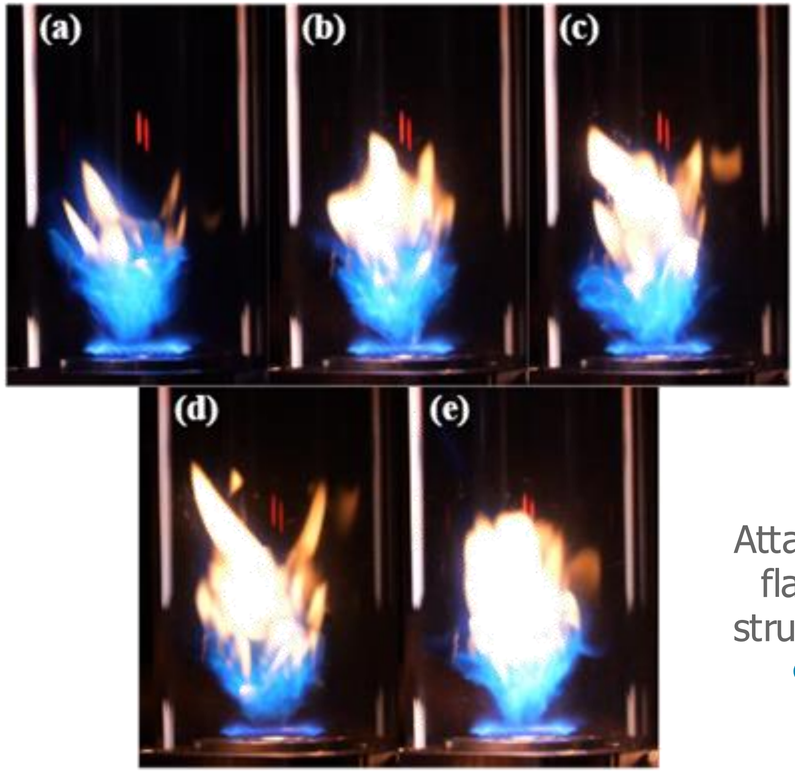


Air enters axially to create bulk motion and tangentially to create swirl

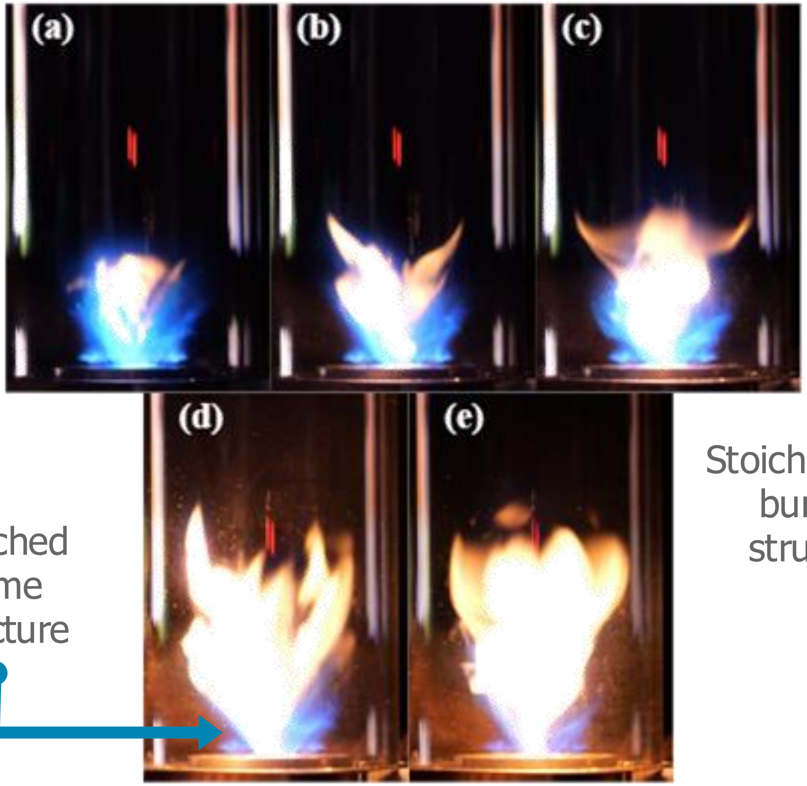
Liquid fuel and carrier gas enters Bronkhurst evaporator where it is evaporated before being mixed with the air

