Effects of burning alternative fuel in a 5-cup combustor sector

K.M. Tacina[1], C.T. Chang[1], C.-M. Lee[1], Z. He[1]
J. Herbon[2]

[1]*Combustion Branch,*
NASA Glenn Research Center, Cleveland, Ohio

[2]*GE Aviation*
Cincinnati, Ohio

A goal of NASA's Environmentally Responsible Aviation (ERA) program is to develop a combustor that will reduce the NO_x emissions and that can burn both standard and alternative fuels. To meet this goal, NASA partnered with General Electric Aviation to develop a 5-cup combustor sector; this sector was tested in NASA Glenn's Advanced Subsonic Combustion Rig (ASCR). To verify that the combustor sector was fuel-flexible, it was tested with a 50-50 blend of JP-8 and a biofuel made from the camelina sativa plant. Results from this test were compared to results from tests where the fuel was neat JP-8. Testing was done at three combustor inlet conditions: cruise, 30% power, and 7% power. When compared to burning JP-8, burning the 50-50 blend did not significantly affect emissions of NO_x, CO, or total hydrocarbons. Furthermore, it did not significantly affect the magnitude and frequency of the dynamic pressure fluctuations.
Keywords: emissions, alternative fuel, biofuel

1   Introduction

The goal of the Environmentally Responsible Aviation (ERA) program is to develop technologies that will simultaneously do the following: reduce aircraft drag by 8%, reduce aircraft weight by 10%, reduce aircraft noise by 12.5%, reduce specific fuel consumption by 15%, and reduce oxides of nitrogen (NO_x) by 75% with respect to the CAEP/6 standards. For a given level of engine technology, reducing specific fuel consumption tends to increase NO_x emissions, so to meet the NO_x reduction goal, new combustor technology needs to be developed.

In addition to reducing NO_x, the new combustor technology needs to be fuel-flexible: it must demonstrate this by running with a 50-50 blend of standard jet fuel and an alternative fuel. Fuel-flexibility is required because of the growing availability of and interest in non-pertroleum-based jet fuels. However, alternative fuels are incompatible with the aircraft engine seals because of their low aromatic content[1]. Therefore, alternative fuels are typically blended with conventional jet fuel. The ASTM standard D7566 has been issued to allow alternative fuels to be mixed with conventional fuels; it allows alternative fuels to be a maximum of 50% of the mixture by volume.

Alternative fuels and 50-50 blends of alternative and conventional jet fuel have been shown to significantly reduce particulate emissions[2, 3, 4]. The effect of alternative fuels on gaseous emissions is less clear. Experiments tend to show that burning an alternative fuel has little or no effect on NO_x emissions[4, 5]. However, some studies show that alternative fuels decrease emissions of CO and unburned hydrocarbons[4], whereas others show little or no effect[5].
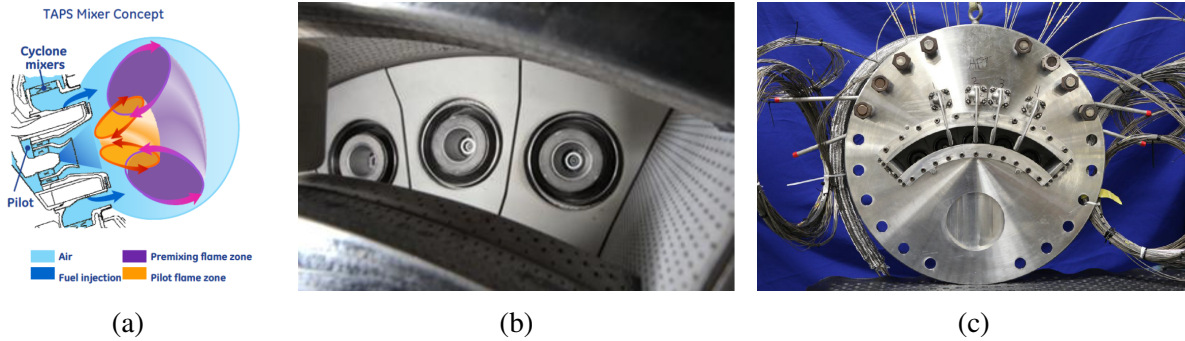
(a)   (b)   (c)

Figure 1: TAPS hardware: (a) a schematic of the TAPS concept, (b) the dome of the ERA sector (3 of 5 cups visible), and (c) the downstream end of the ERA sector showing probe locations. From Herbon et al[8].

