Project 073 Fuel Composition Impact on Combustor Durability

University of Dayton Research Institute

Project Lead Investigator

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- P.I.: Scott Stouffer, PhD, PE
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- Task:
    1. Perform radiation measurements of various fuel types in the referee combustor to evaluate the effect of fuel composition on combustor liner lifetime

Project Funding Level

Amendment	Funding
Amendment No. 029	$299,148
Amendment No. 040	$199,865
Amendment No. 044	$200,000
Amendment No. 054	$130,000
Total	$829,013

Investigation Team

Dr. Scott Stouffer, (P.I.), project direction
Mr. Tyler Hendershott, (research engineer), combustor operations
Dr. Jeff Monfort, (research engineer), radiation measurements
Mr. Harry Grieselhuber, (technician), combustor testing
Ms. Elizabeth Koetter, Student Intern

Project Overview

In this study, the effects of fuel chemical composition on radiative heat transfer and the resulting combustor liner lifetime will be evaluated. Alternative fuels contain ratios of hydrocarbon types that may substantially differ from those in familiar petroleum-based fuels. In petroleum-based fuels, higher aromatic levels are known to contribute to greater particulate matter loading radiative heat transfer and reduced combustor liner lifetimes. Consequently, aromatic compounds are limited to 25 vol% in the ASTM D1655 (ASTM International, 2023) jet fuel specification. Some candidate alternative fuels contain synthetically produced aromatic compounds and cycloparaffins, which must be evaluated for their radiative heat transfer characteristics. The measurements collected in this project will provide insights into the effects of fuel type on liner lifetime. Several fuel types will be investigated, including a synthetic aromatic kerosene, a baseline Jet A fuel, and a fuel high in cycloparaffins. Diagnostic methods to be used in the investigation include the measurement of wall and gas temperatures, and the use of infrared (IR) cameras and radiometers.

Task 1 – Perform Radiation Measurements of Various Fuel Types in the Referee Combustor to Evaluate the Effect of Fuel Composition on Combustor Liner Lifetime

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Objective

The objective of this task is to provide insights into the effect of fuel type on engine combustor liner lifetime. The study conducted under this task will ensure that candidate drop-in fuels will perform satisfactorily in jet engines and will not increase the need for engine maintenance or decrease flight safety. The findings of this study may also indicate which fuel composition changes may reduce radiative heat transfer and therefore increase combustor liner lifetime.

Research Approach

Fuel chemical composition is well known to strongly affect soot formation, smoke production, and radiative heat flux in gas turbine combustors (Chin & Lefebvre, 1990). Studies of petroleum-based fuels with varying levels of aromatic levels have indicated that these properties increase with the overall content of aromatic species. Other parameters such as hydrogen content, hydrogen/carbon ratio, and smoke point have also been correlated with liner temperatures, but the effects of individual types of aromatic species have not been well studied. Candidate alternative fuels may meet the overall limits for aromatic species but may contain individual species or mixtures of species that are markedly different from those in petroleum-derived fuels. Radiation heat transfer to combustor liners is a major issue affecting the durability and operational envelope of gas turbine engines. Radiation can cause high heat fluxes, thus resulting in localized heating, hotspots, and high thermal gradients along and across the liner. Increases in liner temperature can decrease liner durability (Gleason & Bahr, 1980). Intense heating can cause problems with low cycle fatigue, cracking, and buckling of the liner and, in extreme cases, localized melting of the liner. The combustor walls can be convectively cooled by effusion or film cooling; however, film cooling typically imposes a cycle performance penalty, along with elevated levels of carbon monoxide (CO) and unburnt hydrocarbons, particularly at low power settings. Because of concerns regarding the effects of fuel type on radiation, the radiant heat flux is considered a figure of merit by aircraft engine original equipment manufacturers in the evaluation of alternative fuels for aircraft use (Colket et al., 2017).

The radiation from a gas turbine flame has two main components: (a) "non-luminous" radiation from product gases, such as carbon dioxide (CO_2), H_2O, and CO, and (b) luminous radiation from non-volatile particulate matter (principally soot).