Combustor Flame Comparison

No Swirler

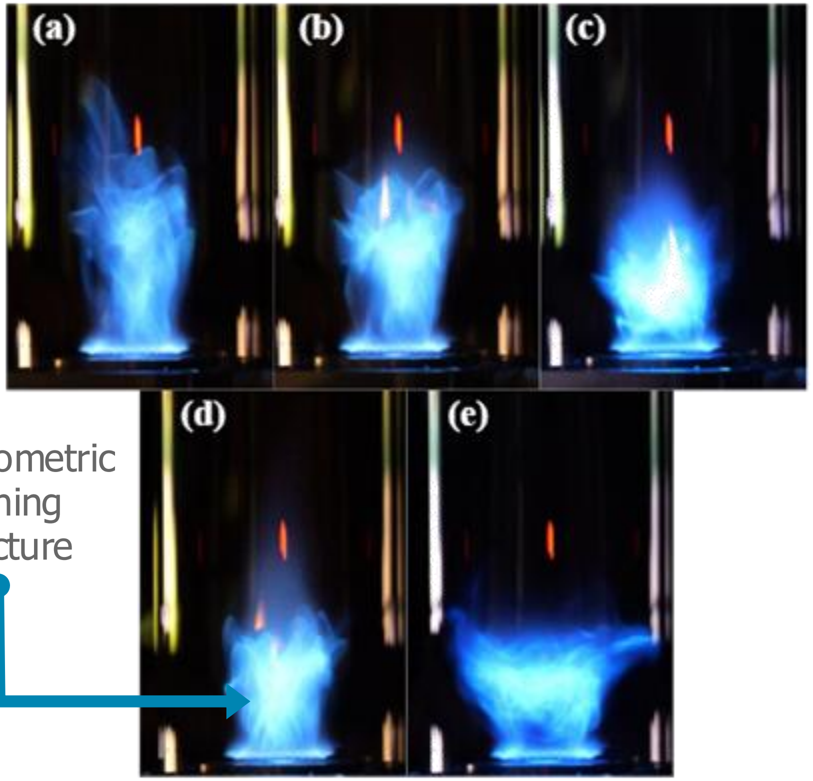


Uni-flow



Attached flame structure

Counter-Flow



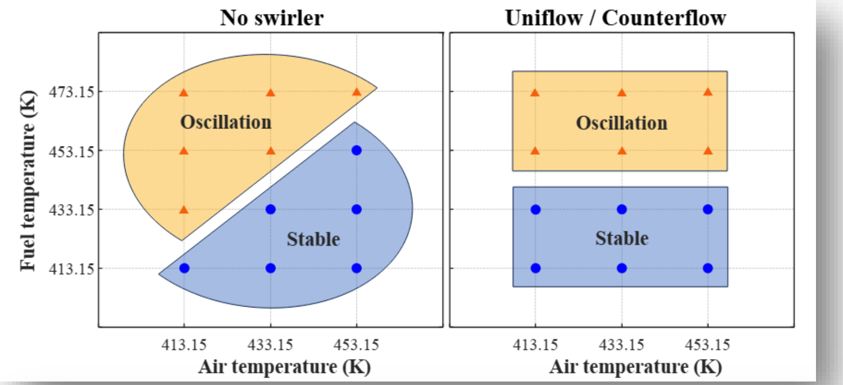
Stoichiometric burning structure

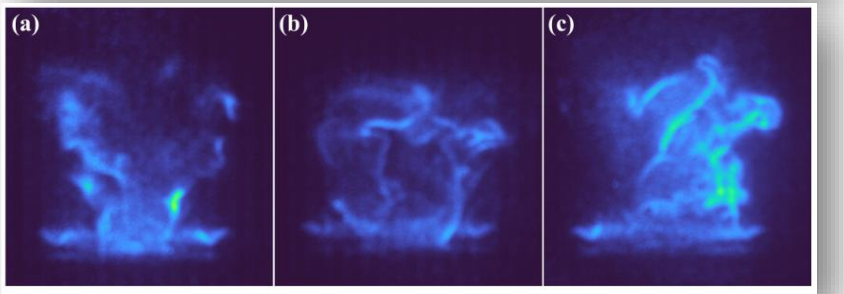
Flame images correlate to increases equivalence ratios from 0.6 to 1.0

Combustor Flame Stability and Efficiency

Air/Fuel Heating

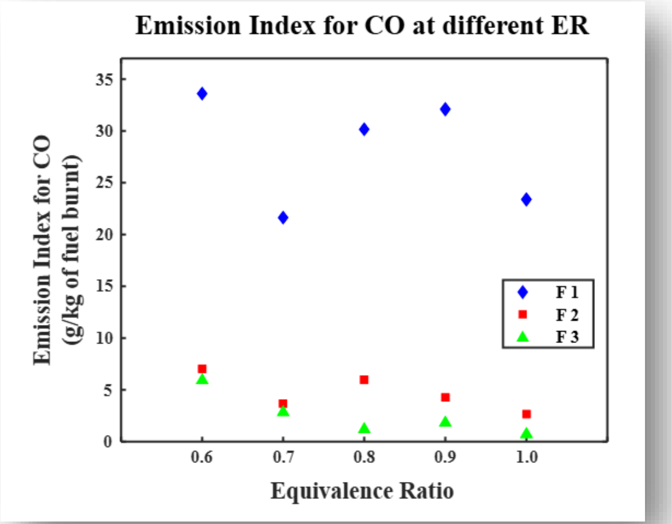
- Higher fuel temperatures lead to flame instability
- For swirlers, stability purely dependent on fuel temperature
- For no swirler, increasing air temperature for constant fuel temp encourages stability





CO Emission Index

- CO emission index used to determine combustion efficiency