To develop fuel-flexible, low-NO_x combustor technology, NASA partnered with General Electric Aviation (GE) to develop and test a 5-cup combustor sector. GE developed the combustor sector, and NASA tested it in the NASA Glenn Research Center Advanced Subsonic Combustion Rig (ASCR) at realistic combustor inlet conditions. It was found to meet the NO_x emissions reduction goal[6, 7]. To verify that the sector met the fuel-flexibility requirement, it was further tested with a 50-50 blend of JP-8 and a biofuel manufactured from camelina. This paper compares gaseous emissions and pressure fluctuations results from the neat JP-8 to a 50-50 blend of JP-8 and a biofuel manufactured from camelina.

2   Hardware and Experimental Facilities

2.1   Combustor Sector

The N+2 combustor that GE developed under the ERA program is based upon the GE's TAPS combustor technology. As shown in Figure 1a, the TAPS concept consists of two independently-controlled annular flames: a pilot for low-power operation and a cyclone for high-power operation. Both flames are swirl-stabilized, and the cyclone is concentric with the pilot.

The ERA N+2 combustor evolved from the earlier-generation TAPS designs. It features a ceramic matrix composite (CMC) liner that allows the liner cooling to be decreased. This decrease in liner cooling allows more of the combustor air to go through the fuel/air mixers; this in turn decreases NO_x emissions.

The 5-cup combustor sector tested at NASA is shown in Figure 1b and c. Four emissions rakes are installed, each with four sample elements. The rakes are located within the middle three cups of the sector and are spaced in different locations relative to the cup centerline in order to capture a comprehensive sample when all 16 sample elements are ganged together.
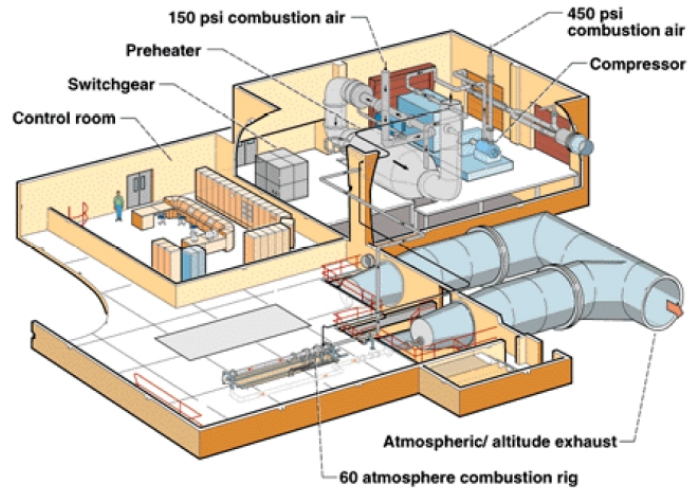
Figure 2: NASA Glenn's Advanced Subsonic Combustion Rig (ASCR)

2.2   Experimental Facilities

All testing was done at NASA Glenn Research Center's Advanced Subsonic Combustion Rig (ASCR). ASCR is designed to test single- or multi-cup combustor sectors. A schematic of ASCR is shown in Figure 2. ASCR can supply nonvitiated air preheated to above 970 K at pressures up to 6-MPa. Up to six fuel circuits are available. Each circuit can supply standard jet fuel, alternative fuel, or a blend of jet and alternative fuel; jet and alternative fuel can be blended on the fly.

2.3   Data Acquisition and Processing

Two data acquisition systems were used for this test. The first is the NASA Glenn ESCORT real-time data acquisition system; it collected steady-state data. The second was a Data Translation DT9841-sb high-speed data acquisition system; it was used to measure dynamic pressure fluctuations.

A standard gas bench was used to measure steady-state gaseous emissions data; it followed the SAE ARP-1256D[9] standard.

