Project 102 Assessment on Contrail Formation via Combustion of SAF

University of Illinois at Urbana–Champaign

Project Lead Investigator

Tonghun Lee
Professor of Mechanical Science & Engineering
University of Illinois at Urbana–Champaign
1206 W. Green St., Urbana, IL 61801
517-290-8005
tonghun@illinois.edu

University Participants

University of Illinois at Urbana–Champaign (UIUC)
- P.I.: Professor Tonghun Lee
- FAA Award Number: 13-C-AJFE-UI-053
- Period of Performance: October 1, 2024, to September 30, 2025
- Tasks:
  1. Development of Environmental Test Chamber Platform
  2. Development of Laboratory Scale Soot Generator
  3. Characterization of Aviation Soot

Project Funding Level

Federal Aviation Administration (FAA) funding level: $250,000
Cost sharing: 100% match provided by software license support from Converge, Inc.

Investigation Team

Prof. Tonghun Lee, (P.I.), All tasks
Sungho Hwang (graduate student), experimental efforts in designing and characterizing the combustor used in soot production.
Connor Malley (graduate student), experimental efforts in designing and characterizing the environmental chamber.
Anson Regi (graduate student), experimental efforts in instrumentation analysis of soot.

Project Overview

This study seeks to develop an environmental testing chamber to allow for the experimental creation and analysis of condensation trails (contrails) in a consistent and repeatable laboratory environment. The goals of this chamber will be to (1) understand the physics of contrail formation using advanced laser and optical diagnostics and potentially develop novel diagnostic methods for contrail characterization, (2) investigate contrail formation for fuels, including sustainable aviation fuels (SAF), and (3) integrate test data with both environmental modeling teams and flight-based tests. This study is done in collaboration with the Sandia National Laboratory (Livermore) where Dr. Lee is affiliated with the Sandia Faculty Loan Program.

Contrails are mainly composed of water (in the form of ice crystals) and contain a nucleus of soot particles. There is a major gap of knowledge in our understanding of the fundamental physics of contrail formation at the molecular level, but in certain supersaturate environments, contrails can form and then persist until they develop into high altitude cloud formations, which can impact the temperature of the Earth's atmosphere through radiative forcing. Due to this reflection of thermal radiation from the Earth's surface, it is believed that contrails contribute to greater than half of aviation's climate impact, the other portions being impacted by carbon dioxide (CO_2) and other greenhouse gases. This chamber aims at

studying these various factors of contrails to better inform efforts to mitigate contrail formation through flight path adjustment, improving engine technologies, and characterizing contrail development for SAFs to better predict the impact of fuel composition.

This project involves four main design considerations: (1) the environmental testing chamber, (2) the soot generating combustor, (3) soot particle parameters, and (4) the laser/optical diagnostic design. The environmental chamber is used to control the relevant conditions of contrail development in an optically accessible environment. The chamber consists of a co-flow section prior to the chamber where humidity and temperature are controlled for incoming air/soot mixtures. This is done using a chiller and heat exchanger, which cools both the chamber walls and the incoming air flow. Attached upstream of the chamber is a vacuum pump exhaust assembly that will control the pressure levels within the chamber and help regulate air speed throughout the system. The intended diagnostics systems consist of Rayleigh scattering for soot density and ice crystal formation, infrared (IR) spectroscopy absorption and optics for soot composition and water-content, and laser induced incandescence for soot diameters along with other non-in situ methods such as transition electron microscopy (TEM), elemental-to-total carbon (EC/TC) analysis, and mobility diameter analysis.

Task 1 – Development of Environmental Test Chamber Platform
University of Illinois at Urbana-Champaign

Objective
The objective of this task is to develop a test chamber. This involves defining the thermodynamic operating ranges for temperature, pressure, humidity, and air speed that are relevant to contrail formation. Once defined, the thermodynamic operating ranges inform the design of the chamber itself, and the cooling, co-flow, and exhaust systems being utilized to control the relevant thermodynamic properties, which will then be assembled.

