Combustion Efficiency of a Model Dual Mode Scramjet Combustor using Infrared Laser Absorption Spectroscopy

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Abstract

In the design of air-breathing engines computational and analytical tools are often used in the early stages of the design process to reduce testing and prototyping. The Aerospace Research Laboratory at The University of Virginia is involved in a project to validate computational fluid dynamics calculations for use in design of scramjet engines. One important parameter used in optimizing performance of scramjets is combustion efficiency. To determine the combustion efficiency of a model scramjet a technique to measure water vapor concentration produced in the combustor is being developed. In a hydrogen fueled scramjet the combustion efficiency can be calculated by measuring the amount water vapor leaving the combustor and finding it's ratio to the amount of fuel supplied. The concentration of water vapor leaving the combustor can be measured by a technique called infrared laser absorption tomography. Infrared laser absorption tomography combines two measurement techniques; infrared laser absorption spectroscopy and tomographic image reconstruction. Tomography, or image reconstruction from projections is the technique used in medical CT scans and produces a spatially resolved two-dimensional distribution of the measurement space. Infrared laser absorption spectroscopy is used to measure species concentration and temperature in many combustion flow applications and will be combined with tomographic imaging and implemented at the supersonic combustion tunnel at The University of Virginia's Aerospace Research Laboratory (ARL).

Introduction

The idea of a supersonic combustion ramjet (SCRAMJET) has been around since the mid 1950's and has spurred a massive volume of literature on the subject. Applications of this technology have been proposed for everything from drag reduction/thrust augmentation and attitude control of supersonic flight vehicles to primary propulsion systems for hypersonic missiles and airplanes and transatmospheric accelerators[1]. NASA has recently successfully flown a scramjet based hypersonic vehicle, the X-43a, which flew at nearly Mach 10[2]. The University of Virginia is involved in NASA's work on the design and development of scramjet technology. The University of Virginia is involved in a research program at the Aerospace Research Laboratory's supersonic combustion facility to validate the computational fluid dynamics codes used in the design and optimization of scramjet engines. The supersonic combustion facility at the University of Virginia is a continuous flow, clean air, Mach 2 wind tunnel equipped with a variety of conventional and laser based diagnostics to measure flow properties such as temperature, pressure and velocity[3]. One quantity of particular interest to designers is combustion efficiency of the scramjet.

To determine the supersonic combustion efficiency of a scramjet we are developing an instrument to measure the concentration of water vapor produced in the combustor. Because of the non-uniform nature of the distribution of water vapor in the flow through a supersonic combustor such measurements are best if they incorporate spatial resolution. To produce two-dimensional spatially resolved water vapor distribution a technique called infrared laser absorption tomography is being used. This technique combines infrared laser absorption spectroscopy and tomographic image reconstruction.

Supersonic Combustion Efficiency

Because of the high flow through velocities in a supersonic combustor the residence time of the fuel in the combustor is very low, on the order of a millisecond. Therefore the fuel and oxidizer must mix and react in a very short time so that combustors can be made to a reasonable length scale and thrust produced by the combustion products leaving the combustor. Combustion efficiency in a supersonic combustor can be defined as the actual heat release divided by the potential heat release of the fuel at the full reaction of all the fuel or oxidizer while still in the combustor section of the engine[4].

$$\eta = \frac{\dot{m}_{H\ Burned}}{\dot{m}_{H\ Total}} \qquad (1)$$

In equation (1), η is the supersonic combustion efficiency, $\dot{m}_{H\ Total}$ is the mass flow rate of hydrogen fuel injected in the scramjet and $\dot{m}_{H\ Burned}$ is the mass flow rate of hydrogen in the form of combustion products leaving the combustor. In a hydrogen fueled, clean air facility such as the one in use at the University of Virginia, the combustion of hydrogen can be simply modeled by:

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (2)$$

This simple stoichiometric balance can be used because the incoming air is dry and free of vitiates that complicate the composition of the test gas.

Because of the three-dimensional nature of the flow through the combustor the concentration of reactants and products is not uniform in space and therefore equation (1) can be recast to include spatial resolution.

$$\eta = \frac{\int_{exit} m_{H\ Burned}(x,y)\cdot V(x,y)dA}{\dot{m}_{H\ Total}} \qquad (3)$$

Where $m_{H\ Burned}(x,y)$ is the two-dimensional distribution of water vapor concentration and $V(x,y)$ is the axial flow velocity distribution out of the combustor. The integral in the numerator of (3) provides the two-dimensional distribution of water vapor flux at the exit plane of the combustor. The velocity will be measured using particle image velocimitry[5] and the concentration of water vapor is measured by infrared laser absorption tomography.