The data was post-processed to account for variations in fuel properties; the post-processing followed the SAE ARP-1533B[10] standard. Samples of both the neat JP-8 fuel used in this test and the neat camelina fuel were taken and sent for analysis. The measured hydrogen/carbon ratios were then used in the analysis of gaseous emissions, which was done according to SAE ARP-1533B. In addition, the measured lower heating value was used to calculate the adiabatic flame temperature.[1] Unless otherwise noted, all flame temperatures are based on the fuel/air ratio calculated from the

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[1]The flame temperature was calculated using the NASA Chemical Equilibrium for Applications (CEA) program. The Jet-A(L) entry from the standard CEA thermo.lib file was modified to create new two entries for the JP-8 and camelina fuels: the hydrogen/carbon ratio and the heat of formation were changed based on the measured values.

Table 1: Comparison of JP-8 and alternative fuels.

Fuel	Carbon	Hydrogen	H/C	Lower Heating Value	Fuel Density (20 C)
	% mass	% mass		MJ/kg	kg/m^3
JP-8	85.64	13.81	1.92	43.0	816
Camelina	85.31	14.42	2.01	43.3	778
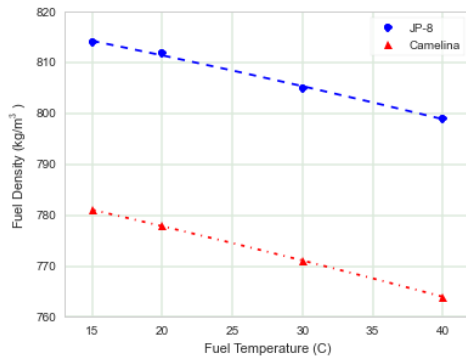
(a) Fuel density
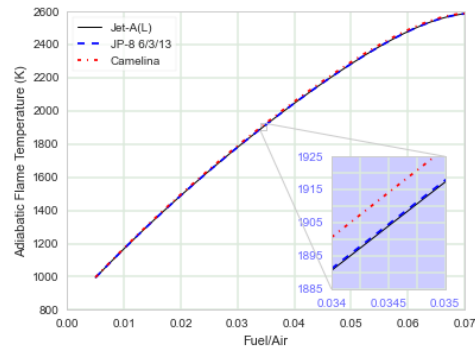
(b) Adiabatic flame temperature

Figure 3: Comparison of JP-8 and camelina fuels.

gas analysis, not from the fuel/air ratio based on fuel and air metering. (The ratio of gas sample fuel/air ratio to metered fuel/air ratio (FARR) is between 0.9 and 1.0 and is shown in the appendix.)

2.4   Fuel

The alternative fuel chosen was made from the camelina sativa plant. This fuel has properties very similar to JP-8. Table 1 and Fig. 3 compare the properties of the camelina biofuel to samples of JP-8. The differences between JP-8 and camelina are small; the most important difference is that camelina has a slightly higher H/C ratio, 2.0 vs. 1.9 for JP-8. This increase in H/C ratio leads to an increase in the lower heating value of the camelina. At the same fuel/air ratio, the camelina fuel will have a slightly higher adiabatic flame temperature (∼10 K). All emissions results are presented as a function of adiabatic flame temperature instead of fuel/air or equivalence ratio.

3   Results and Discussion

3.1   Emissions

Burning with the 50-50 blend has at most a small effect on emissions. This is shown in Figures 4–6. In most cases, there is no noticeable effect on emissions. This is the case for: NO$_x$ at cruise, NO$_x$ at 30% power, CO at 30% power, total hydrocarbons at 30% power, CO at 7% power, and total hydrocarbons at 7% power. Burning with the 50-50 blend may slightly decrease the CO and total hydrocarbons emissions at cruise conditions. However, more data is needed to verify that this
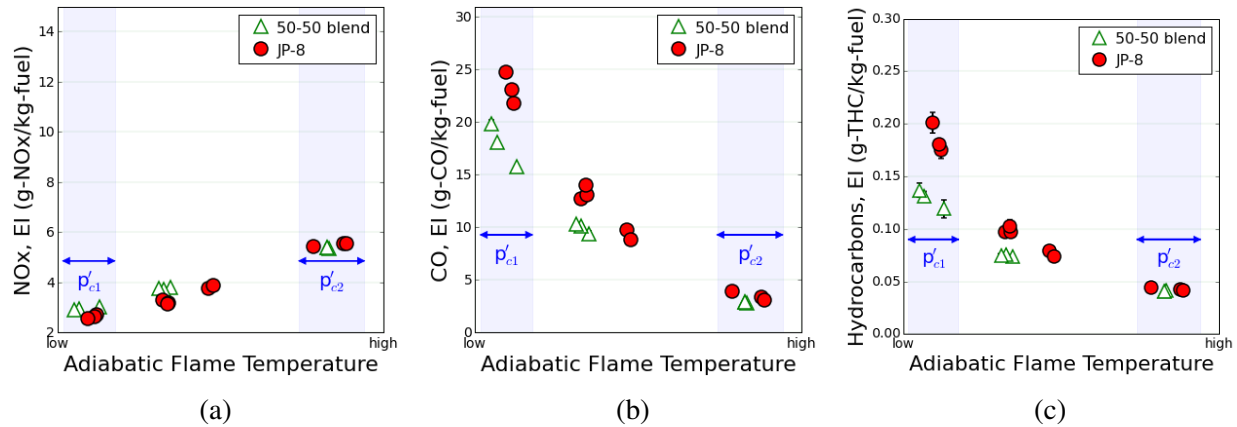
(a)   (b)   (c)