Research Approach
The purpose of this study is to provide a controllable laboratory method for contrail formation and analysis to better inform environmental modeling of contrails and to corroborate and prevent the extensive need for expensive/difficult in-situ methods directly involving aircraft (e.g., chase planes). This is conducted by developing a controllable environmental chamber in which sample soot and cold air flow through with diagnostic access through chamber viewports and soot sample collection methods. This task is completed by utilizing a cooling co-flow upstream of the chamber and a vacuum exhaust system downstream of the chamber. The primary concern of the chamber system is the control of pressure, temperature, humidity, and air speed. The relevant formation physics of the contrails are collected using laser/optical diagnostics utilizing both in situ (through the viewports) and non-in-situ (collected soot particulate matter) methods. The properties that will be measured are soot density, soot diameter, soot composition, particle porosity, ice crystal growth, and temperature gradients within the flow as heat is transferred to create the ice crystals.
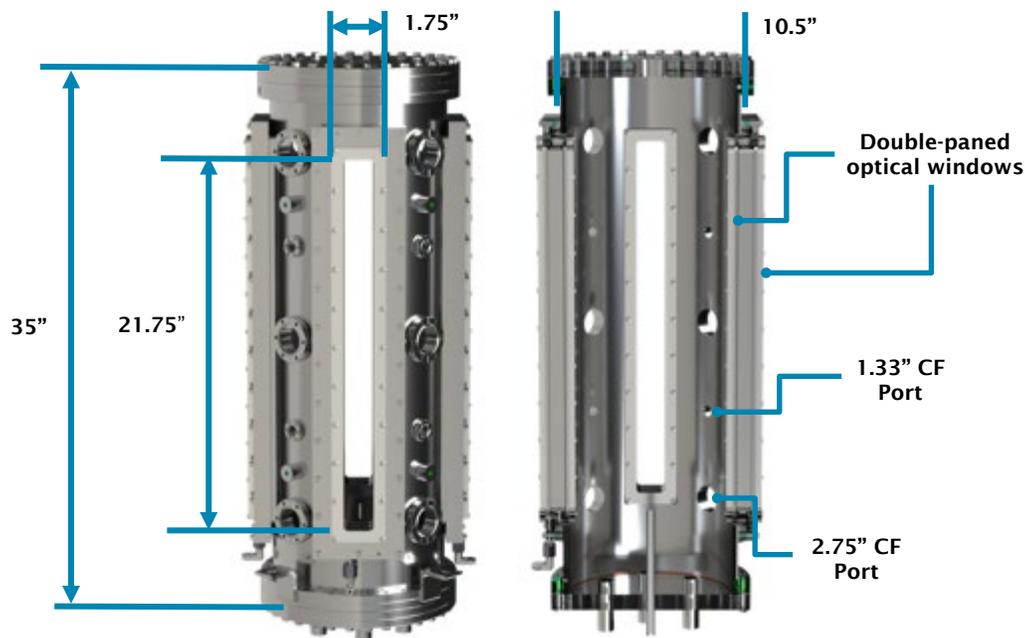
Environmental Test Chamber
The environmental test chamber is designed to mimic high atmospheric conditions in a controlled laboratory environment. It will do this through a co-flow and vacuum exhaust control system. Table 1 outlines the relevant operational ranges of the chamber. Pressure within the chamber will be able to range from 1 bar to near vacuum conditions with the standard experimental range being 0.2-0.5 bar. The temperature will have an ultimate range of 200-300K with the standard experimental range being 217K to 250K. This represents an atmospheric range of sea-level conditions to the tropopause. The maximum water content within the chamber will be roughly 1,000 ppm with the intent being able to create a supersaturated region with respect to water within the chamber. The system has the ability to add water content through wet air injections but for most experiments the water produced from combustion of the burner should be enough to create supersaturation and therefore contrails. The internal environment will be a pressure-controlled air/nitrogen gas environment with the air acting as the source for additional water content when needed. In general, internal cooling of the chamber will utilize air flow through a heat exchanger. This is due to limited supply of nitrogen through gas cylinders while filtered building air is effectively infinite. The maximum flow rate throughout the entire system will be 10 g/s with a maximum velocity of roughly 1.9 m/s. Normal experimental speeds will be significantly lower with the intent of producing the maximum residence time of 9 s with speeds as low as 0.1 m/s. The atmosphere within the system will be composed of air and nitrogen gas with soot included during operation.

Table 1. Environmental Test Chamber Operational Conditions.

Parameter	Range
Pressure	0.01-1 bar
Temperature	200-300 K
Maximum Water Content	~1000 ppm
Maximum Flow Rate	10 g/s
Maximum Chamber Speed	1.9 m/s
Maximum Residence Time	~9 s
Chamber Atmosphere	Air/N_2

The chamber design is shown in Figure 1. The chamber is double-walled stainless steel with coolant running between the walls to maintain the wall temperature to levels seen in the co-flow entering the chamber. It is roughly 13.5 in. in diameter and 35 in. tall. The inner wall has a 10-in. outer diameter while the outer wall has a 10.5-in. outer diameter. The chamber has four larger optical windows (21.75 in. by 1.75 in.) that are double-paned to allow their interior to be vacuum pumped to prevent condensation. One pair of these windows is made of Corning® 7980 fused silica, and the other pair is TSC-3 fused quartz to allow for varying spectrum transmission options for laser diagnostics. Between the windows there are twelve 2.75-in. ConFlat (CF) ports and eight 1.33-in. CF ports to allow for specialty windows or sensors. The bottom of the chamber (not shown) has six to eight equidistant holes, which the co-flow will be pumped through, centered around a smaller hole where the sample exhaust from the combustor is injected. The top of the chamber has an exhaust port that will connect to an Edwards® nES220 vacuum pump that will serve as the air speed and pressure control for the chamber. Both the top and the bottom ports are attached to 12-in. CF flanges.

Figure 1. Environmental Test Chamber Design.