Non-luminous radiation corresponds to the IR region and has a spectral distribution, whereas the luminous radiation is broadband, and a fraction of the radiation appears at visible wavelengths. Typically, as the pressure is increased, the luminous radiation from soot particles becomes the dominant source of heat flux to the liner walls. Whereas the convective component of the wall heat transfer depends on the fluid dynamics and gas temperature distribution near the walls, the peak radiant fluxes are related to the combinations of high-temperature gas and non-volatile particulate matter.

The emissivity of the combustion gases is typically related in an expression such as:

$$\epsilon_g = 1 - exp\left[-aPL(ql)^{0.5}T_g^{-1.5}\right] \qquad \text{(Eq. 1)}$$

where ϵ_g = emissivity of the combustion gases (non-dimensional)
P = gas pressure in kPa
l = characteristic length factor, which is a function of combustor geometry
T_g = gas temperature in K
q = fuel-to-air ratio

L = luminosity factor

The luminosity factor is set to 1 for gaseous emissivity. For sooting flames associated with liquid aviation fuels, the luminosity is greater than 1 and can be correlated with the fuel composition. Several relations between luminosity and fuel type have been reported in the literature (Lefebvre, 1999; Naegeli & Moses, 1980; Clark, 1982). In general, the luminosity factor has been found to decrease with increasing hydrogen/carbon ratio and decreasing aromatic content of the fuel. Other correlations in the literature have addressed the correlations with smoke point and naphthalene content. Although IR has been used as a diagnostic tool in basic flame experiments (Rankin et al., 2012), very little work using multiple radiometers and/or planar measurements of IR emissions in practical combustors has been reported in the literature. The referee rig combustor is ideal for assessing radiation heat transfer because the walls are heavily cooled—a condition that tends to suppress the convective component and thus the background radiant heating from opposing walls, so that the wall heat transfer is primarily from the flame radiation.

The referee rig combustor was developed to conduct experimental combustion research. Highlights of previous contributions to the evaluation of alternative fuels include the following:

1. Experimental measurements of lean blowout (LBO) for fuels at conditions of interest to original equipment manufacturers and the National Jet Fuels Combustion Program, which have resulted in the unexpected finding of a high correlation between the derived cetane number and the LBO limit.
2. Experimental measurements of boundary conditions for the combustor, including air flow splits to support numerical combustion modeling efforts.
3. Development of cold air and cold fuel capabilities for the facility, to enable atmospheric cold start ignition experiments to be conducted over a range of conditions.
4. Further extension of the facility’s ability to allow altitude relight experiments to be conducted with a range of fuels at simulated altitudes of 25,000 ft.
5. Examination of the effects of heated fuels on combustion characteristics and emissions.

The work with the referee rig combustor has yielded publications that detail cold start ignition (Hendershott et al., 2018), ignition at elevated temperatures (Stouffer et al., 2017), LBO characteristics (Corporan et al., 2017; Esclapez et al., 2017; Colborn et al., 2020), particulate and gaseous emissions (Corporan et al., 2017), acoustic response (Monfort et al., 2017), flow through the liner effusion passages (Erdmann et al., 2017; Briones et al., 2017), spray characteristics (Mayhew et al., 2017), and altitude relight (Stouffer et al., 2020; Stouffer et al., 2021).

Milestones

Milestone	Planned Due Date
Provided test plan	December 1, 2020
Conducted initial instrumentation experiments	September 2022
Perform detailed testing for a range of fuels	April 1, 2026
Complete final report	September 30, 2026

Major Accomplishments

The experimental research facility used for the combustion experiments, which is owned by the United States Air Force Research Laboratory (AFRL), was unavailable during the past year for this program because of issues with construction programs and other AFRL programs that had priority over the past year. Experiments are expected to resume in spring 2026. During the past year, the ASCENT Project 073 team was able to make progress with the analysis of data from the previous year these results are discussed below.