- Swirlers experienced significantly higher efficiency (lower emission index)
- Efficiency tended to increase as equivalence ration approached stoichiometric
- $EI_{CO} = \frac{X_{CO}}{(X_{CO}+X_{CO_2})}\left(\frac{xM_{w_{CO}}}{M_{w_F}}\right)$



OH* Chemiluminescence Imaging

- The no swirler (a) suggests that air did not penetrate the fuel jet enough leading to insufficient mixing as OH* molecules populated bottom layer
- Uni-flow (b) suggests even heat release and mixing
- Counter-flow (c) suggests increase in heat release zone and intensity with strengthened turbulence, leading to enhanced mixing and efficiency

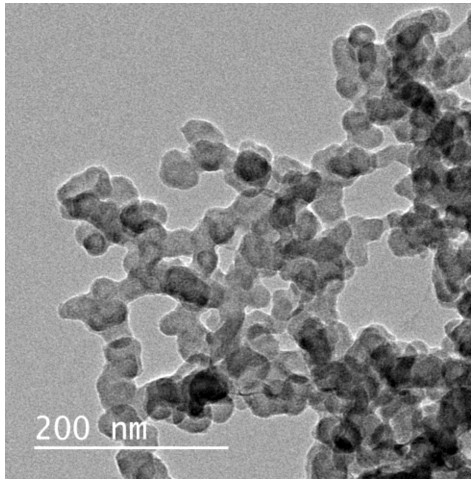
Primary Particle Size and Elemental Carbon Ratio

