Analysis of a Tomography Technique for a Scramjet Wind Tunnel

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Abstract
An experimental activity is currently underway to develop a tunable diode laser absorption tomography (TDLAT) technique to measure flow properties in a supersonic combustion wind tunnel. The present study simulates the reconstruction of spectroscopic measurements to determine the effects of data collection geometry and ambient water vapor on reconstruction accuracy. The study also proposes a way to remove the effects of ambient water vapor absorption. Overall, results show that TDLAT data collection time can be significantly reduced while maintaining reconstruction accuracy by taking fewer projections with a high density of rays and by correcting for ambient water vapor absorption.

1. INTRODUCTION

An experimental study is currently underway with the aim of developing a tunable diode laser absorption tomography (TDLAT) technique to measure flow properties in a supersonic combustion facility [1]. This work is part of a larger effort to quantify combustion efficiency in scramjet engines. A direct way to define combustion efficiency is the degree of completion of the reaction, or fraction of fuel burnt [2]. When using hydrogen fuel, the fraction of fueled burnt is calculated by determining the fraction of hydrogen converted to water vapor during the combustion process [2]. This is done by comparing the water vapor flux at the combustor exit to a known hydrogen flux injected into the combustor. In order to calculate the water vapor flux, the water vapor concentration across the exit plane must be measured. This paper focuses on determining the water vapor concentration using tunable diode laser spectroscopy (TDLAS) and a technique called computed tomography, which is used to reconstruct two-dimensional (2D) images.

The TDLAT technique is being developed on a flat flame burner to validate the laser and hardware setup. Preliminary tomography research was performed to determine the desirable laser path geometry and to select the data processing methodology [2]. As the TDLAT hardware is transitioned to the supersonic combustion facility, the tomographic process must be analyzed for reconstructions of the flow field expected at the scramjet combustor exit.

The ultimate goal of the present research effort is to determine the optimal data collection geometry for the TDLAT experiment on a supersonic combustion facility in order to provide the most accurate reconstructions with the least amount of data collection time. Since run times are limited by available scramjet fuel, data collection times are of great importance for supersonic combustion experiments. The accuracy of the reconstructions is quantified by calculating the normalized mean absolute distance measure, a common image comparison method [3]. The specific objectives of this TDLAT study are the following:

1. Create an accurate simulation of the data collection technique used in the experiment,
2. Determine trends in reconstruction error based on data collection geometry and ambient water vapor absorption,
3. Correct for ambient water vapor absorption, and,
4. Recommend a data collection geometry based on an optimization of data collection time and reconstruction accuracy.

The quantification of reconstruction error based on simulated spectroscopic absorption data collection is an important step in understanding the application of tomographic spectroscopy to supersonic combusting flows. The TDLAT technique is the first technique aimed at directly measuring combustion efficiency for scramjet combustors in which the distribution of water vapor, a main combustion product, can be mapped at the combustor exit. Because this is the first time tomographic spectroscopy using a full filtered backprojection tomographic reconstruction has been applied to a model scramjet, the optimal data collection geometry and the effect of ambient water vapor on reconstruction accuracy have not to our knowledge been studied previously. The results of this study show how data collection time can be minimized while maintaining reconstruction accuracy, making the TDLAT technique a promising application for combustion experiments.

1.1 Experimental Setup

The TDLAT hardware will be mounted at the scramjet combustor exit in the University of Virginia's supersonic combustion wind tunnel [4]. The wind tunnel has a continuous air supply that is electrically heated to avoid adding vitiates, or contaminates, into the air stream. This gives the facility a unique capacity to do water vapor measurements without the effects of these contaminants. The wind tunnel is vertically mounted with optical access to the combustor section of the test section. Air passes through a Mach 2 nozzle and into the combustor section that houses a ramp fuel injector.

Figure 1 provides a top view schematic of the TDLAT hardware with the combustor flow exiting through the center of the diagram. A laser beam is emitted from an optics box that functions as both an emitter and detector. The laser signal is reflected back into the optics box via a retro-reflector located on the opposite side of the flow. The optics box is mounted on a Velmex rotational stage which rotates the laser beam through a fan geometry, stopping at user-defined increments. The Velmex rotational stage is mounted on a Newport rotational stage which allows the optics box to travel in a full circle around the combustor exit, stopping at user-defined increments. Further details of the TDLAT hardware can be found in Ref. 1.