The fuels that were studied in the previous year are briefly described here to provide context for the discussion to follow. The fuels for the experiments are listed in Table 1 which shows a top-level breakdown of the chemical constituents. The fuels are listed in order of increasing total aromatic fraction. The Fischer Tropsch (FT) fuel is a low aromatic fuel consisting mainly of iso-paraffins. The A2 fuel is a “middle of the road” Jet A fuel studied extensively in the National Jet Fuels Combustion Program. A 50% blend of the A2/FT fuel was also considered to examine the effect of lowering the aromatic content of Jet A fuel. A mixture of synthetic aromatic kerosene (SAK) and Jet Propellant-8 (JP8) fuels was also studied, this fuel contained more than twice the number of single ring aromatic compounds (alkybenzenes) but lower levels of diaromatics, and cycloaromatics. A final blend of aromatic compounds (30% volume) mixed with FT (70%) fuel was created to examine the effect of high levels of both total aromatics and diaromatic compounds on soot and radiation.

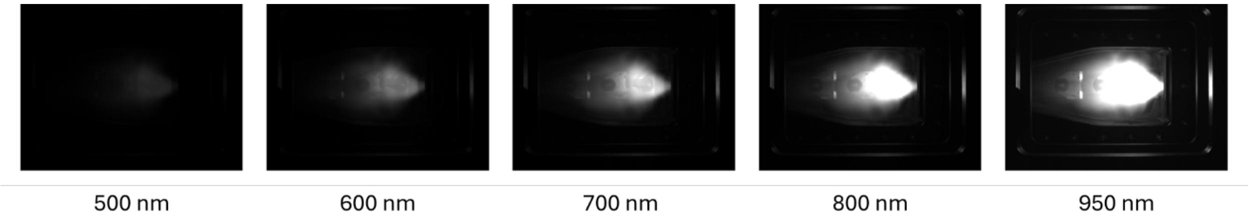
Table 1. Properties of the fuels studied.

	Volume %								Empirical Formula		
	Aromatics				Paraffins						
Fuel	**Total Alkylbenzenes**	**Total Diaromatics**	**Total Cycloaromatics**	**Total Aromatics**	**Total Isoparaffins**	**Total n-paraffins**	**Total Cycloparaffins**	**Total Paraffins**	**C**	**H**	**MW**
Fisher Tropsch (FT)	0.37	0.02	0.13	0.51	94.31	0.32	4.87	99.49	10.80	23.50	153.2
50% FT/50& Jet A	6.10	0.93	1.47	8.50	62.88	10.77	17.85	91.51	11.10	22.74	156.1
Jet A (A2)	11.84	1.84	2.81	16.49	31.46	21.23	30.83	83.52	11.40	22.10	159.0
JP8/SAK Blend	23.36	0.62	1.35	25.33	33.62	23.18	17.87	74.67	10.50	19.90	146.0
70% FT/30% Aromatic Blend	24.50	3.73	1.92	30.15	66.21	0.23	3.41	69.85	10.48	19.56	145.5

Analysis of Experimental Results

The observed limitations surrounding the transmission of long-wavelength radiation through the quartz side windows highlight the need for an alternate solution by which the relevant properties of interest could be established. Previous work has suggested that there is a fuel sensitivity realized by the relative distribution within the combustor of the high-temperature regions. The limited number of surface thermocouples does not afford the required spatial resolution necessary for effective analysis. A proof-of concept exercise was conducted to evaluate the feasibility of using images collected with the near IR camera to calculate an apparent temperature distribution from the soot within the combustor, using only shorter-wavelength data.

For a given fuel and a given condition, there is a clear difference between the captured images as a function of wavelength. Figure 1 shows a series of time-averaged, long-duration images, each corrected for the various acquisition parameters, for each of the five wavelengths of interest.



500 nm 600 nm 700 nm 800 nm 950 nm

Figure 1. Images for A2 fuel vs. wavelength.

The differences, both in terms of absolute intensity and relative shape, suggest that there is a link between the temperature observed at a given location (pixel) and the ratio between the signals at that location for multiple wavelengths. To model this temperature-based link, the assumption is made that the radiation-emitting particles within the combustor act as blackbodies. Figure 2 shows a series of blackbody curves over a range of temperatures between 300 K and 3,000 K. Over the range of temperatures and wavelengths, each curve is monotonically increasing, with no overlap between the traces, indicating that if given a pair of known wavelengths, the ratio between the emissive power at those two wavelengths can be traced back to a single temperature.

