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Real-Time Optical Fuel-to-Air Ratio Sensor for Gas Turbine Combustors

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ABSTRACT

The measurement of the temporal distribution of fuel in gas turbine combustors is important in considering pollution, combustion efficiency and combustor dynamics and acoustics. Much of the previous work in measuring fuel distributions in gas turbine combustors has focused on the spatial aspect of the distribution. The temporal aspect however, has often been overlooked, even though it is just as important. In part, this is due to the challenges of applying real-time diagnostic techniques in a high pressure and high temperature environment.

A simple and low-cost instrument that non-intrusively measures the real-time fuel-to-air ratio (FAR) in a gas turbine combustor has been developed. The device uses a dual wavelength laser absorption technique to measure the concentration of most hydrocarbon fuels such as jet fuel, methane, propane, etc. The device can be configured to use fiber optics to measure the local FAR inside a high pressure test rig without the need for windows. Alternatively, the device can readily be used in test rigs that have existing windows without modifications.

An initial application of this instrument was to obtain time-resolved measurements of the FAR in the premixer of a lean premixed prevaporized (LPP) combustor at inlet air pressures and temperatures as high as 17 atm @ 800 K, with liquid JP-8 as the fuel. Results will be presented that quantitatively show the transient nature of the local FAR inside a LPP gas turbine combustor at actual operating conditions. The high speed (kHz) time resolution of this device, combined with a rugged fiber optic delivery system, should enable the realization of a flight capable active-feedback and control system for the abatement of noise and pollutant emissions in the future. Other applications that require an in-situ and time-resolved measurement of fuel vapor concentrations should also find this device to be of use.

Keywords: Gas turbine engines, hydrocarbon vapor sensor, jet fuel vapor sensor, active combustion control, combustor dynamics, infrared absorption, fiber optic sensor.

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1. INTRODUCTION

Today's advanced gas turbine engines have entered what has been described as the final frontier of aero-engine research: the active control of combustion driven noise and dynamics. Active combustion control has been recognized as a promising solution that simultaneously reduces chemical and acoustic emissions while providing enhanced engine performance and reliability.[1] Tomorrow's aircraft will have to fly faster, farther, and must do so cleanly and quietly. To achieve these goals using active control, we must be able to first model and then control the dynamics of this new breed of engine. The effective control of any dynamic system begins with the measurement or sensing of a primary observable in the system. This paper describes a novel optical absorption technique that measures the real-time concentrations of hydrocarbon (HC) fuels inside a gas turbine combustor.[2] The measurement of the fluctuations in the fuel-air concentration can then be used as input to an active combustion control system. Although the results presented here were obtained using a combustor test rig fitted with windows, future versions will utilize fiber optic delivery for windowless access to the combustor.

The governing equations that describe the acoustics and dynamics of gas turbine combustors require knowledge of the time-varying heat-release rate as a forcing function.[3] The heat-release rate is the dominant source-term in the governing equations and its measurement is paramount to the understanding of the physics that govern combustor noise and dynamics. The extent of fuel-air mixing is quantified by a term called the unmixedness parameter U, which equals zero for a perfectly mixed stream and equal to unity for a perfectly unmixed stream.[4] Although the measurement of the of fuel-air unmixedness is not a direct indicator of the heat-release rate, fluctuations in the fuel-air unmixedness however, must directly affect the fluctuations in the heat-release rate.[5] Thus, we are measuring a significant source of the fluctuations in the heat-release rate. The measurement of the fluctuations in the fuel-air unmixedness coupled with the traditional data will provide valuable insight into the physics that govern combustor acoustics and instabilities.