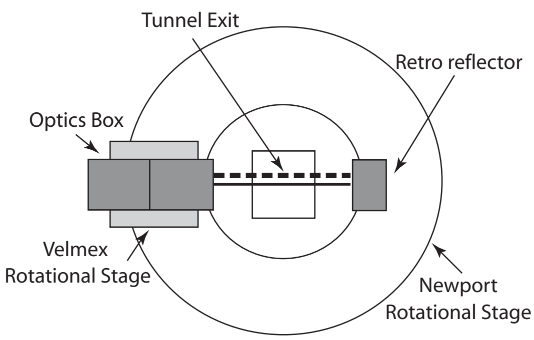

Figure 1. Schematic of TDLAT hardware. The optics box functions as both an emitter and detector. A laser beam is directed across the flow and reflected back into the optics box. The optics box is mounted on two rotational stages that stop at user-defined positions to provide data in a fanbeam geometry.

2. TECHNICAL APPROACH

In the TDLAT technique, laser absorption spectroscopy and tomographic image reconstruction are combined to produce 2D distributions of flow properties across the combustor exit. The coupling of these two techniques is critical to resolve the spatial mapping of the highly variable flow properties in supersonic combustion. Laser absorption spectroscopy is a common diagnostic tool; its application in the TDLAT experiment is fully described by Snyder [2]. Tomography is the cross-sectional imaging of an object from projection data taken at different angles around the object [5].

The optimal collection geometry for tomographic reconstruction and the effects of ambient water vapor were explored through a theoretical reconstruction study done in MATLAB using the Image Processing Toolbox. The TDLAT experiment was simulated by creating an image, or “numerical phantom,” which represents the expected water vapor absorbance per cm at the scramjet combustor exit. For simplicity, the numerical phantom was created for only one frequency bin at the peak of the high temperature transition. Line-of-sight spectroscopic data collection is simulated by performing a Radon transform. The data in the TDLAT experiment is collected using a fanbeam geometry where the fan ray angle is the distance between rays in the fan and the fan rotation increment is the angular distance between the fan vertices. This process is simulated by a code written to collect data from a numerical phantom for a specified fan rotation angle and ray angle input, perform a Radon transform, and output a sinogram. The sinogram simulates experimental data taken by the TDLAT hardware and is the input for the MATLAB ifanbeam function. The ifanbeam function reconstructs the sinogram projection data by performing an inverse Radon transform using the filtered backprojection algorithm. The problem of the inverse crime, where the effect of one operator perfectly nullifies another, is not an issue in this process because different grid resolutions are used to generate the projection data and to reconstruct the data. The result of the simulation is a reconstructed image of the original numerical phantom.

2.1 Creation of the Numerical Phantom

A numerical phantom was first created to match the expected absorbance per cm of water vapor at the combustor exit at the high temperature transition peak at 7277.6 cm^{-1}. Figure 2 shows the process used to create the numerical phantom. The University of Virginia’s supersonic combustion facility has a combustor exit area of 38.1 mm by 40.8 mm [4]. This corresponds to approximately 0.4 mm per pixel in the images. Computational Fluid Dynamics (CFD) solutions of the expected water vapor concentration and temperature at the combustor exit of the supersonic combustion facility were used to generate absorbance spectra. The solutions were generated using a numerical model developed using the Wind-US code [6]. For the purposes of this study, the representative nature of the temperature and water vapor distributions is more important than the accuracy of the predictor. The predicted distributions of water vapor concentration and temperature are seen in Figure 2a and Figure 2b. In the supersonic combustion facility, a ramp fuel injector is located on the wall pictured on the bottom of the images in Figure 2; this will be referred to as the injector wall [4]. Both the water vapor concentration and temperature tend to be higher closer to the injector wall.