Figure 2 summarizes the control system in its entirety. The co-flow system outputs "hot" air and nitrogen into a heat exchanger which cools down the flow before it enters the testing chamber. The heat exchanger uses cold TMC HFE-347 coolant fluid from a Thermonics® water-cooled chiller. The chiller has a temperature range of -80°C to +25°C with a cooling capacity of 1,800W at -80°C. It has an 8-gallons-per-minute (50 psi at 60 Hz) pump and relies on 480V, three-phase power. A portion of this coolant is siphoned off prior to the external heat exchanger to be supplied into the interior of the double-walls to decrease the chamber wall temperature. The "hot" fluid from the heat exchanger and the chamber walls are then combined again before being pumped into the chiller to be cooled again by the in-house water system. After the chamber is the exhaust vacuum system. This system includes an inline heater, control valve panel, and a vacuum pump. The inline heater is a TEMPCO® circulation heater with 6,000 W heating and a control range of 60° to 250°F. The heater raises the temperature of the exhaust from the chamber to prevent the vacuum pump from cold conditions. The control valve panel is composed of a major ball valve and two smaller needle valves. The ball valve acts as the evacuation control and is used during the chamber cooling phase and general pressure-down of the chamber. The needle valves then act as the flow rate controls during experimentation by limiting the pull of the pump in the chamber to control the flow speed. The vacuum pump is an Edwards® nES220 single stage rotary vane pump with an ultimate vacuum of 0.08 mbar and pumping speeds of 125 cfm. This pump is what brings the chamber down to experimental pressures. The last major section of the experimental platform is the soot generating combustor which burns liquid aviation fuel and sends portions of the soot to the chamber and to a diffusion dryer for soot instrumentation.
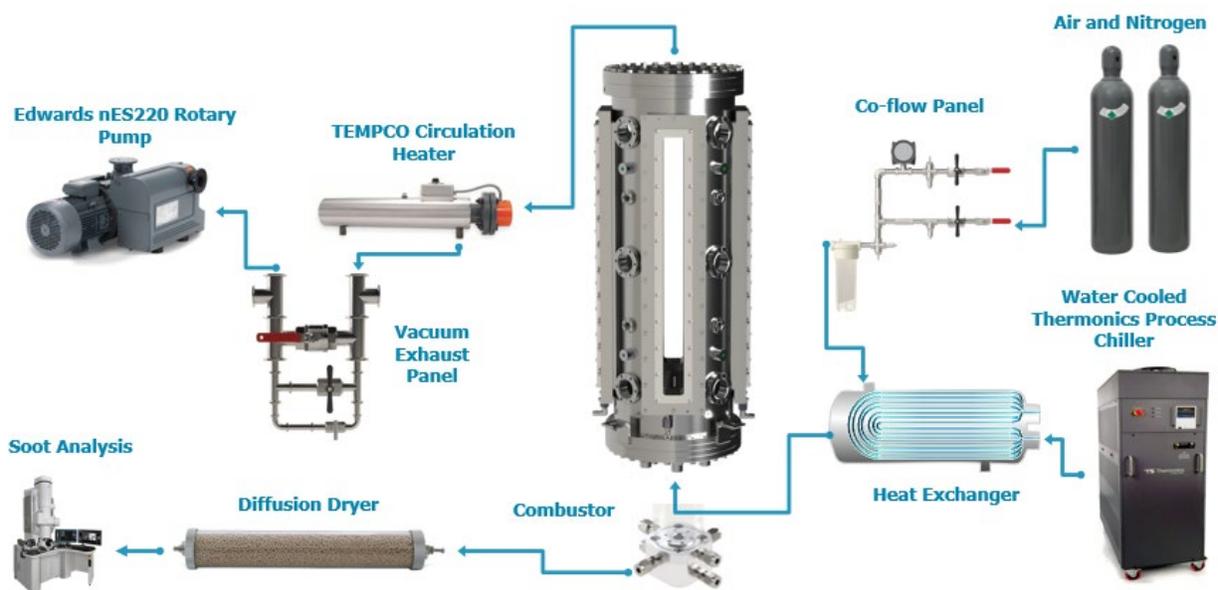

Figure 2. Control system overview.

The final portion of the chamber design is a smaller chamber shown in Figure 3. This chamber is roughly 6 in. in diameter and 16 in. in height. This chamber would focus exclusively on the initial nucleation of soot for contrails and have the advantage of shorter cooling times with the drawback of shorter residence times. It was designed with the intention of even faster experimentation for focused areas and for easier transportation with the intent of utilizing it to take experimental data using instrumentation at national laboratories that we may not have direct access to. The new chamber would have roughly 27% of the internal volume and 27% the internal surface area of the larger chamber and would have roughly half the residence time. It is expected to drop the 3-hr required cooling time of the larger chamber to roughly 1 to 1.5 hr of cooling time depending on coolant flow rates within the interior of the walls.

® Thermonics is a registered trademark of Temptronic Corporation, Mansfield, Massachusetts.
® TEMPCO is a registered trademark of TEMPCO Electric Heater Corporation, Wood Dale, Illinois.
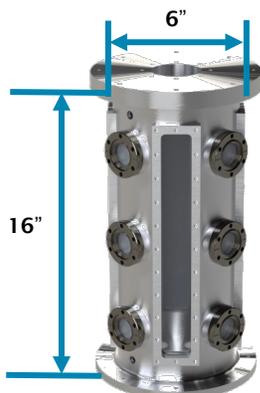® Edwards is a registered trademark of Edwards Limited, Burgess Hill, England.

Figure 3. Small experimental chamber design.

Task 2 – Development of Laboratory Scale Soot Generator
University of Illinois at Urbana-Champaign

Objectives
The objective of this task is to develop a soot generating combustor for liquid aviation fuel. This combustor is designed to evaporate and burn such fuel in varying ways with the intent of modulating soot parameters. By modulating such parameters, specific physical and chemical considerations may be explored within the contrail chamber to determine the impact of soot parameters on ice crystal nucleation. The soot parameters of interest are primary particle diameter, mobility diameter, EC/TC ratio, and porosity. This starts with an objective of stabilizing and characterizing the flame to ensure consistency in soot production.