2. THEORY OF OPERATION

Measurement of the fuel vapor concentration prior to combustion provides a means of measuring the fuel-to-air ratio (FAR). The FAR probe operates on the principle of line-of-sight absorption of a special 3.39 μm wavelength HeNe laser that is directed into the combustor of a gas turbine engine using either, conventional optics or high-temperature sapphire optical fibers. The wavelength of this HeNe laser fortuitously coincides with a strong absorption feature found in HC fuels. This absorption is well known and the absorption coefficient for various HC fuels have been extensively measured over a broad range of temperatures and pressures by Tsuboi et al.[6] The FAR probe is the scalar analog of a hot-wire anemometer – it has a small measurement volume and high speed response. The measurement of the vapor component of liquid HC fuels is complicated by the fact that some of the liquid-phase fuel scatters and/or absorbs light. By using a second non-spectrally absorbing wavelength, the contribution of the liquid-phase component can be logarithmically subtracted out following Drallmeier.[7] The expression for the mole fraction of the fuel vapor is given by:

$$\chi(t) = \frac{-\log(\tau_{VIS}\,\eta - \tau_{IR})\,R\,T}{\varepsilon\,L\,P_{TOTAL}} \quad , \qquad (1)$$

where τ_{VIS} and τ_{IR} are the time-dependent transmittance of the visible and infrared beams, respectively, R is the universal gas constant [m^3 atm kmol^{-1} K^{-1}], T is the temperature [K], P_{TOTAL} is the total pressure of the mixture [atm], L is the absorption pathlength [cm], ε is the decadic extinction coefficient [cm^2 mol^{-1}], and η is the optical thickness ratio. The optical thickness ratio is a complex function of the droplet diameter, and wavelengths of light used (633 nm and 3.39 μm in this case) and can be calculated from Mie scattering theory. However, for droplets larger than 20 μm, η is close to unity, and Eqn. 1 can be used to calculate the fuel vapor fraction to within 10%.[7] For droplet diameters below 20 μm however, the errors associated with subtracting out the liquid-phase scattering becomes progressively larger.

3. EXPERIMENTAL SETUP

Figure 1 shows a schematic of the high temperature and pressure combustor test rig and the approximate location of the measurement zone for the fuel vapor measurement. The test rig is capable of operating with inlet air conditions of up to 860 K and 16 atm at a flow rate up to 6 kg/s. The laser probe volume is directed across the exit plane of the premixed fuel-air inlet to the combustion chamber. The probe volume is located approximately 1 mm downstream of the sudden expansion wall. Fig. 2 shows a schematic of the optical layout and instrumentation of the FAR sensor apparatus. Laser emission at 3.39 μm from a 2 mW polarized HeNe laser is combined with 633 nm light from a 10 mW polarized HeNe laser using a Si beamsplitter. The coaxial beams are then directed through the measurement zone into the combustor measurement section using Au coated mirrors. The transmitted beam is then separated with another Si beamsplitter whereupon the visible and IR portions are directed towards a Si photodiode and TE-cooled HgCdZnTe IR detector/preamplifier assemblies, respectively.

The visible 633 nm beam serves two functions: as an alignment aid and to normalize for the effects of liquid droplet scattering/absorption as described in the above section. The photocurrents from the detectors are then digitized with 16-bits of resolution, analyzed and recorded with a 100 kHz multi-channel real-time digital signal processor. Although the electronic bandwidth of the detection system is 100 kHz, the signals are digitized at 5 kHz, reducing the computer storage requirements for the data. As most dynamic phenomena inside the combustor in this study have spectral features below 2.5 kHz, a sampling frequency of 5 kHz adequately satisfies the Nyquist criterion.

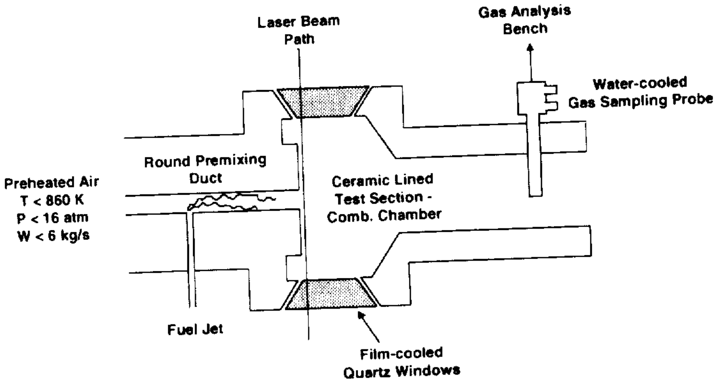

Figure 1: Schematic of high pressure combustor facility and measurement zone. Optical access provided by windows are also used for PLIF imaging and PDPA laser diagnostics.