Infrared Laser Absorption Tomography

To determine the two-dimensional distribution of water vapor leaving the combustor requires a measurement technique that accounts for the spatial variation in the measured property. This can be done by combining two techniques; infrared laser absorption spectroscopy and tomographic image reconstruction. Infrared laser absorption spectroscopy is currently widely used in many combustion diagnostic applications in both research and industry. Tomographic image reconstruction is the basis of medical CT scans.

Infrared Laser Absorption Spectroscopy

Room temperature infrared diode lasers are regularly used to develop sensing techniques in combustion flows in laboratory and industrial settings[6]. Absorption of radiation at a frequency, ν, by an absorbing medium can be expressed by Beer-Lambert's law (4).

$$I(\nu) = I_0(\nu)\exp[-\alpha(\nu)L] \qquad (4)$$

Where I(ν) is the transmitted intensity, $I_0(\nu)$ is the incident intensity, α(ν) is the absorption coefficient, and L is the optical path length. The absorption coefficient is a function of temperature and number density of the absorbing species and can be expressed by

$$\alpha(\nu) = S(T)g(\nu - \nu_o)N \qquad (5)$$

where S(T) is the temperature dependent line strength, $g(\nu - \nu_o)$ is the line shape function, and N is the number density of the absorbing species. If the temperature and lineshape are known then the absorption measured from a single spectroscopic line feature may be used to determine the number density of the absorbing species by inverting equation (4).

However, if temperature is unknown, measurements of absorption of two absorption features in the spectrum may be used to determine the temperature. The ratio of the integrated absorbance of two lines may be used. From this ratio the temperature may be determined, and the corresponding water vapor concentration may be found using one or both of the probed absorption lines[7].This method of relating the concentration of a specific species to the reduced intensity of light transmitted through the absorbing medium is called direct absorption. For strong absorption where there is a sufficient amount of the absorbing species present (high mole fraction or long optical path length) direct absorption works well.

For short path lengths and small concentrations direct absorption signals can be weak and difficult to analyze due to low signal to noise ratios. Figure 1 is from a direct absorption measurement in a flat flame Henken burner. The graph is of measured laser intensity and the dip in intensity is the direct absorption of the laser by the water vapor in the combustion products of the flame.

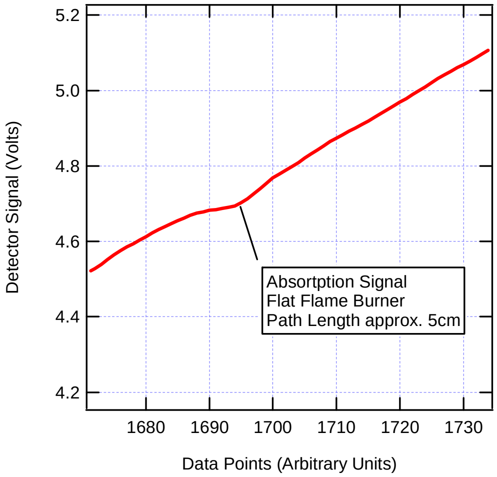

Figure 1. Raw infrared laser absorption data taken from a bench top flat flame burner. The optical path length is about 5 cm. The graph scale has been expanded to show detail.

For flows where a more sensitive measurement method is required harmonic detection techniques may be used. This introduces the possibility of phase sensitive detection of the absorption signal. This increases the signal-to-noise ratio and allows detection of much smaller absorbances. This is accomplished by imposing a sinusoidal variation on the injection current about some average. The resulting variation of the laser frequency is of the following form

$$\nu(t) = \bar{\nu} + a\cos\omega t \qquad (6)$$

The absorption coefficient can now be expressed as an even time dependent function

$$\alpha\left(\bar{\nu} + a\cos\omega t\right) \qquad (7)$$

Equation (7) can be expanded in a cosine Fourier series

$$\alpha\left(\bar{\nu} + a\cos\omega t\right) = \sum_{n=0}^{\infty} H_n\left(\bar{\nu}\right)\cos n\omega t \qquad (8)$$

$H_n\left(\bar{\nu}\right)$ is the nth Fourier component of the absorption coefficient of the signal modulated at frequency ω. This component of the signal from the detector can now be selected by the use of a lock-in amplifier and the strength of the signal is proportional to

$$I_o H_n\left(\bar{\nu}\right)L, \quad n \geq 1 \qquad (9)$$

The form of the harmonic signals depends on the absorption coefficient, α(ν), which can be described by Lorentzian, Doppler, or Voigt functions. Determination of the absorption coefficients and the accompanying second harmonic line shapes is given in detail by Reid and Labrie (ref. 8) and their cited references.