Research Approach
The soot particulate matter (PM) is provided to the chamber through the burning of liquid aviation fuel in a fully characterized soot generator. The generator has the primary goal of controlling PM sizes and maintaining a relatively uniform PM size of roughly 10-30 nm in diameter. It also has the goal of developing soot that can mimic the EC/TC ratio of aviation-derived soot, which has a value of roughly 0.75-0.8. Other relevant soot parameters that may be researched are mobility diameter and porosity. To confirm the ability of the soot generator to create soot of varying features, multiple fuels are tested and different equivalence ratios, mixing speeds, and mixing geometry. Stability and efficiency of the combustor is studied through oscillation observations, carbon monoxide (CO) emission index, and hydroxyl radical (OH*) chemiluminescence.

Combustor Design
The combustor has been completed and is shown in Figure 4 below. It is made of aluminum and is modular to allow for iterative designing. Its main components are the gas ports for air, nitrogen, and methane gas, an interior cavity, a pilot flame ring, and a quartz tube for soot collection and flame stability. The gas ports are 1/4-in. npt to 1/8-in. Swagelok® tubing. The output for the pilot flame is composed of two concentric rings of 0.04 in. diameter holes. The combustor is roughly 60 mm in width, and the fuel exhaust is 12 nm in diameter. Fuel is injected with a 1.6 mm inner diameter tube. The combustor is 2.36 in. wide in a square shape at its further edges with rounded corners with a radius of 0.59 in. The height of the combustor is 1.57 in. without the pilot flame plate and 1.75 in. with the pilot flame plate. The three modular components of the combustor are secured with four 18-8 stainless steel socket head screws, and the different components are sealed from fuel leaks using o-rings. The pilot flame plate is secured to the top of the modular combustor using six 18-8 stainless steel hex drive flat head screws. The combustor is secured to a raised aluminum breadboard with two M5 screws to allow fuel to be evaporated and injected underneath the combustor. This evaporation is done using either a Bronkhorst evaporation unit or an insulated inline heater. The internal geometry is shown in Figure 5.

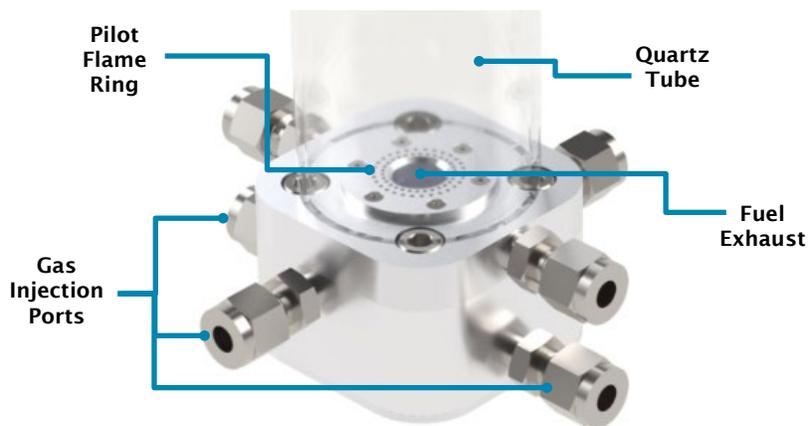® Swagelok is a registered trademark of Swagelok Company, Solon, Ohio.
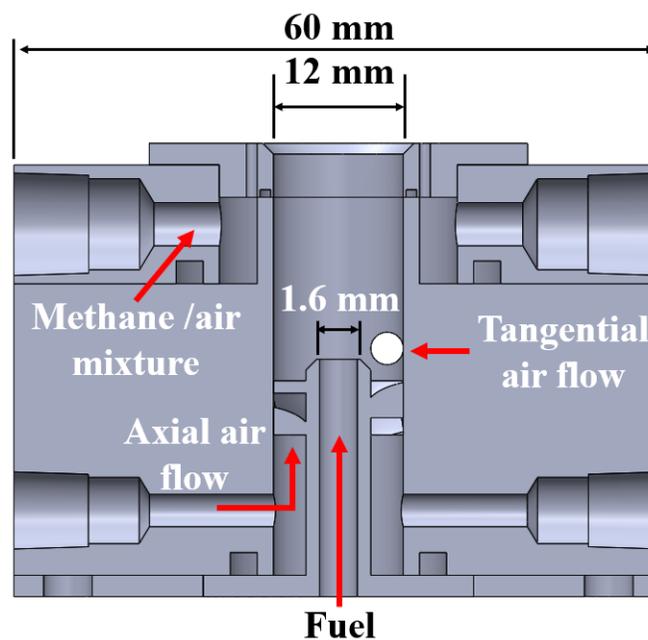
Figure 4. Soot-generating combustor.

Figure 5. Combustor internal geometry.