Figure 4: Emissions at cruise as a function of the calculated adiabatic flame temperature. Shown are the emissions indices for (a) NO$_x$, (b) CO, (c) total hydrocarbons. The shaded areas show the points that correspond to the dynamic pressure measurements presented as points cruise 1 (c1) and cruise 2 (c2) in Figures 7a,b and 8a,b.
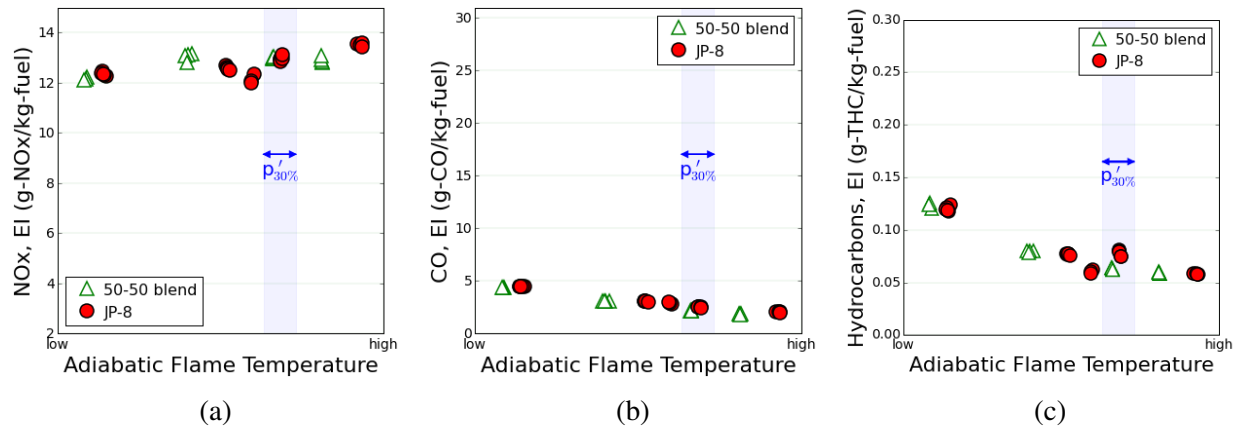

(a)   (b)   (c)

Figure 5: Emissions at 30% power as a function of the calculated adiabatic flame temperature. Shown are the emissions indices for (a) NO$_x$, (b) CO, and (c) total hydrocarbons. The shaded areas show the points that correspond to the dynamic pressure measurements presented as point 30% in Figures 7c and 8c.

effect is real; this is discussed in more detail in the appendix. Finally, burning with the 50-50 blend does seem to decrease the NO$_x$ slightly — by 0.2-0.3 EI — at 7% power conditions.