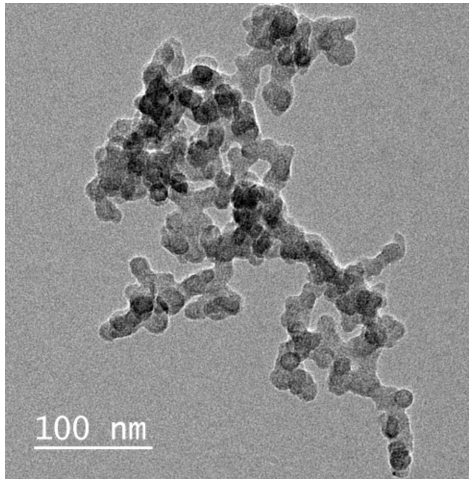
According to Yu et al. (2024), exhaust at contrail-forming altitudes have primary particle (PP) diameters of 5-30 nm and form aggregates of 20-50 nm in diameter

- Average: 27.28 for EQ = 1.0
  - Standard deviation: 6.63 nm

According to Scott et al. (2024), expected EC/TC (elemental carbon to total carbon) ratio for JetA1 is 0.75-0.95 for equivalence ratio 7-13

- Collected values are a maximum of 0.04 with no consistent trend for the range of 0.6-1.0
- Indicates burner may be inconsistent or too lean to match EC/TC of aircraft soot with straight inner body





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Summary

Enhancing the Understanding of Contrail Formation Physics

The goal of this project is to grow the knowledge of the basic formation physics of contrails, particularly as they pertain changes in the composition of the fuel being burned. To start, this involves understanding the composition of exhaust products produced in flight. From here, the ice nucleation rates for specific particles can be studied. As ice nucleates around the particles, ice growth and shape becomes of major concern. Finally, understanding how the ice shape and crystal numbers/density influences scattering will help to build upon radiative forcing predictions to estimate climate impacts of contrails formed through the combustion of SAF.

- **Nucleation rates** and ice crystal growth will inform contrail formation models for varying particles and fuels
  - Polarization data will help to accurately track changes in ice crystal growth/shape
- **Backscatter and extinction coefficients** will help to inform climate models
  - Individual particle/agglomerate data will improve modeling of interactions within larger cloud systems