Implementation of wavelength modulation spectroscopy requires that the modulated laser be swept across two adjacent absorption features and the magnitude of the normalized second harmonic signal be used in the ratio to determine temperature. Then the lineshape can be used for either feature to determine concentration of water vapor.

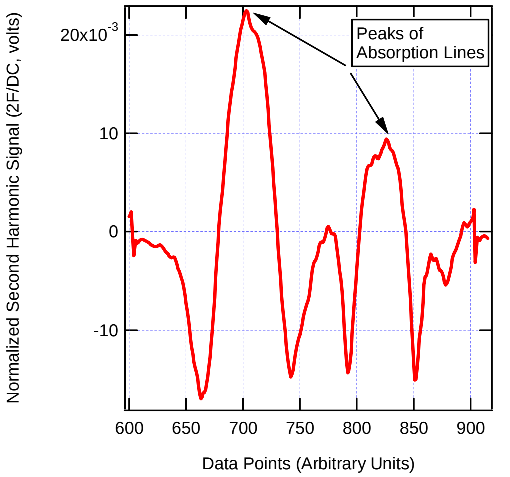

Figure 2. Normalized Second Harmonic signal of wavelength modulation spectroscopy of a flat flame burner. The modulated laser is swept across two adjacent absorption features so the ratio of the peaks of the absorption lines may be used to determine the temperature.

Tomographic Image Reconstruction

The line-of-sight infrared absorption spectroscopy described in the previous section is by definition a one dimensional measurement that yields an integrated value for water vapor concentration along the optical path. As pointed out earlier to determine the combustion efficiency of a scramjet combustor a spatially resolved distribution is required. To create this distribution the line-of-sight absorption measurements are combined with tomographic image reconstruction techniques.

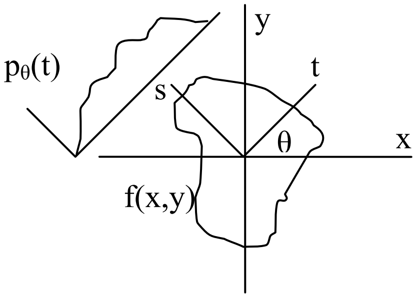

Figure 3. The projection, $p_\theta(t)$ of a distribution represented by the function f(x,y) oriented at an angle (θ) to the embedded (x,y) laboratory coordinate system. The projections are taken in the rotated (s,t) measurement coordinate system as expressed in equation (10).

Tomography, or multi-angular scanning, creates and image from M parallel line-of-sight measurements taken at an angle θ. This ensemble of measurements at the same orientation makes up a projection (equation 10).

Projections are then taken from N angles spaced around 180° of the measurement space resulting in an MxN array of measurements.

$$p_\theta(t) = \int_{-\infty}^{+\infty} f(s,t)\,ds \qquad (10)$$

The Fourier slice theorem is used to reconstruct the image of the sample space. The Fourier slice theorem states that the Fourier transform of a projection of the measurement space is equivalent to a line in the two-dimensional spectrum oriented at the same angle as the projection (figure 4). What this means from a practical stand point is that the two-dimensional Fourier transform of the distribution can be constructed from the one-dimensional Fourier transforms of the projections placed in the frequency domain at their proper orientation. The image or distribution can then be reconstructed by taking the inverse two-dimensional Fourier transform.

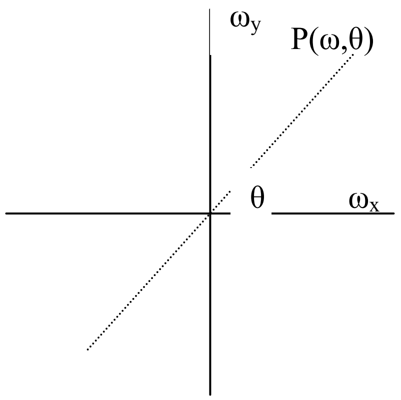

Figure 4. One-dimensional Fourier transform, P(ω,θ) of a projection, $p_\theta(t)$ placed in the proper orientation in the frequency domain.

As a proof of concept this reconstruction technique has been applied to a test image or numerical phantom. Figure 5 is the tomographic reconstruction of a numerical phantom of a computational fluid dynamics prediction of water vapor concentration in a model scramjet combustor. It was made from 220 parallel line-of-sight integrations (M=220) and an angular separation (Δθ) of 10° (N=18).