3.2   Pressure Fluctuations

As is the case with emissions, burning with the 50-50 blend does not significantly affect the pressure fluctuations: changes in the magnitude and frequency of the pressure fluctuations are small to nonexistent. This is shown in Figures 7 and 8 for three conditions, two cruise conditions and one 30% power condition. At the lower flame temperature cruise condition, c1, burning with the 50-50 blend does not change either the magnitude or the frequency of the pressure fluctuations; see
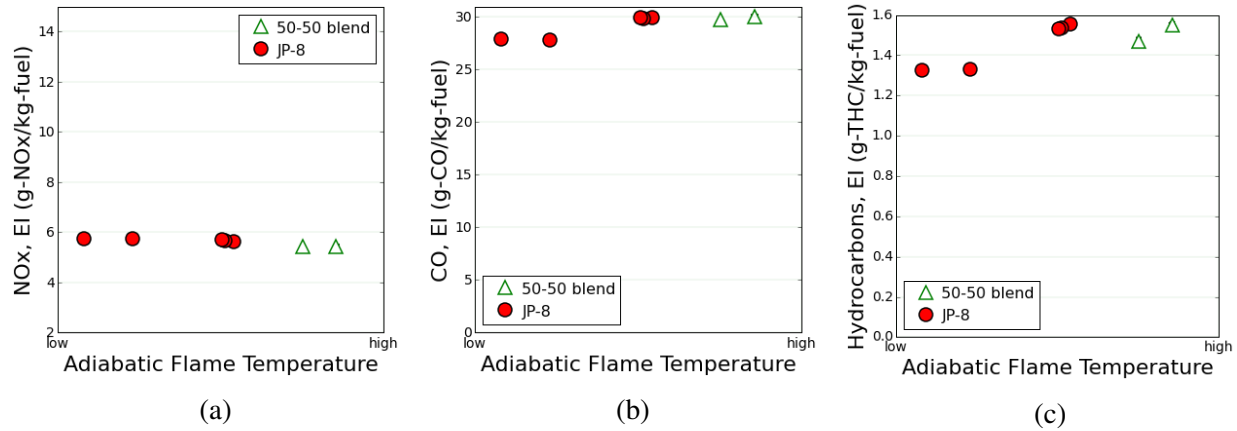
(a)   (b)   (c)

Figure 6: Emissions at 7% power as a function of the calculated adiabatic flame temperature. Shown are the emissions indices for (a) NO$_x$, (b) CO, and (c) total hydrocarbons. Note that the difference between the minimum and maximum flame temperature is small, less than 30 K.

(a)   (b)   (c)
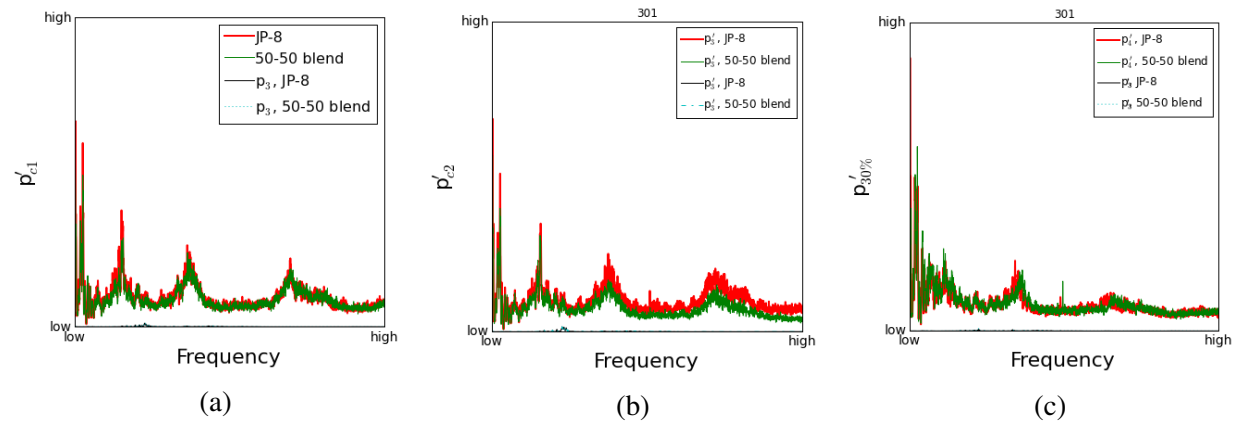
Figure 7: Pressure fluctuations in the combustor, directly downstream of a fuel injector. Conditions are (a) the first cruise condition, (b) the second cruise condition, and the (c) the 30% power condition.