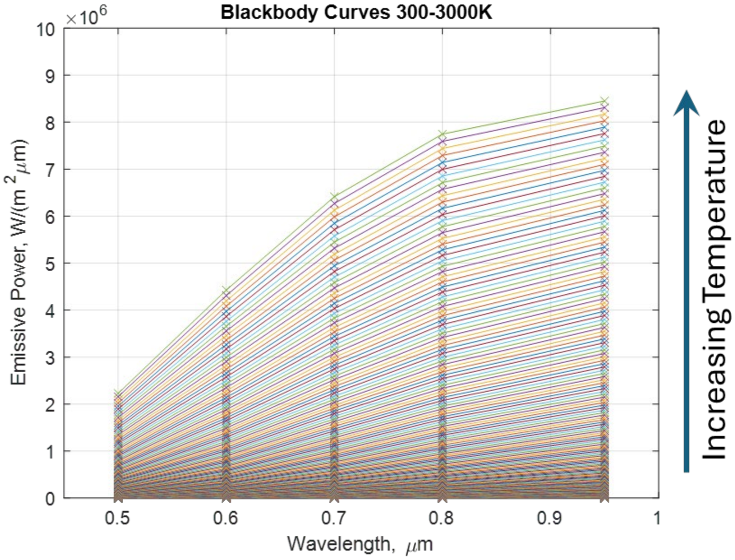


Figure 2. Graph of Blackbody radiation curves.

A multi-column lookup table was generated, which links the ratios of each pair of wavelengths to the modeled blackbody temperature. The lookup table is then applied to ratio maps, which are calculated on a pixel-by-pixel basis for each of the wavelength pairs and the time-averaged images. Figure 3 shows the results of the applied temperature-based correlations for a single fuel at a single condition, for each of the wavelength pairs.