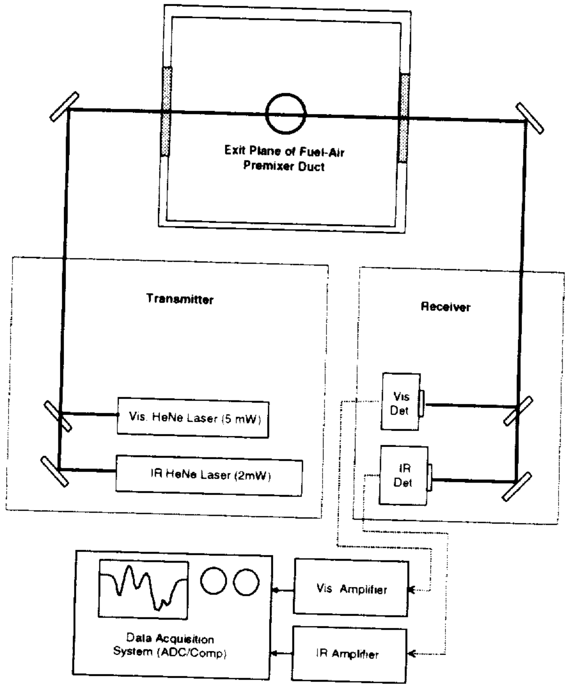

Figure 2: Schematic of optical setup and instrumentation. Si windows are used for dichroic beamsplitters, quartz (UV grade fused silica) windows permit 3.39 micron transmission with only 15% attenuation.

4. RESULTS

Figure 3 shows the time-resolved fuel vapor measurement in a lean premixed prevaporized combustor operating on JP-8 fuel with an inlet air condition of 4.42 atm and 616 K. The effect of liquid-phase droplet scattering/absorption is shown in the corrected IR transmittance compared to the uncorrected signal. The resulting time-varying line-of-sight averaged equivalence ratio was calculated from Eqn. 1, using an average decadic absorption coefficient obtained from calibrating the absorption of JP-8 at a high inlet air temperature case (all vapor) and using an approximate absorption path length of 2.7 cm, as defined by the exit plane.

JP-8 is composed of many hydrocarbon compounds, including aromatics (approx. 20%), with paraffins being the major constituent.[8] All of the higher HC's however, have a decadic absorption coefficient around 2×10^{-5} [$cm^2\ mol^{-1}$] that is relatively insensitive to temperature.[6] Thus we can use an average empirically derived absorption coefficient for a complex mixture such as JP-8 or Jet-A at a variety of temperatures and pressures ($2.4\times10^{-5}\ cm^2\ mol^{-1}$). This is confirmed by the self consistent measurements we obtain at different temperatures and pressures from using a single average absorption coefficient. The equivalence ratio or FAR can be seen to vary significantly in time. The mean value of the measured equivalence ratio compares well with the metered equivalence ratio of 0.57. Fig. 3 also shows the simultaneous fluctuating pressure as measured with a semi-infinite tube microphone pressure tap. For the conditions encountered in these tests, no coupling between the FAR fluctuations and the fluctuating pressure measurements was observed.