Figures 7a and 8a. At the higher flame temperature cruise condition, c2, it may slightly decrease magnitude of the pressure fluctuations at the location directly downstream of the fuel injector; see Figure 7b. However, there is no decrease in magnitude at the location between the fuel injectors; see Figure 8b. Finally, at the 30% power condition, burning with the 50-50 blend may shift the peaks to slightly higher frequencies at the 30% power condition; see Figures 7c and 8c.[2]

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[2] For reference, the combustor inlet pressure fluctuations, p$_3'$, are also plotted in Figures 7 and 8. The inlet pressure fluctuations are extremely small — they are barely visible in the figures. A further examination of the inlet pressure fluctuations showed that they were similar at all three combustor conditions.
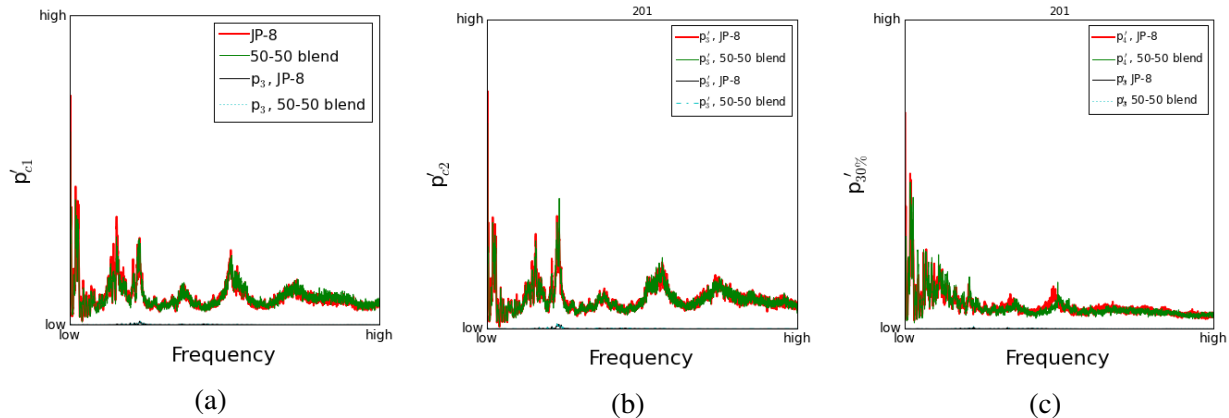
Figure 8: Pressure fluctuations in the combustor, between two fuel injectors. Conditions are (a) the first cruise condition, (b) the second cruise condition, and the (c) the 30% power condition.

4   Conclusions

Under the ERA program, NASA partnered with GE to develop a low-NO$_x$ combustor sector. NASA and GE tested this 5-cup sector in NASA's ASCR facility with both neat JP-8 and a 50-50 blend JP-8 and camelina. Testing was done at three combustor inlet conditions: cruise, 30% power, and 7% power. When compared to burning JP-8, burning the 50-50 blend did not significantly affect emissions of NO$_x$, CO, or total hydrocarbons. Furthermore, it did not significantly affect the magnitude and frequency of the dynamic pressure fluctuations.

Acknowledgments

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Appendix

To assess emissions data quality, the fuel/air ratio (f/a) calculated from the gas analysis was compared to the f/a calculated from the metered fuel and air flow rates. This value is called FARR. Ideally, FARR is between 0.95 and 1.05. For these tests, it was slightly lower than desired, between 0.90 and 1.00. See Figure 9. In addition, the FARR for the 50-50 blend is systematically different than the FARR for the neat JP-8. This difference changes with test condition: it is greatest at 30% power and least at idle. This probably indicates a slight inaccuracy in one or more of the fuel flow meters. There are five flow meters on each fuel circuit: two turbine meters on the jet fuel, two turbine meters on the alternative fuel, and one coriolis meter after the jet and alternative fuels are mixed. Future analysis will look at the calibrations for each of flow meters in detail; this should improve the accuracy of the metered f/a.