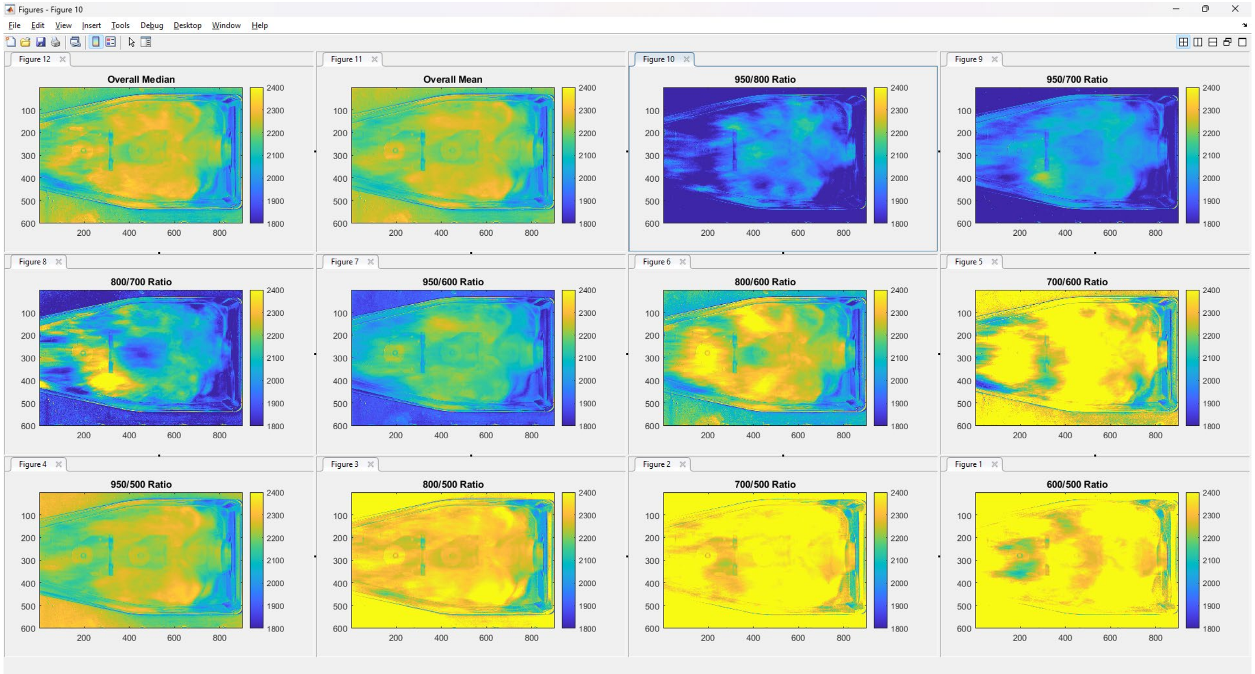


Figure 3. Calculated Pairwise Temperature fits based on a blackbody assumption from a near infrared camera.

Literature on the subject suggests that the quality of the correlation is very dependent on the wavelengths selected. Improved quality is usually achieved via the selection of wavelengths at the long end of the spectrum, with a moderate sized difference between the two chosen wavelengths. This advice seems to hold true in this case, with the flame features being most identifiable in the 950/800, 950/700, and 800/700 nanometer pairs. A limitation noted with this average-based approach is that the non-linearities associated with the lookup table result in significant uncertainty in the correlated temperature values. An improved approach utilizes multiple pairs of individual images, with the averaging process applied to the resulting temperature maps. Figure 4 shows the results of such an approach, using the 950 and 700 nanometer data, across the same range of conditions evaluated via other means.

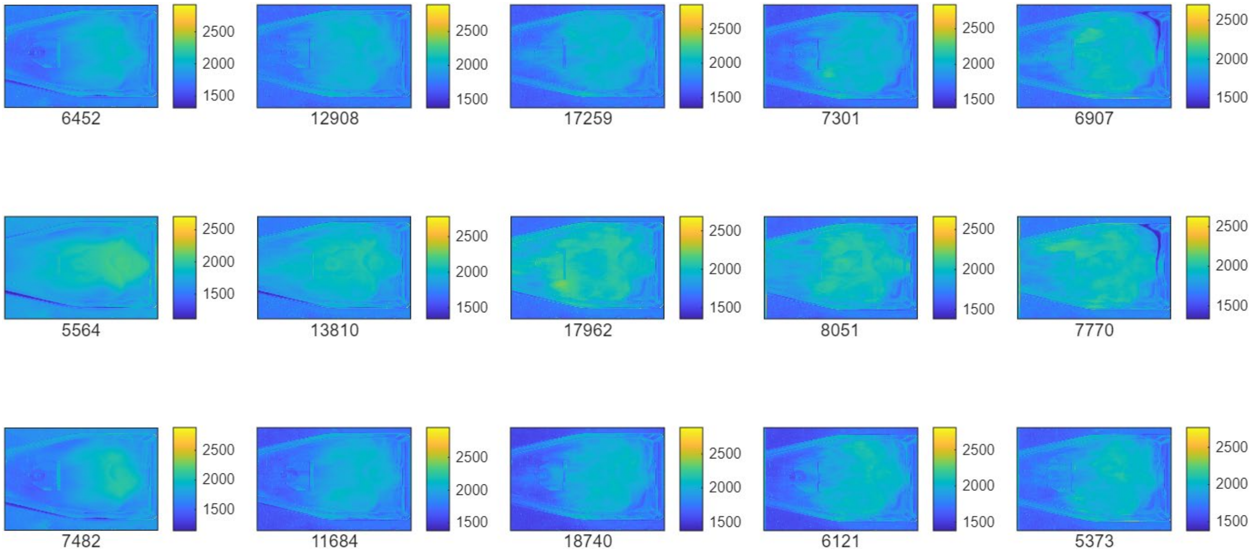


Figure 4. Calculated Temperature fits based on a blackbody assumption using multiple pairs of images from the near infrared camera.

The results here suggest that some condition and fuel sensitivity might be identifiable, but that the image pairs need to be collected simultaneously, and over a long enough duration to mitigate the effects of any experimental uncertainty, and the dynamic nature of the moving flame. Further work is underway to develop a method by which images can be collected simultaneously for a chosen pair of wavelengths. The approach requires the use of two cameras, and an algorithm by which the slight perspective differences between the two can be corrected.