For each pixel, the water vapor concentration and temperature were used to generate an absorbance spectrum using spectroscopic parameters from the HITRAN database [7]. The absorbance per cm of the high temperature line at 7277.6 cm^{-1} was plotted for each pixel, creating a map of absorbance per cm expected at the combustor exit, seen in Fig. 2c. The absorbance distribution is highest at the injector wall and has a plume structure with various rings of absorbance values. The final numerical phantom was created by adding ambient water vapor absorbance (assuming a 0.01 H_2O mole fraction at 298 K) around the combustor exit absorbance plot to simulate the room air that the laser must pass through during the experiment. The resulting image was smoothed with a Gaussian filter to simulate the mixing of the combustor exit flow with the room air as it leaves the wind tunnel. The smoothing occurred over approximately 4 pixels, equivalent to a 10° half angle spreading of the flow at 5mm above the exit plane where the TDLAT measurements occur. This phantom, shown in Figure 2d, was used for all studies of data collection geometry presented in this paper. Additionally, the amount of ambient water vapor absorption outside of the combustor exit was varied to create several different versions of this numerical phantom that were used to study the effects of laser absorption of ambient water vapor on tomographic reconstructions. A sample reconstruction is shown in Fig. 2e.

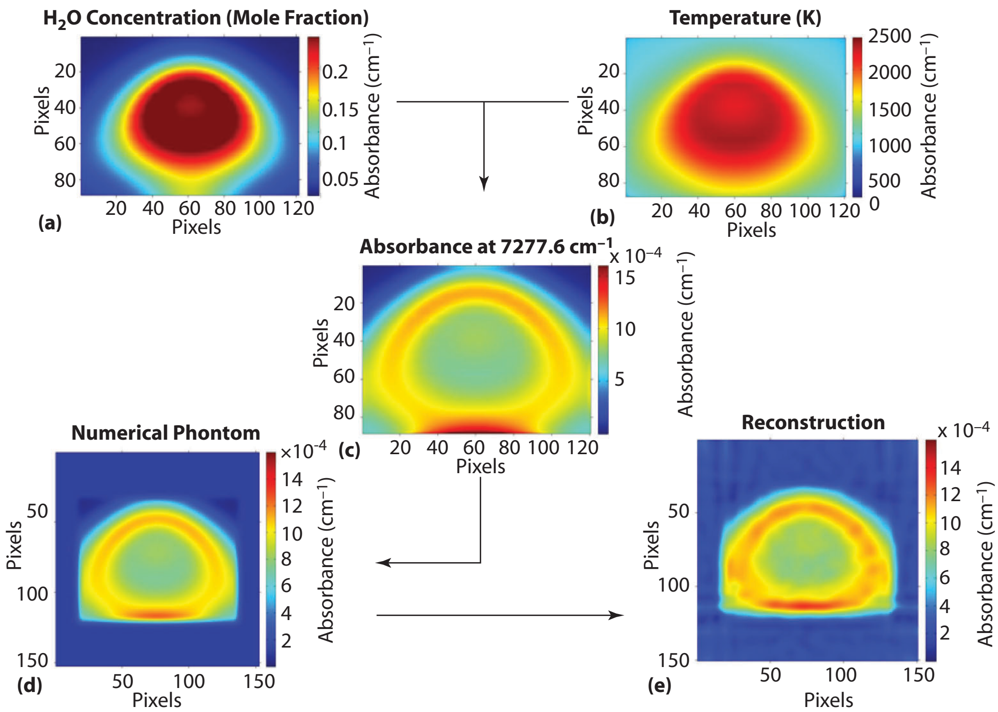

Figure 2. The process used to generate the numerical phantom. Water vapor concentration and temperature CFD solutions were used to determine absorbance at the combustor exit. CFD predictions of the (a) H_2O concentration and (b) temperature were used to determine absorbance spectra. (c) The high temperature peak of each spectrum was used to create an absorbance plot. (d) Ambient water vapor absorbance was added around the absorbance plot to simulate the room air around the combustor exit. (e) The numerical phantom can then be reconstructed.