Fortunately, the FARR affected the conclusions at only one condition: cruise. Compare the CO and total hydrocarbon results in Figures 4 and 10. When the f/a from gas analysis is used to calculate the adiabatic flame temperature, burning the 50-50 blend appears to slightly decrease the CO and total hydrocarbons emissions. However, when f/a from metering is used to calculate the adiabatic flame temperature, burning the 50-50 blend appears to have no effect on emissions. Since the FARR results seem to indicate a slight inaccuracy in the fuel metering, the flame temperature from the gas analysis is probably more accurate.
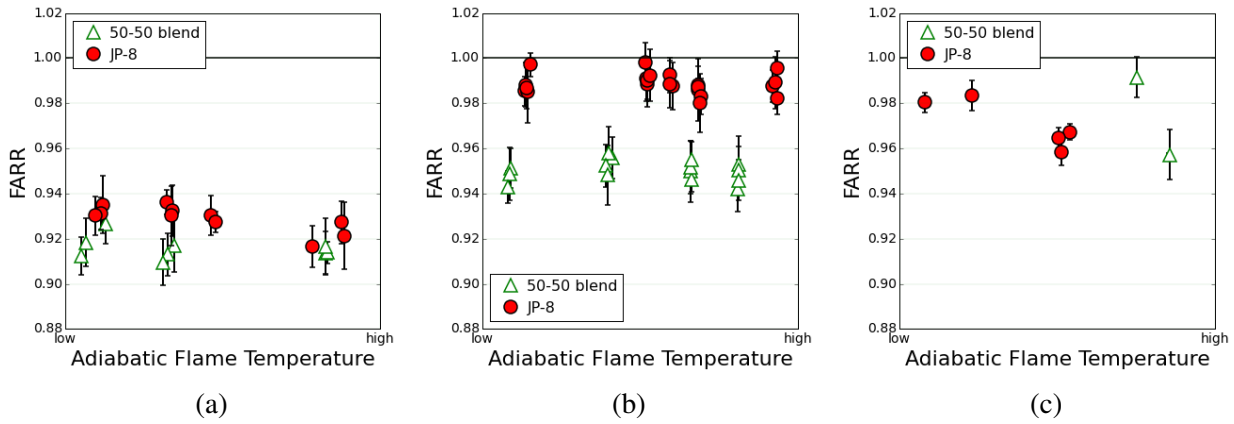
(a)   (b)   (c)

Figure 9: The ratio of f/a from gas analysis to the f/a from the metered fuel and air values for (a) cruise, (b) 30% power, and (c) 7% power.

(a)   (b)   (c)
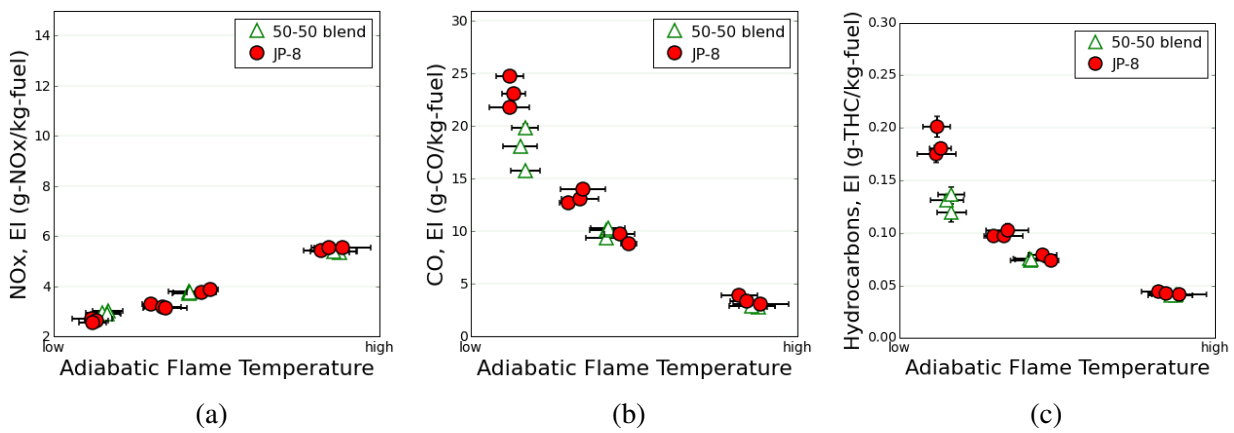
Figure 10: Emissions at cruise as a function of the adiabatic flame temperature calculated from the metered fuel and air flow rates. Shown are the emissions indices for (a) NO$_{\text{x}}$, (b) CO, (c) total hydrocarbons.