Previous efforts had shown that the spatially-integrated intensities collected within the image data correlated quite strongly with parameters such as fuel aromatic content, equivalence ratio, and combustor mass flow. A sample of such data is shown in Figure 5. The image data had also shown, in a qualitative sense, that the relative locations of the high-intensity regions shift as functions of the same parameters.

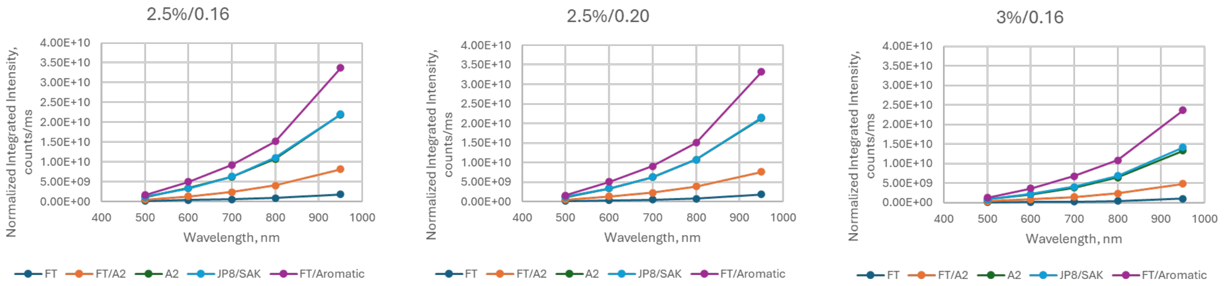


Figure 5. Three graphs showing Spatially and Temporally Integrated radiation for each of the fuels.

The overall integrated radiation intensity measured in the near infrared (950 nm) was compared side by side with the measured total particle number count at the exit of the combustor in Figure 6. The results show a strong relation between the particle concentration at the exit of the combustor and the total radiation measured by the camera.

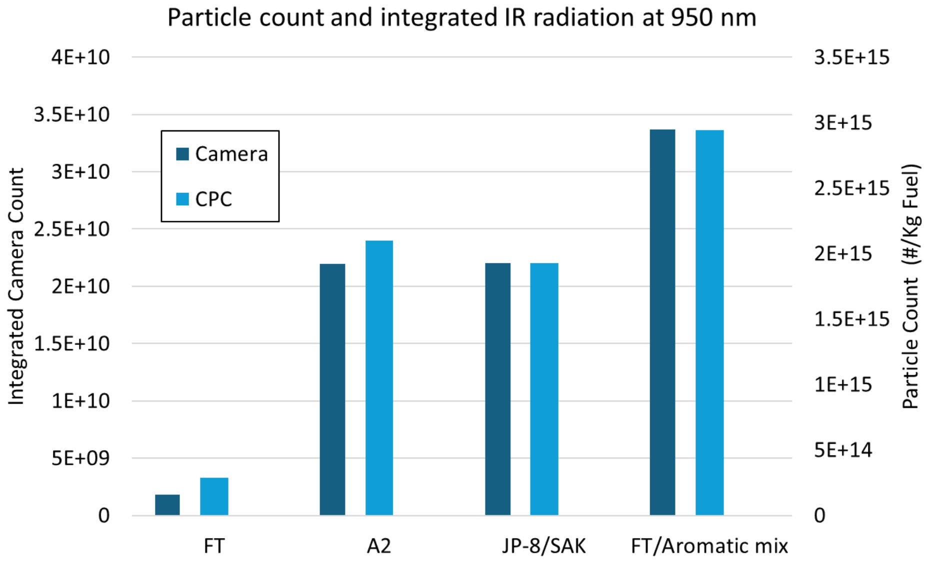


Figure 6. Graph of particle count at combustor exit and integrated IR radiation at 950 nm.