2.2 Development of an Alternate Radon Transform Code

An important part of the tomography study is accurately simulating the experimental data collection process using the numerical phantom. The fanbeam function in the MATLAB Image Processing Toolbox requires the vertex of each fan to be outside of the image. However, in the experiment, the laser beam comes into contact with water vapor in the room air from the time it leaves the emitter to when it arrives at the detector, not just when it passes through the combustor exit region. The ambient water vapor affects the spectroscopic measurements by absorbing a small amount of laser light outside the combustor exit and distorting the incident intensity of the beam on the detector. In order to account for this difference, an alternate Radon transform code was created to generate a sinogram, accounting for room air along the laser path outside the combustor region. The Radon transform code allows the user to specify the distance, D, between the image center and the fan vertex, the fan rotation angle, the fan ray angle, and the total angle that each fan sweeps through. This allows the code to simulate the experimental parameters for D and various fan increments and ray angles and to output a sinogram for reconstruction. The code also allows the users to specify the number of grid points to use along each ray during the Radon transformation so that a different grid resolution is used to generate the projection data than to reconstruct the data. Further details of how the code functions are provided by Martin [8].

There is not expected to be significant beam steering during the wind tunnel experiments. This is because experimental measurements with line-of-sight measurements taken across the flow at various angles of incidence revealed no significant beam steering. In addition, calculations taking into account tunnel flow and ambient air index of refraction indicate maximum beam steering to be of similar magnitude or smaller than the diameter of the laser beam. Therefore ray bending is not accounted for in the Radon transform code.

3. RESULTS

Results are presented on the effects of data collection geometry and ambient water vapor on reconstruction accuracy. Additionally, a procedure to eliminate the effect of ambient water vapor absorption is demonstrated. Data collection was simulated for various combinations of fan rotation increment and fan ray angles. These data were generated using the alternate Radon transform code and the error was calculated between the reconstruction and numerical phantom. The normalized mean absolute error was calculated in order to determine the error between the reconstructed image and the numerical phantom [3]. The ambient water vapor concentration surrounding the combustor exit was varied in the phantom and data collection was simulated for a 1 degree fan ray angle and 1 degree fan rotation increment for each new phantom. The ifanbeam function was used to reconstruct the resulting sinograms to compare reconstruction error with ambient water vapor absorption.

In order to quantitatively analyze trends in reconstruction error due to various data collection geometries, a plot of reconstruction error verses fan ray angle and fan rotation increment is shown in Figure 3a. All cases were run with a numerical phantom with ambient absorbance equivalent to a water vapor concentration of 0.01 mole fraction at 298K to simulate a typical air-conditioned room. The expected trend is seen; the error increases with increasing fan ray angle and fan rotation increment. The exception to this trend is the slight increase in reconstruction error when the fan ray angle becomes smaller than 1 degree. This suggests that a 1 degree fan ray angle should be used in the TDLAT experiment. A significant result is seen when inspecting Fig. 3a; the error is more dependent on the fan ray angle than the fan rotation increment. This has implications for data collection time. Total data collection time is calculated by assuming a collection time of 1 second per ray, 45 rays per fan, 0.5 second between each ray, and 5 seconds between each fan rotation. These times are based on previous experimental run times [2]. The results show that, at a constant fan ray angle, the fan rotation increment can be increased from 1 to 15 degrees without significantly increasing the reconstruction error. In fact, the error only changes from 0.056 (5.6%) at a 1 degree fan rotation increment to 0.062 at a 15 degree fan rotation increment. This means that data collection time is reduced from 7.2 hours with a 1 degree fan rotation increment to 29 minutes with a 15 degree fan rotation increment without significantly affecting reconstruction accuracy. Data collection time is a major consideration for ground testing facilities with limited run times.

Another consideration in reconstruction accuracy is the effect of ambient water vapor in the room air. In the TDLAT experiment, the laser path is exposed to some amount of ambient water vapor. In order to determine the effect of this water vapor on the reconstructions, the amount of ambient water vapor absorbance was varied in the numerical phantom. Figure 3b shows that as the ambient water vapor concentration increases, for example on progressively more humid days, the reconstruction error increases with the exception of the slight decrease from 0 to 0.5% mole fraction. Ambient water vapor at 1% mole fraction was used as the baseline value; reconstruction error increases from 0.035 to 0.056 as ambient water vapor increases from 0 to 1% at a 1 degree fan ray angle and a 1 degree fan rotation increment. As the ambient water vapor concentration increases beyond 1%, there appears to be a linear trend between error and ambient water vapor concentration. If for some reason the ambient water vapor in the room was increased to 2% on a humid day, reconstruction error increases to 0.130. This is a significant difference from a reconstruction with no ambient water vapor. This demonstrates the importance of mitigating the effects of ambient water vapor absorption.