The internal geometry of the combustor is composed of fueling sections, the mixing cavity, and the inner bodies. Axial air enters parallel to the injected fuel stream and provides the bulk of the upwards momentum to the flow. Tangential air is injected directly above the fuel at off-axis locations to provide swirl mixing to the flow within the mixing cavity. Methane and air are mixed outside of the combustor and injected into the top where they exit through a ring of miniature injection ports where it is ignited by a lighter during experimentation. A summary of the external injection scheme is shown in Figure 6.
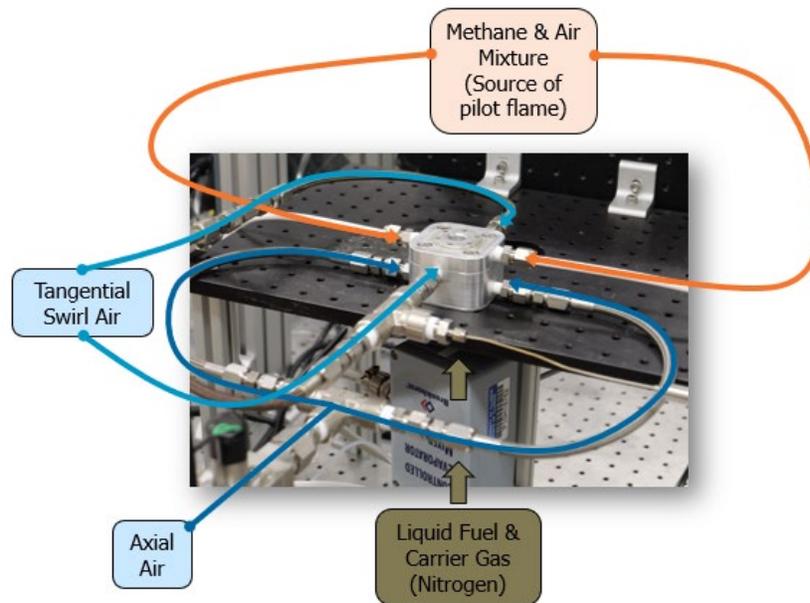
Figure 6. Combustor experimental platform.

The combustor experimental platform is summarized. It is important to note that liquid aviation fuel is evaporated within a Bronkhorst evaporation unit before being carried by nitrogen gas to be injected into the mixing cavity of the soot generating combustor. Different inner bodies are also utilized within the interior of the combustor to modify the momentum of the axial air injection with the intent of producing different mixing environments within the mixing cavity. These inner bodies are shown in Figure 7.
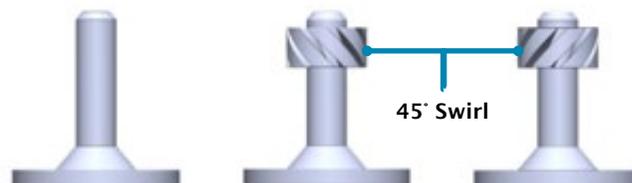
Figure 7. Combustor inner bodies.

There are three inner bodies of interest. The first is the straight body, which is the base case that adds no change to the axial air flow. The second is the uni-flow body, which adds swirling momentum to the axial air flow in the same rotational direction as the tangential air flow. The last is the counter-flow body, which swirls the axial air flow in a counter rotating pattern relative to the tangential flow, providing the highest level of mixing within the combustor cavity while also reducing the net momentum of the swirl. The inner bodies are all made of three-dimensional printed stainless steel from Protolabs Inc.

Combustor Characterization
The combustor was tested for flame stability and combustion efficiency. The goal was to define the conditions which influenced the stability of the flames as this was thought to have an impact on the uniformity of the soot production. There was also an interest in the efficiency of the combustor based on the different inner bodies. One of the primary methods used to stabilize the flame was heating of the injected air lines. It was believed that heated air would reduce the chances of fuel recondensing and decrease temperature gradients within the gas mixture of the cavity. The results of this are shown in Figure 8 below. Oscillation was determined visually based on fluctuation in the maximum height of the flame. Flames

that rapidly cut their heights in half in cycles were deemed oscillatory. The evaporation temperature of the fuel was modulated along with the temperature of the injected air to determine the impacts on the flame stability. When using the straight body, it was found that oscillation was experienced when the evaporations temperature was greater than the air temperature. For the two swirling inner bodies, oscillation only occurred when the evaporation temperature was greater than 433.15 K for all air temperatures tested. This demonstrated that for the straight body, increased air temperature improved stability, and for the swirlers the stability is dependent solely on the fuel evaporation temperature.
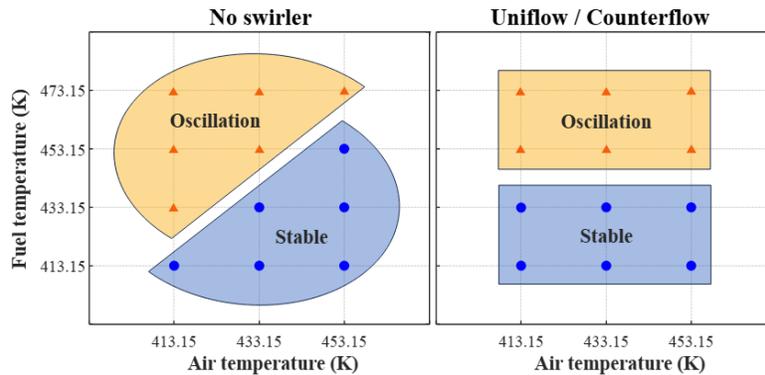

Figure 8. Impact of temperature on flame oscillation.