Dr. Julien Manin & Dr. Deniz Kaya Eyice

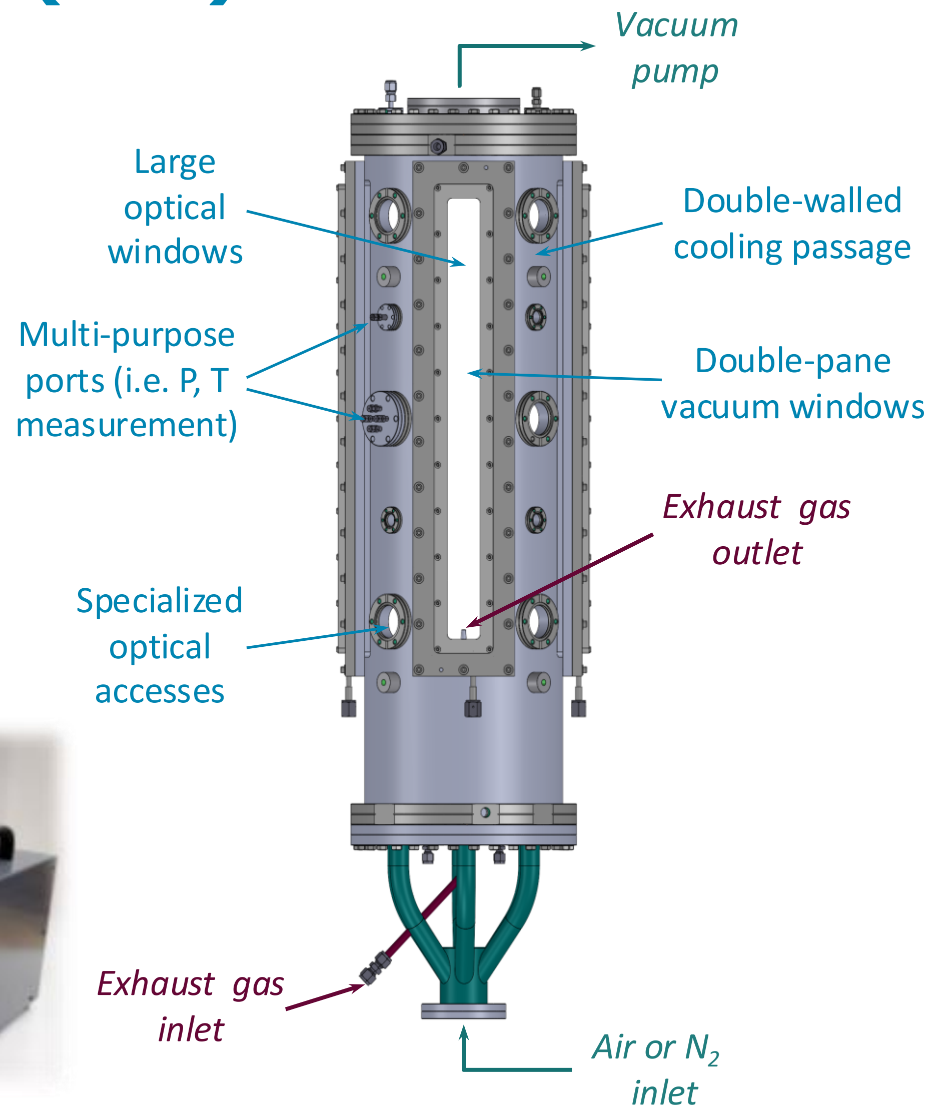
SANDIA NATIONAL LABORATORY (LIVERMORE)

Sandia's Atmospheric Physics Laboratory (APL)

- The Atmospheric Physics Lab (APL) at Sandia is a state-of-the-art altitude chamber facility aimed at studying contrail nucleation physics
- Temperature and pressure conditions from sea level up to the stratopause
- Large/specialized optical accesses to enable advanced optical and laser diagnostics deployment

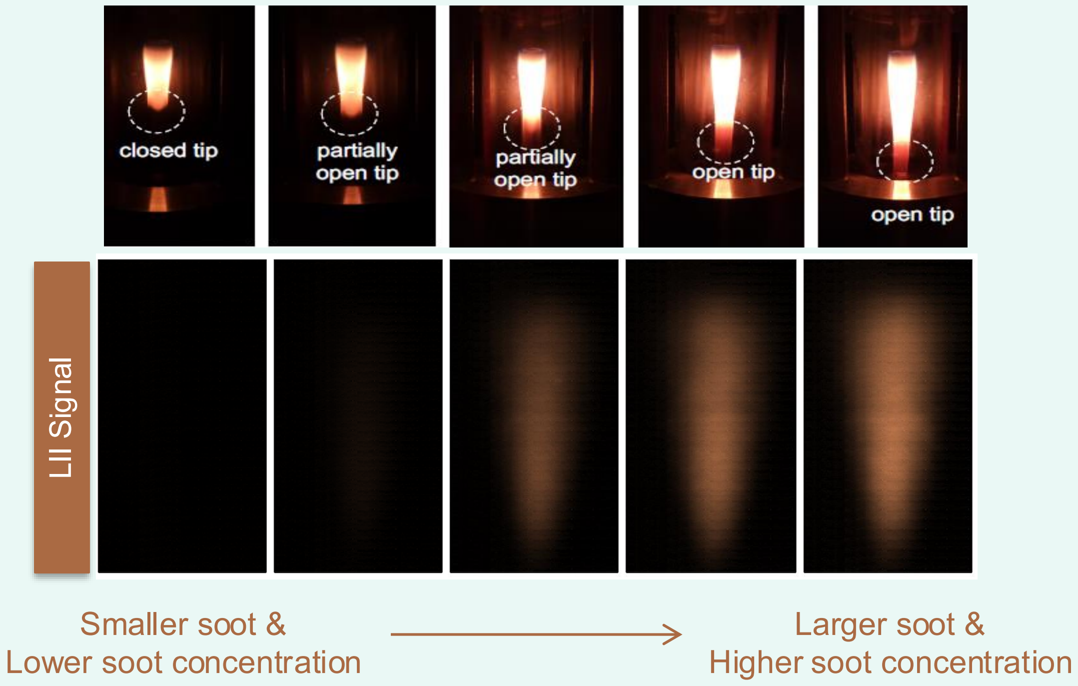
Parameter	Quantity
Pressure	0.001 atm to 1 atm
Temperature	200 to 300 K
Atmosphere surrogate	Air or N_2
Water content	Up to 1000 ppm
Air/N_2 Flow rate	Up to 10 g/s