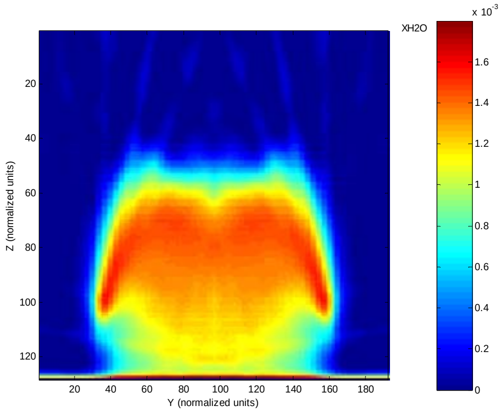

Figure 5. Reconstruction of a numerical phantom CFD result of water vapor concentration in a model dual-mode scramjet combustor. The original from which this numerical phantom was reconstructed was supplied by Carlos Rodriquez NASA LaRC.

In addition to reconstructing a numerical phantom, the Fourier slice theorem was applied to the reconstruction of a physical phantom as well. In this case the physical phantom was a half inch diameter metal rod placed in the measurement space. A HeNe laser was used to create the projections from 20 evenly spaced angles with a sample resolution of 5 mm, corresponding to 20 samples. The reconstructed cross sectional shape is shown in figure 6.

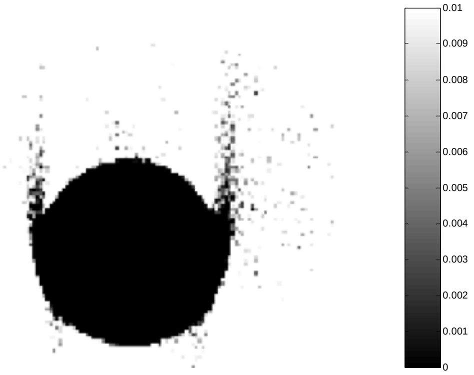

Figure 6. A 0.5 inch diameter circular metal rod used as a physical phantom and the cross-sectional shape reconstructed form a 20 x 20 data set.

Experimental Program

Implementation of these two measurement techniques on the supersonic combustion facility at the Aerospace Research Laboratory has presented many technical challenges beyond understanding of the theory of either infrared laser absorption spectroscopy or tomographic image reconstruction. One of the obstacles is to get the infrared laser light from the diode to the measurement space at the combustion tunnel with out passing through the humid room air that would introduce extraneous absorption and mask the absorption signal from the tunnel. It was decided that this would be accomplished through the use of optical fibers. The use of single mode optical fibers requires that the laser be precisely focused onto the end of the fiber the core of which is only 9 microns in diameter. This required much patience and tedious fine tuning adjustment of specialized optical equipment. The use of single mode optical fibers is necessitated because the mode scrambling effect of the much larger multimode fiber interferes with the absorption signal.

The second difficulty is how to traverse the laser around the tunnel in such a manner that the amount of room air in the optical path between the emitter and the edge of the measurement space is minimized. Having limited optical access and a rectangular measurement space imposed the additional difficulty of not being able to use many of the standard tomographic inversion algorithms without significant modification first. Considerable development has gone into motion control and data sorting algorithms that permit line-of-sight measurements to be taken out of order and then reassembled into projections before undergoing tomographic reconstruction. This aspect of the program yields the additional benefit of the being able to scale the instrument up to fit wind tunnels of other sizes and geometries.

The experimental program currently under way has two phases; first bench top testing of the infrared laser absorption tomography system. This consists of line-of-sight calibration measurements in a high temperature absorption cell and a flat flame burner as well as tomographic reconstruction of the burner flame. The second phase is in the supersonic combustion tunnel itself. This consists of line-of-sight measurements of a known quantity of steam and in a hydrogen flame and culminates in the full tomographic imaging of the model dual-mode scramjet combustor, the results of which will be used in the combustion efficiency calculations.

Conclusion

To determine the combustion efficiency of a dual-mode scramjet combustor by measuring the combustion products spatial variations in concentration must be taken into account. To do this researchers at NASA and The University of Virginia are developing infrared laser absorption tomography. Infrared laser absorption tomography combines the techniques of infrared laser absorption spectroscopy and tomographic image reconstruction to produce a two-dimensional spatially resolved distribution of water vapor concentration. This distribution will be used with independent velocity measurements to calculate the combustion efficiency of the combustor.

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