Combustion efficiency was determined to understand the mixing triggered by the various inner bodies and the effective production of soot. It was defined through the emission index of CO gas (grams of CO per kg of fuel) using an MRU™ AMPRO plus combustion and emission analyzer placed above the flame. The results are shown in Figure 9. Within Figure 9, "F1" represents the straight body, "F2" the uni-flow body, and "F3" the counter-flow body. The emission indexes were studied for lean flames as they were expected to best represent turbine combustion with regards to primary particle diameter. There was no trend with the straight body, but it was about an order of magnitude greater in values than the swirler bodies with the range of 20-25 g/kg. The swirlers saw roughly the same values with emission index decreasing as the equivalence ratio approached stoichiometric. This indicated that the swirlers increased mixing in the combustor as expected. As a result, it would be expected that the combustor would produce less soot when utilizing those bodies for the same equivalence ratios compared to the straight body.
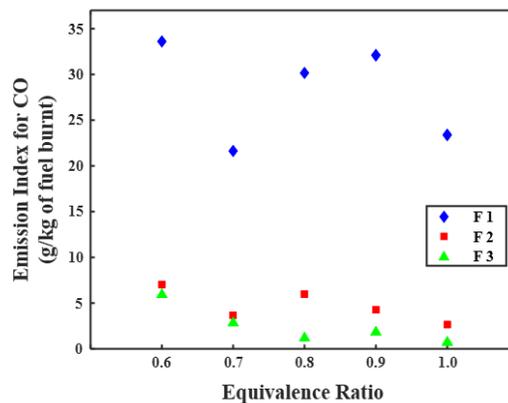

Figure 9. Emission Index for carbon dioxide (CO).

™ MRU is a trademark of MRU Instruments, Inc., Humble, Texas.

The final method of characterization for the combustor was OH* chemiluminescence imaging. Representative snapshots for each inner body are shown in Figure 10. This provided a qualitative indication of the location of the flame front and heat release zone. This gives a general sense of how well mixed the gases in the flame are, and therefore how efficient the combustion is. The emitted light of OH* molecules were collected using a band pass filter (310 nm) attached to a Cerco 100 mm ultraviolet (UV) lens (f/2.8). A HighSpeed IRO (LaVision®) UV intensifier was used in conjunction with a FASTCAM SA5 (Photron®) to collect the images. From left to right, (a) is the straight body, (b) is the uni-flow body, and (3) is the counter-flow body. The straight body had OH* molecules along the bottom and sides of the flame structure, which suggested that the air did not penetrate the fuel jet significantly, resulting in insufficient mixing. The uni-flow body had OH* molecules throughout the entire flame, indicating even mixing and heat release relative to the straight body. Lastly, the counter-flow body showed a similar level of mixing to the uni-flow body but with more vibrant emission. This suggested increased turbulence that resulted in a higher heat release and mixing compared to both the straight and the uni-flow bodies.
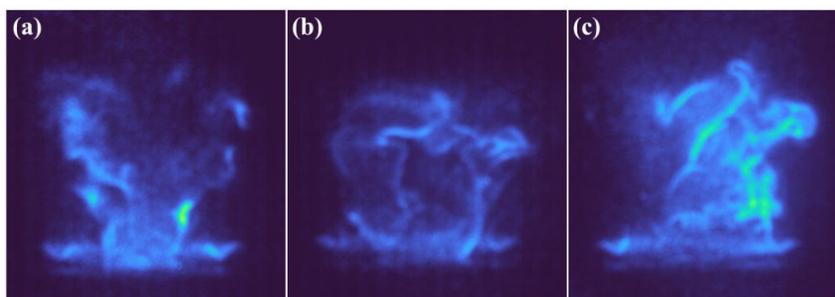
Figure 10. Hydroxyl radical chemiluminescence imaging. From left to right, (a) is the straight body, (b) is the uni-flow body, and (3) is the counter-flow body.

Task 3 – Characterization of Aviation Soot
University of Illinois at Urbana-Champaign

Objectives
The objective of this task is to characterize the soot parameters of soot derived from burning aviation fuel. The first tests burnt Jet-A fuel (properties shown in Table 2) to be used as a reference point, while later tests will focus on alcohol-to-jet (ATJ) and CycloSAF. The parameters of interest are primary particle diameter, EC/TC ratio, mobility diameter, and porosity.

Research Approach
The soot from these experiments is analyzed through a JEOL® 1200 transmission electron microscope (TEM) and a Sunset® carbon aerosol analyzer. After a stable flame is created for a desired equivalence ratio and inner body, soot is collected through a port within the quartz tube. A pump pulls soot from above the flame through this port into insulated lines that lead to a diffusion dryer filled with activated alumina desiccant beads to remove any water moisture from the stream. The soot is then collected onto a quartz filter where it can be weighed by a Thermo Cahn C-31 microbalance. The soot is then transferred to a copper grid for TEM or placed directly into an organic and elemental carbon analyzer utilizing the NIOSH 930 protocol.

® LaVision is a registered trademark of LaVision GmbH, Gottingen, Germany.
® Photron is a registered trademark of Photron Limited, Tokyo, Japan.
® JOEL is a registered trademark of JEOL LTD., Tokyo, Japan.
® Sunset is a registered trademark of Sunset Laboratory Incorporated, Beaverton, Oregon.