- A miniature inverted soot generator was designed to produce exhaust streams that closely mimic soot emissions from jet engines

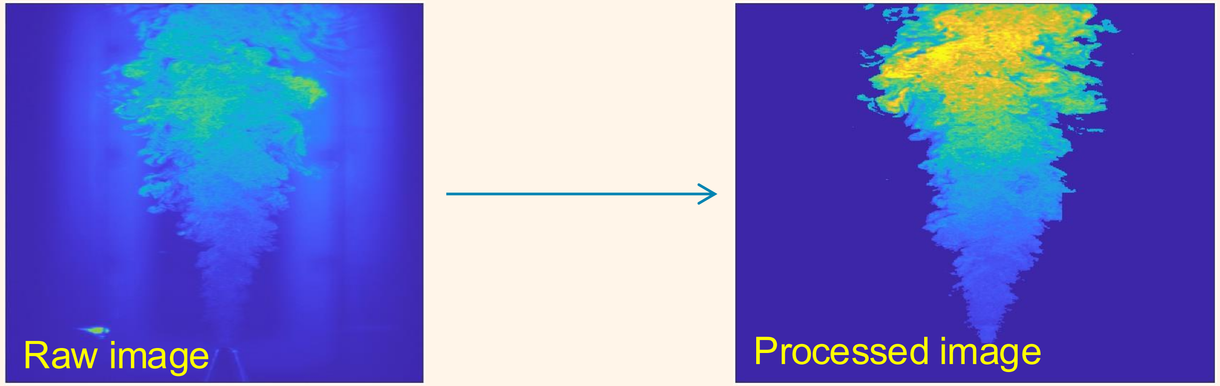


Characterizing soot emissions and contrails formation

- Soot emissions characterized via AVL Micro Soot Sensor (MSS) and AVL Advanced Particle Counter (APC) to measure PM mass and numbers
- Laser-Induced Incandescence (LII) is applied to observe and quantify the soot field inside the chamber