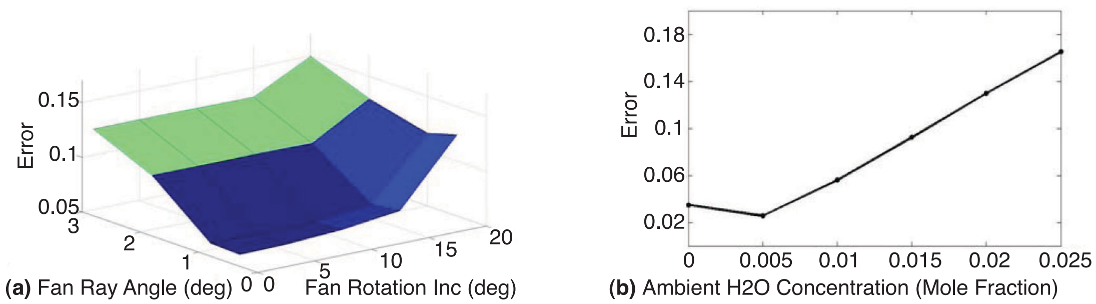

Figure 3. (a) Reconstruction error for varying fan rotation increment and fan ray angle and (b) reconstruction error versus ambient water vapor concentration.

To address the effect of ambient water vapor on reconstruction accuracy, a method was developed to subtract out the ambient water vapor absorption from the reconstruction of the numerical phantom with a 1% ambient water vapor concentration field surrounding the tunnel exit region. First, an identical numerical phantom was created and all the absorption values in the combustor exit region were set to zero. The resulting phantom consisted of only ambient water vapor outside the region of interest. This ambient water vapor phantom was reconstructed using the Radon transform code and the ifanbeam function. The resulting reconstruction of the ambient water vapor was then subtracted from the reconstruction of the original numerical phantom yielding a reconstruction that more accurately represents the combustor exit region. This method can be extended to the TDLAT experiment provided that the water vapor concentration in the room is known.

The results from this study suggest that the optimal data collection geometry for the UVa TDLAT experiment is a 15 degree fan rotation increment with 1 degree fan sensor spacing. The reconstruction error is 0.062 using this collection geometry, which is reduced to 0.054 after correcting for the ambient water vapor. The reconstruction error results show that the error remains approximately constant as the fan rotation increment is increased from 1 to 15 degrees. However, above a 15 degree fan rotation increment, the error begins to increase rapidly. It is important to use the smallest number of fans as possible, while maintaining the integrity of the reconstruction, in order to reduce data collection time for ground testing facilities with limited run times. The supersonic combustion facility at the University of Virginia has a maximum run time of 1.5 hours before the hydrogen fuel supply is exhausted. The results of this study show that data collection time can be reduced to 29 minutes, much less than the facility run time, without reducing reconstruction accuracy.

4. CONCLUSION

The results of this study suggest that a 15 degree fan rotation increment with a 1 degree fan ray angle is the optimal data collection geometry for the TDLAT experiment due to the fact that reconstruction error is largely independent of fan rotation increment below a 15 degree increment. These numbers apply specifically to the absorption transition studied in the TDLAT technique and to the particular flow and geometry of this experiment; however, this method is applicable to other cases as well. Given the temperature and water vapor concentration distributions, this method could be applied to other supersonic combustion facilities or flames. The general error trends are expected to be the same, but the analysis may result in a different combination of fan rotation increment and fan ray angle as well as a different reconstruction error value. Additionally, a correction for ambient water vapor was successfully demonstrated that can be easily implemented in TDLAT techniques at other facilities.

An assessment of the accuracy of tomographic reconstructions using laser absorption spectroscopic measurements of scramjet combustion has not previously been reported in literature. The amount of data needed for a full filtered backprojection tomographic reconstruction can lead to experimental run times that exceed facility run times. This study of data collection geometry on reconstruction accuracy has shown that fewer projections can be used if each projection has a small enough fan ray spacing. This significantly reduces data collection time by reducing the number of spectroscopic line-of-sight measurements needed for reconstruction. A reduction in experimental run time of the TDLAT technique increases its viability for use on other supersonic combustion facilities.

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