Table 2. Jet-A 10325 Fuel Information.

Parameter	Range	Chemical Compound	Percent
CAS # (Kerosine)	8008-20-6	alkylbenzenes	12.90%
CAS # (Naphthalene)	91-20-3	diaromatics	2.33%
Freezing Point (°C)	-56 to -39	cycloaromatics	3.28%
Boiling Range (°C)	134 to 294	n-parafins	19.98%
Flash Point (°C)	42-62	iso-parafins	29.69%
Flammability in air (%)	0.4-5.0	monocycloparaffins	25.07%
Relative Density	0.7-0.82	dicycloparaffins	6.55%

Soot Characterization

Figure 11 shows representative images of soot particles for primary particle diameter (PPD) measurements imaged using a JEOL JEM-2100 TEM. Only some preliminary images have been taken so far. One measured sample so far is from the uni-flow inner body with a burner equivalence ratio (EQ) of 2 for Jet-A fuel. The mean PPD for this soot taken from roughly 50 particle measurements was 19.2 nm with a standard deviation of 3.32 nm. Another sample was taken from the straight body with an EQ of 1.4. The mean PPD was 20.04 nm with a standard deviation of 3.53 nm. The last condition studied to this date was the straight body with an EQ of 2. The mean diameter of this sample was 20.81 nm with a standard deviation of 5.06 nm. This is promising as it is representative of the expected 20-50 nm range for aviation soot with minimal variation in soot size.
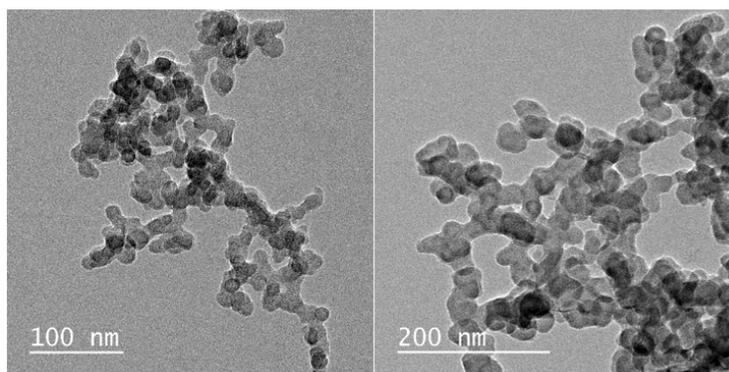

Figure 11. Example transition electron microscopy (TEM) images for Jet-A fuel.

Figure 12 presents the soot mass production per minute for varying EQs of Jet-A fuel. For the uni-flow and counter-flow bodies the mass production increases with EQ up to EQ = 3. From there, both bodies experience a drop before the counter-flow continues to increase at EQ = 4. The production for the straight body was too inconsistent but shows a general trend of increasing with EQ. It is theorized that the inconsistencies seen within this data are caused by the fixed sampling height of the collection port along the quartz tube. Because the sampling port is at a fixed height of roughly 8 in. above the combustor, it is possible that different flame heights with changing EQ is leading to different amounts of soot being collected. Lower heights may be losing too much soot to the open atmosphere above the tube as it has more time to spread to the edges of the tube and out the top. Too high flames may also be causing too much soot to be collected as the flame may be interacting with gases and soot inside the collection port causing reburn and reoxidation or even prevent soot from being collected as it is released from the flame above the collection port. An adjustable port will be designed.
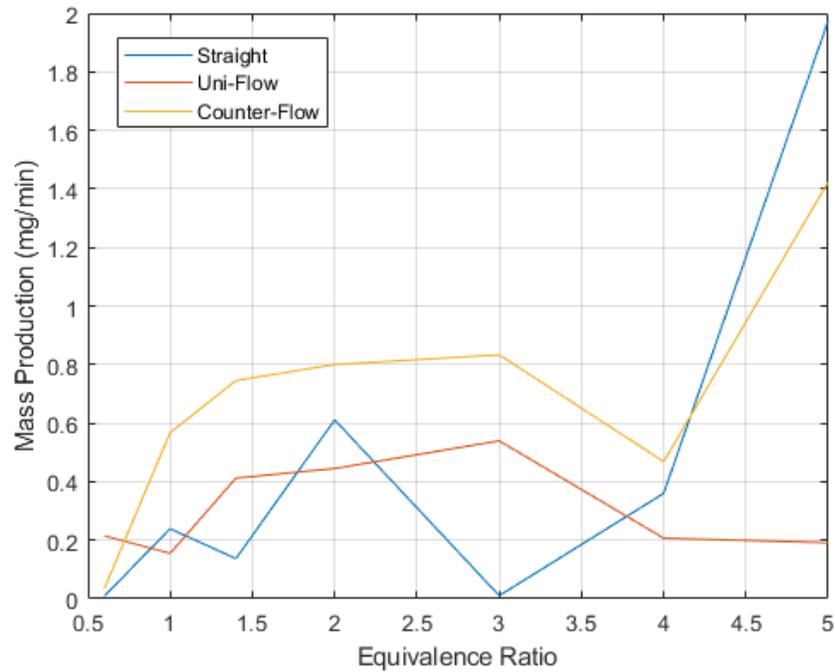
Figure 12. Soot mass production for Jet-A fuel.