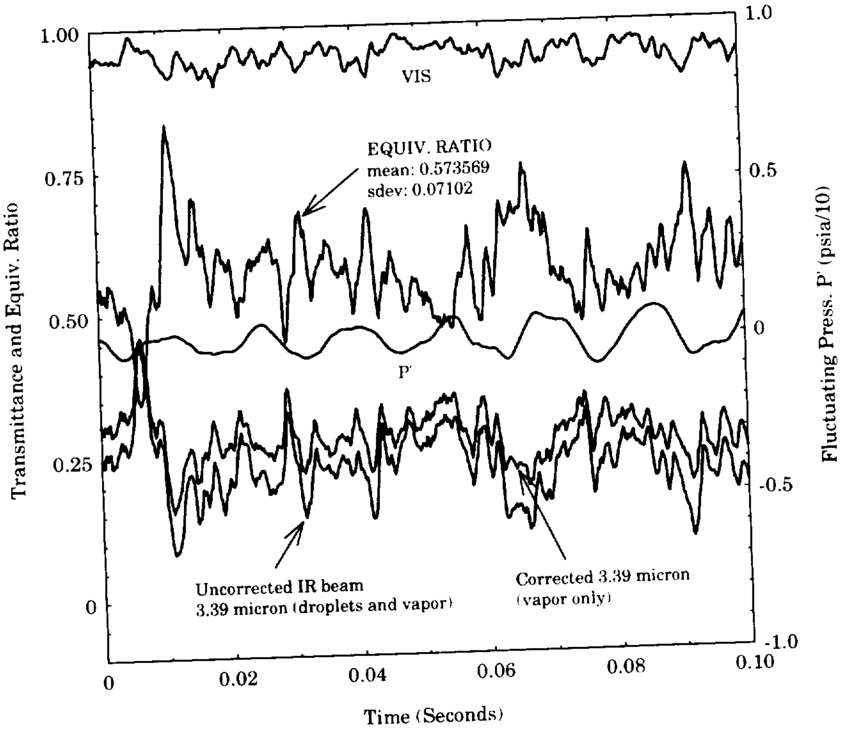

Figure 3: Time-resolved FAR measurements at 4.42 atm, 616 K, approx. 2.7 cm pathlength, FAR_{METER} = 0.039 (Phi=0.57).

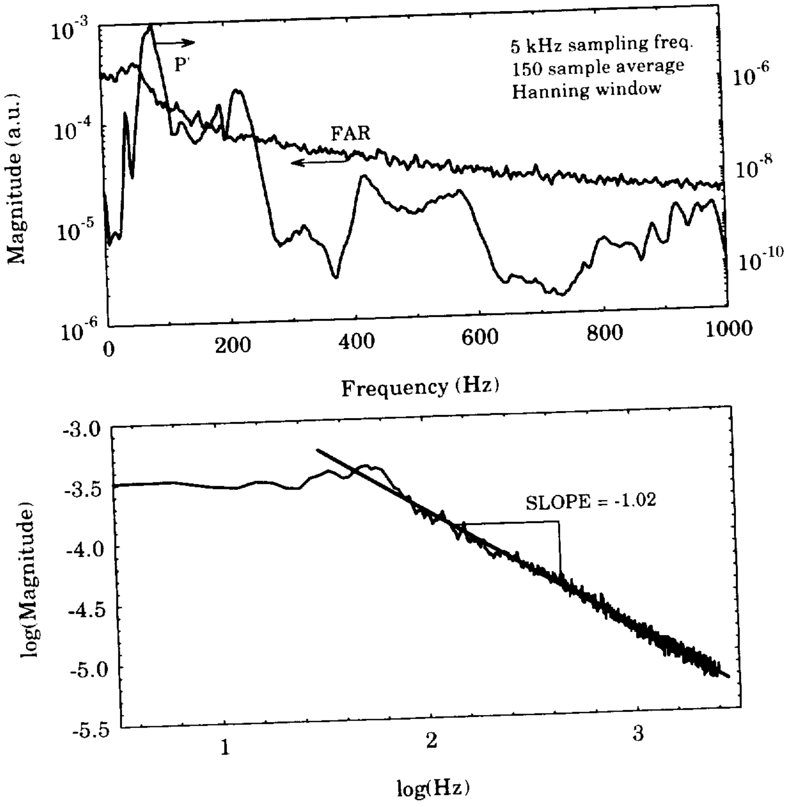

Figure 4: Frequency domain analysis of FAR and fluctuating pressure measurements.

Fig. 4 shows the spectral energy of the FAR and fluctuating pressure measurements. The dominant acoustic frequency is approximately 87 Hz and corresponds to the first longitudinal mode of the combustor rig at this temperature. Fig. 4 also shows the spectral energy decay of the FAR measurement resulting from turbulent mixing and dissipation. The decay slope does not match the classic turbulent decay slope of -5/2 since the smallest spatial scales of turbulence are not resolved in this line-of-sight measurement.[9] However, when using a small fiber optic sensor in which the smallest scales of turbulence are resolved, the decay slope was shown by Mongia et al. to equal -5/2. [5]