Further analysis on the spectrally-filtered emission data has been conducted, with the intent of being able to add some quantitative basis for comparisons of relative locations, and to link the data collected via the near IR camera to the radiometer output. Given that the radiometers are located within the field of view of the camera, it can be assumed that certain portions of the resultant images should correlate with the total radiation signals collected via the radiometers, at least within the range of wavelengths available. For reference the radiometer locations are shown in Figure 7 so that R1 corresponds to the location of the upstream radiometer near the dome and R2 corresponds to the location of the radiometer at the mid combustor. The camera signal at each radiometer location was integrated in a 1-in. diameter circle centered on the radiometer locations for each wavelength using five filters. The integrated signal from these locations is assumed to represent the regions at the combustor midplane which are most impactful on the radiometer signals, when considering their relatively wide cone angles, and the complicated geometry related to their fields of view.

The results are shown in Figure 8 which shows the ratio of the spatially integrated radiation from the camera at the upstream radiometer location divided by that at the mid combustor location, denoted as the R1/R2 ratio. Note that for all of the points shown the upstream radiation level is higher than that at the downstream side. The difference in this ratio is more pronounced for the lower equivalence ratio cases (R1/R2 is higher for the $\phi = 0.16$ case) because for the higher equivalence ratio cases the flame extends over a larger portion of the combustor. Moreover, there appears to be a clear upward trend in the intensity ratios, indicating an increased importance of the near-dome region as a function of increased aromatic content. The combination of these observations leads to the conclusion that the increased aromatic content has two effects: it serves to increase the overall intensity and sooting propensity, and that it will preferentially locate the highest intensity regions within a relatively small area at the upstream portion of the combustor.

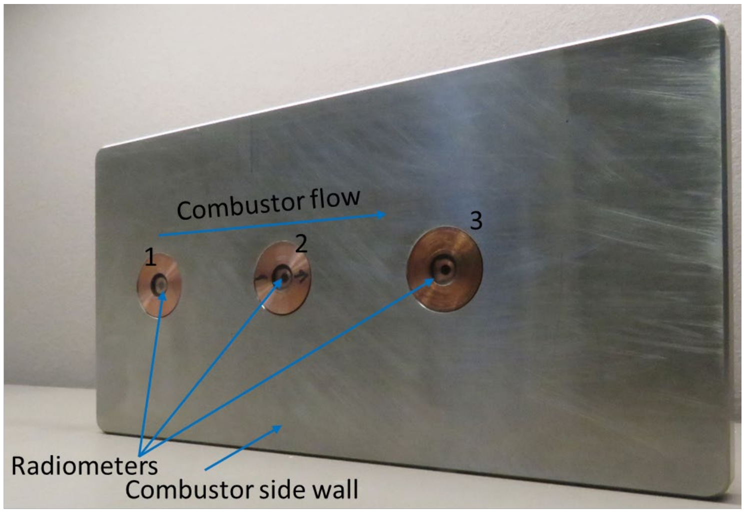


Figure 7. Combustor radiometer section.