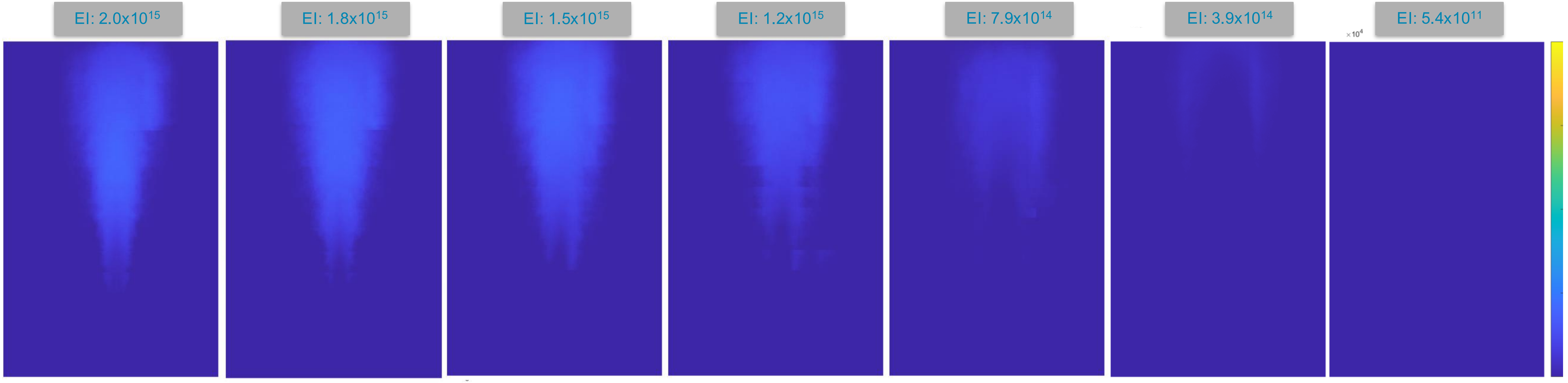


- Two-dimensional laser Rayleigh/Mie scattering diagnostic implemented to monitor contrail nucleation and growth
  - Diagnostic provides combined information about particle number density and size in a single measurement
- Enhanced dynamic range imaging to cover the wide intensity variations across conditions
- Advanced image processing methods to correlate contrail intensity with fuels and conditions



- Additional diagnostics already implemented or in development to scrutinize contrail formation process

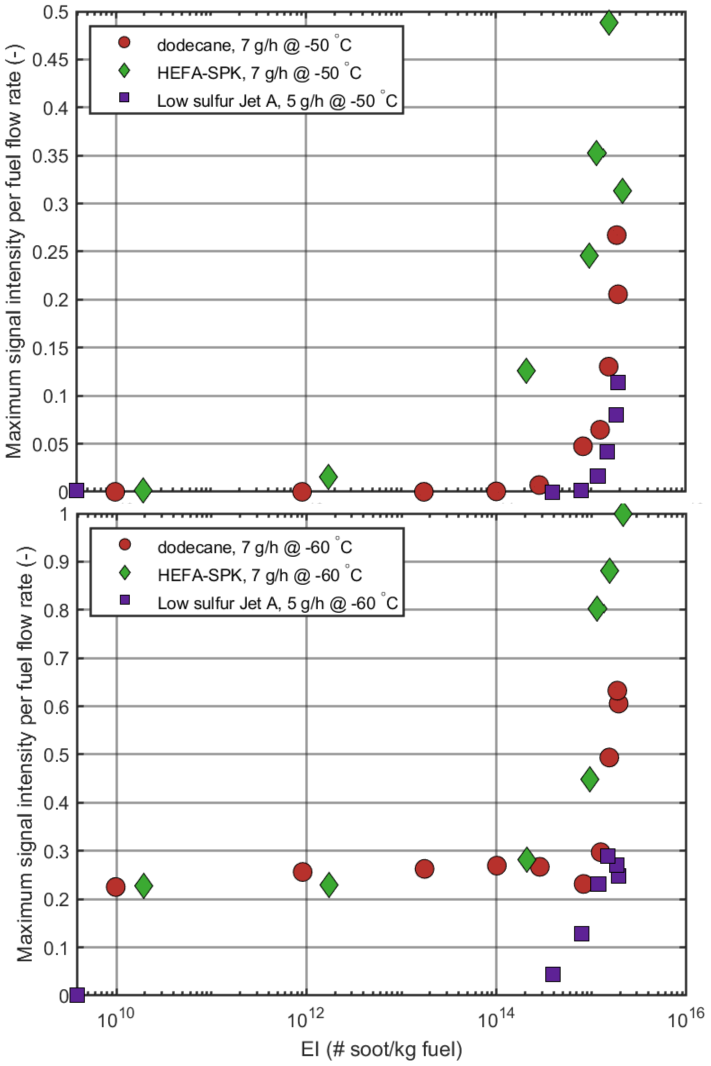
How important are soot emissions?