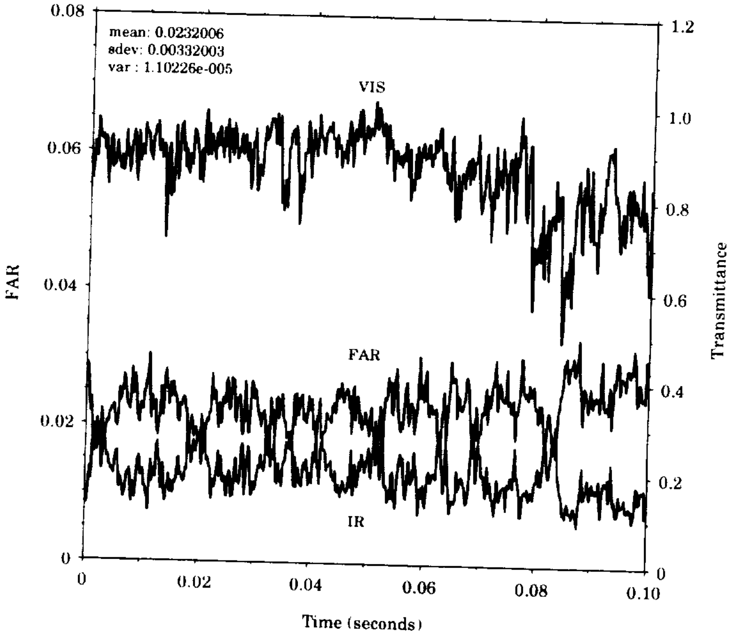

Figure 3: Time-resolved measurements at 14.9 atm, 755 K, $FAR_{METER} = 0.022$ (Phi=0.32).

Figure 5 shows the time-resolved fuel vapor measurement at a higher inlet air temperature of 755 K and 15 atm. For this condition, we would expect that all the fuel is in the form of vapor. However, we observe a dramatic attenuation of the visible laser signal when the flame is on. With the fuel turned off and no flame, the 40% absorption of the visible beam goes away. We suspect that the attenuation of the visible light results from the scattering from the ultra-small droplet with diameters on the order the wavelength of the visible light. From Phase/Doppler Particle Analyzer (PDPA) measurements of the droplet size distribution at the lower temperature case, and by invoking the D^2 law for droplet evaporation (Glassman, 1987), it is plausible that there are numerous sub 1-μm (of order 633 nm) droplets still remaining in the flow field even though we would like to think that they have all evaporated. These sub micron droplets essentially act as a fog that scatters approximately 40% of the 633 nm light. For this case, we simply ignored the contribution from the visible wavelength to obtain a FAR that matches the metered value of 0.022. We also considered the possibility that the attenuation of the visible beam resulted from a thermal beam steering effect that is more pronounced in the 633 nm beam path. However, this seems unlikely in view of the fact that both the IR and visible beams should experience the same thermal beam steering effects since the index of refraction of air does not vary significantly enough between 633 nm and 3.39 µm in wavelength. Ignoring the effects of the 633 nm beam, we can see that the optically measured FAR fluctuates a lot less than the previous case with the cooler inlet air temperature. This is expected as this particular combustor operates much more efficiently and quieter at the higher temperatures and pressures due to the enhanced fuel mixing and evaporation.

5. CONCLUSIONS

A novel, quantitative optical technique to measure the time-resolved fuel-to-air ratio inside a lean premixed pre-vaporized combustor was demonstrated. The use of an empirically derived, average absorption coefficient for JP-8 or Jet-A was demonstrated at actual operating conditions of high pressure and temperature, to provide a satisfactory value for the complex mixtures that comprise commercial gas turbine aviation fuel. The device uses a dual wavelength laser absorption technique to measure the concentration of most hydrocarbon fuels such as jet fuel, methane, propane, etc. The device can be configured to use fiber optics to measure the local FAR inside a high pressure test rig without the need for windows. Alternatively, the device can readily be used in test rigs that have existing windows without modifications.

The high speed (kHz) time resolution of this device, combined with a rugged fiber optic delivery system, should enable the realization of a flight capable active-feedback and control system for the abatement of noise and pollutant emissions in the future. Other applications that require an in-situ and time-resolved measurement of fuel vapor concentrations should also find this device to be of use.

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