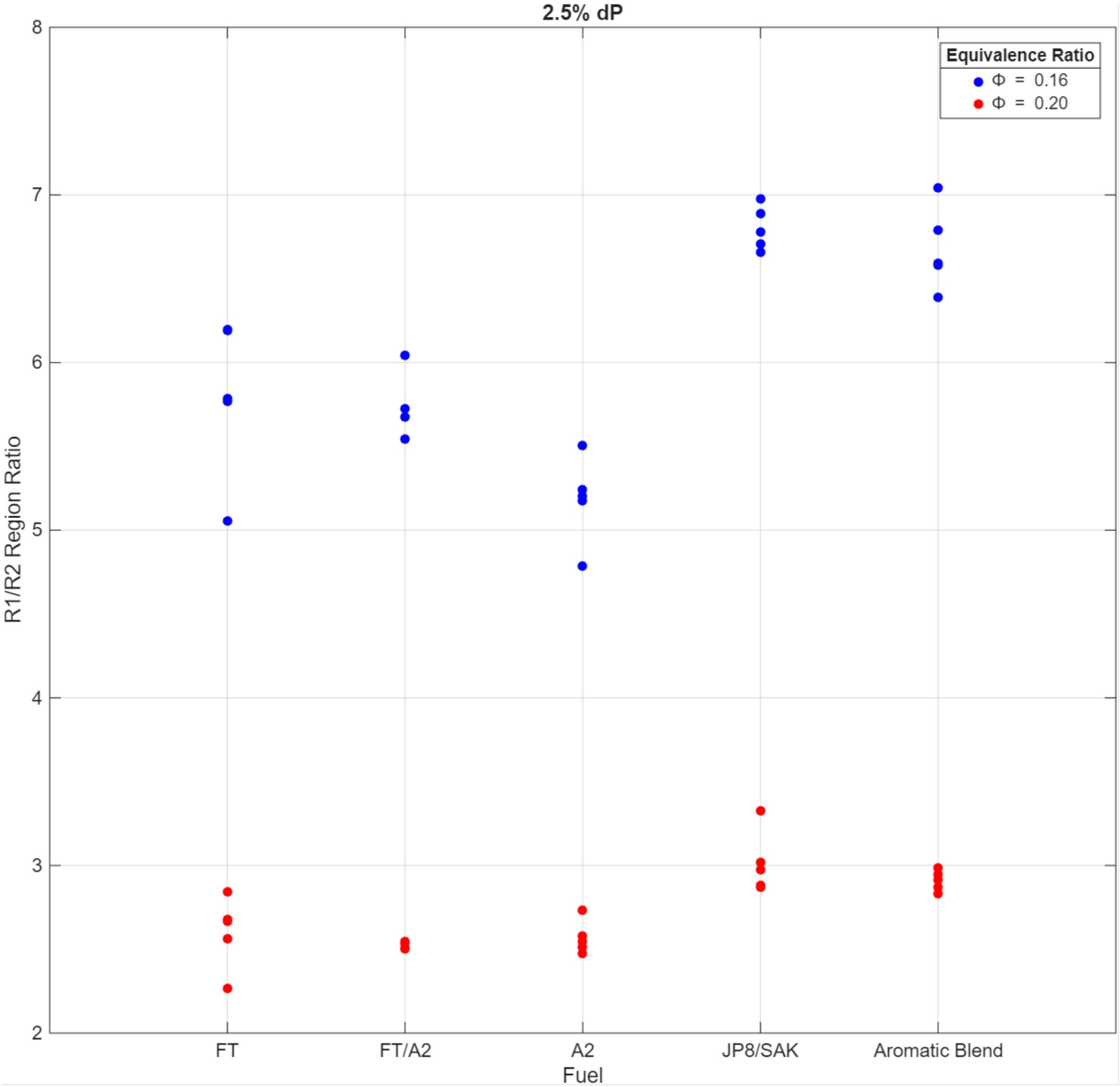


Figure 8. Ratio of the spatially and temporally integrated signal at the upstream (R1) and downstream (R2) radiometer locations.

The plan for the next series of experiments is to conduct the experiment at different pressures to allow further insight into the relative contributions of gaseous and particulate radiation. Planned instrumentation will include near infrared and infrared imaging. For the infrared images, further spectral filtering of the IR images will be explored to allow separation of the effects of radiation from gases and particulates.

Publications

None.

Outreach Efforts

As part of this work, a parallel modeling effort has been started by the National Aeronautics and Space Administration (NASA) Glenn Research Center. Our contribution so far has been to provide boundary conditions to the NASA team, who will use the data from this effort to validate combustion models of the Referee Combustor that incorporate radiation calculations within the computational fluid dynamics framework.

Awards

None.

Student Involvement

An undergraduate student intern (Elizabeth Koetter) has started to work with the ASCENT Project 073 team and will be working with us through the spring.

Plans for Next Period

Conduct future tests are at higher pressures and consider high cycloparaffin fuels. It is thought that at the test conditions, the radiation from soot, while showing a strong relation to fuel type, does not overwhelm the gaseous component of the radiation, resulting lower fuel differences in the broad-spectrum radiation detected by the radiometer. The radiating gases (CO_2, H_2O, and CO) are expected to be similar for a given temperature and pressure condition for all the fuels. The ratio between particulate (soot) and gaseous radiation is expected to change as pressure increases.

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