Figure 13 shows the EC/TC data for varying EQ of Jet-A fuel. An increase in EC/TC is expected with increase in EQ. This held true for the straight and counter-flow bodies until EQ = 2 where the EC/TC ratio proceeded to drop. For the uni-flow body, this held true until EQ = 1.4 and then occurred again after EQ = 3. It is believed that the deviation from the expected trends also resulted in this case from the fixed height of the collection port. Soot collected from taller flames may be collected from within the flame itself and as a result lack the needed exposure to oxygen from the ambient atmospheric air need for the oxidation to mature the soot. However, there seems to be a consistent trend of dropping EC/TC ratio after a peak point and this may be the result of the methodology of the burns. These experiments modified the air flow rates and kept the fuel flow rates fixed for the rich conditions to preserve fuel and because there was a limit to fuel supply due to the diameter of the fuel injection. This not only impacts the mixing as the Reynolds number changes with change in air momentum but also means there is less overall air within the quartz system. This means that for richer conditions there may not be enough oxygen within the quartz tube to properly oxidize the soot as expected. It is recommended that both an adjustable collection port be implemented along with modulating fuel rates while keeping air rates the same.
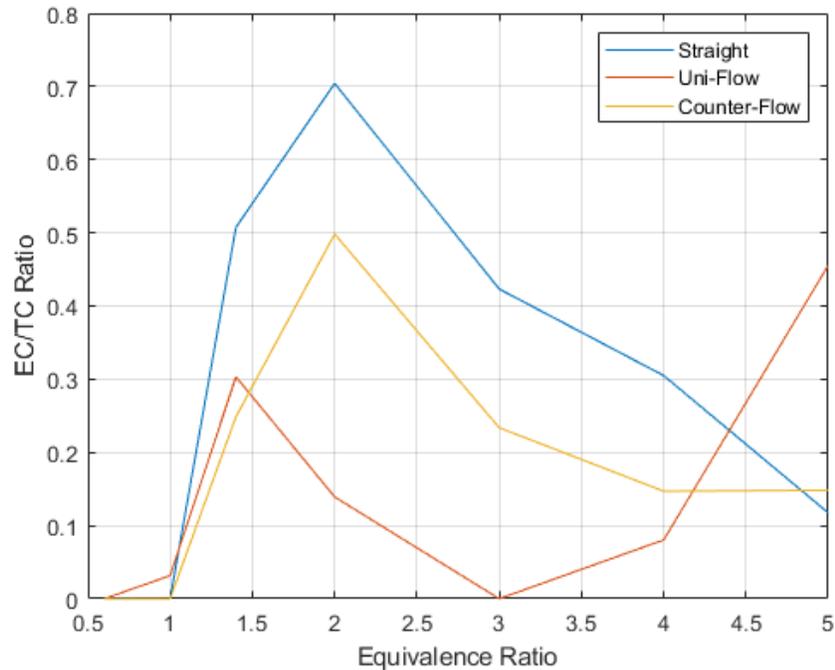
Figure 13. Soot EC/TC Ratio for Jet-A fuel.

Milestones
- Finished manufacturing of the chamber and control systems (at 3 months).
- Finished design and manufacturing of the laboratory-scale soot generating combustor (at 6 months).
- Finished characterizing the stability of Jet-A fueled flames and began to characterize ATJ, CycloSAF, and hydro-processed renewable jet (HRJ) fuel flames (at 9 months).
- Finished analyzing primary particle diameters, soot mass production, and EC/TC ratio for varying equivalence ratios of a Jet-A flame (at 12 months).

Major Accomplishments
The most important accomplishment to date is the establishment of a partnership with the Sandia National Laboratory (Livermore), of which Dr. Lee is now an employee. The Sandia National Laboratory has already developed their own contrail chamber, and with their advisement, we have been able to properly identify operation goals and methods to explore in the development of our own chamber. We have finished development and stability characterization of our own laboratory-scale soot generating combustor that burns liquid aviation fuel and are in the process of characterizing the soot production.

Publications
None.

Outreach Efforts
All test data will be made accessible through https://altjetfuels.illinois.edu/.

Awards
None.

Student Involvement

This project was conducted by PhD student, Sungho Hwang, who is developing the combustor for the chamber; PhD student, Connor Malley, who is developing the chamber and stabilizing the flame; and master's student, Anson Regi, who is developing the soot diagnostic systems.

Plans for Next Period

Our plan for the next period is to fully characterize the limits of the soot production for the combustor. This involves finishing the data for primary particle diameter and EC/TC while also collecting new data on mobility diameter and porosity for Jet-A. This will be done by modulating the equivalence ratios and inner bodies of the combustor. We also intend to collect data for ATJ, HRJ, and CycloSAF fuels. For the contrail chamber, characterization will consist of confirming operational environmental ranges for temperature, pressure, humidity, and air speed. After both characterization tasks are complete, the ASCENT Project 102 team will develop a test plan and perform our first attempt at creating a contrail in a controlled experimental environment utilizing generic fuel (e.g., Jet-A fuel). This will involve using our laser/optical diagnostics to gather data on soot density, diameter, composition, and ice crystal growth.