- Scattering intensity (or contrail thickness) is highly affected by the sooting level
- Measurements show that lower temperatures increase scattered intensity
  - Confirms that nucleation and/or growth rates increase as temperature decreases
  - Nucleation onset changes with temperature and sooting level
- Contrail still detected at extremely low soot levels (below instruments lower threshold) at lowest temperature
  - We also expect contrails to form downstream of the present field of view under some conditions…

Fuel: low-sulfur Jet A
Amb. gas: N_2 (dry)
Amb. temp.: -60°C
Amb. Press.: 30 kPa

The role of fuel-specific soot properties



- Comparing fuels over the particle number-based soot emission index reveals differences between fuels
  - Same fuel flow rate for HEFA and n-dodecane shows that n-dodecane produces "less" contrails than HEFA at equivalent soot emission levels
- Contrails still forming as soot emission levels decrease, with a near-constant intensity
  - This indicates that contrail formation becomes independent of soot emission level below a given threshold
  - This threshold appears to be around EI ($\#_{part.}/kg_{fuel}$) = 10^{15} in these experiments
- As already mentioned, contrails likely to form downstream of the measurement location
- Jet A fuel flow rate had to be set lower to cover the desired EI range, thus these results are not directly comparable
  - Our analysis, correlating these results with other fuel flow rate data, is that Jet A has a higher contrail growth rate for a given soot level
  - Compounded with the higher soot emission levels of Jet A, it is expected for more contrails to form using Jet A

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Participants

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- Anson Regi
- Connor Malley
- Kyra Schmidt (Sandia)

ENGINEERING AT ILLINOIS

Advanced Propulsion and Energy Laboratory

Sandia National Laboratories

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Paper Citations

Kärcher, B. (2018). Formation and radiative forcing of Contrail Cirrus. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-018-04068-0

Lao, C. T., Akroyd, J., Smith, A., Morgan, N., Lee, K. F., Nurkowski, D., & Kraft, M. (2021). Modelling investigation of the thermal treatment of ash-contaminated particulate filters. *Emission Control Science and Technology*, *7*(4), 265–286. https://doi.org/10.1007/s40825-021-00197-z

Roosenbrand, E. J., Sun, J., & Hoekstra, J. M. (2022). Examining Contrail Formation Models with Open Flight and Remote Sensing Data. 1-8. Paper presented at 12th SESAR Innovation Days, Budapest, Hungary.

Scott, J., Sipkens, T. A., Smallwood, G., Mehri, R., Corbin, J. C., Lobo, P., & Kholghy, M. R. (2024). Rapid assessment of jet engine-like soot from combustion of conventional and sustainable aviation fuels using flame spray pyrolysis. *Aerosol Science and Technology*, *58*(6), 595–609. https://doi.org/10.1080/02786826.2024.2316190

Shishko, V. A., Timofeev, D. N., Konoshonkin, A. V., Kustova, N. V., Kan, N., Tkachev, I. V., Masuda, K., Ishimoto, H., Okamoto, H., & Borovoi, A. G. (2022). Backscattering characteristics of optical and electromagnetic waves in joint sensing of cirrus clouds by a polarizing lidar (0.355 MM) and a 94-GHz radar. *Atmospheric and Oceanic Optics*, *35*(6), 775–781. https://doi.org/10.1134/s1024856022060239

Yu, F., Kärcher, B., & Anderson, B. E. (2024). Revisiting contrail ice formation: Impact of primary soot particle sizes and contribution of volatile particles. *Environmental Science & Technology*, *58*(40), 17650–17660. https://doi.org/10.1021/acs.est.4c04340