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# USING PLIF DETERMINED FLAME STRUCTURE TO ANALYZE SUPERSONIC COMBUSTION EFFICIENCIES

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## Abstract

A hydrogen-air flame was stabilized along the axis of a supersonic windtunnel which flowed Mach 2.5 coflow air. Planar laser induced fluorescence (PLIF) images of acetone vapor seeded in the fuel stream and OH produced in the reaction zone were collected from the supersonic combustor. A water cooled probe was employed to sample the gas downstream of the combustor to detect unburned fuel for combustion efficiency measurements. The combustion efficiency increased as the fuel mass flow rate was increased due to the increased flow blockage and heat addition. The PLIF images show that the fuel and air are premixed prior to reaction at the flame zone due to the intense recirculation at the fuel injector exit. Therefore the premixed gas either reacts at the flame zone or flows around it and exits the combustor. High fuel mass flow rate flames are larger and therefore react more efficiently.

## Introduction

Supersonic combustion ramjet (scramjet) engines have been proposed as propulsion devices for air-breathing hypersonic aircraft. As with any aircraft component, weight restrictions impose limits on the size, specifically the length, of scramjet engines. Therefore, the injection of fuel with optimal mixing and combustion within the time and space constraints of the scramjet is a major design issue. Many studies have applied significant effort to understand the supersonic flame for application to scramjets[2,3,6,8,9]. Combustion efficiency is an appropriate parameter to define how well the mixing and combustion proceeds in a scramjet. Ratner and Driscoll[7] studied the effects of induced shock waves on supersonic combustion efficiency by collecting gas samples downstream of the combustor. The present work uses planar laser induced fluorescence (PLIF) images of the fuel mixing and the reaction zone to further understand the results of the previous probe sampling measurements in a supersonic combustor.

## Experimental Technique

The supersonic combustor employed for this study is displayed in Figure 1. Fuel was injected along the axis of the combustor from a stainless steel tube into a supersonic air stream. The tube had an inner diameter of 7 mm and the outer diameter was tapered to 25.4 mm at the exit to create a bluff body for flame stabilization. The fuel flow was frictionally choked and therefore issued from the tube at sonic conditions. The two dimensional windtunnel section was design to issue coflow air at Mach 2.5 into the plane of the fuel tube exit. The combustor section employed fused silica windows for entry and exit of the UV laser sheet and for collection of the laser induced fluorescence.

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Greater detail of the supersonic combustor facility is presented by Huh[5].

Samples of unburned gas were acquired with a sample probe placed on the centerline of the flue pipe about 2 meters downstream of the combustor. At this location the flow was assumed to be well mixed. The sampled gas was conditioned to remove water vapor to confirm a dry gas reading and fed through a solid state detector[7]. PLIF images of the fuel mixing and reaction zone were acquired by exciting acetone seeded in the fuel stream and OH produced in the reaction zone with 266 nm and 282.75 nm laser sheets from a Nd:YAG and a Nd:YAG pumped dye laser system. The fluorescence images were recorded by an intensified CCD camera oriented perpendicular to the laser sheet. The area imaged by the camera was 76.2 mm x 50.8 mm which required the camera and laser sheet to be traversed vertically five times in order to image the entire viewable flame region. The PLIF system and data acquisition is presented in greater detail by Bryant[1].

## Results

The results of the unburned fuel sampling conducted by Ratner and Driscoll[7] are displayed as combustion efficiency quantities in Figure 2. A linear increase for the combustion efficiency is observed as the fuel mass flow rate is increased. Adding more fuel causes the flame to become larger which creates more of a flow blockage and also causes more of the surrounding fluid to be heated. The larger flame which occupies a constant volume combustor decreases the possibility that unburned fuel will escape the combustor, hence the combustion efficiency increases. The PLIF images of the acetone seeded in the fuel stream and OH produced in the reaction zone offer greater insight into where the fuel is being burned as well as the structure of this specific supersonic flame.

Two flame conditions were studied for the PLIF imaging experiments: fuel mass flow rates of 0.95 and 1.4 g/s. At the larger fuel flow rate the flame was still of suitable size that many of the interesting features of the reaction zone could be imaged within the viewing constraints of the combustor windows. The fuel stream consists of hydrogen seeded with acetone at mole fractions of 0.0072 and 0.0058 for the 1.4 g/s and 0.95 g/s fuel mass flow rates, respectively.

One hundred PLIF images of the acetone excited by the 266 nm laser sheet were recorded for each flame condition. The acetone fluorescence represents fuel rich regions of the flow where the gas temperature is below 1400 K. The mean images of acetone PLIF for the two flame conditions are displayed in Figure 3. Radial profiles at three axial locations are displayed to the right of each image. It should first be noted that the horizontal line in the center of the fuel jet at $x/d \sim 1.5$ is due to a reflection from the back wall of the combustor which was only partially eliminated by the image processing procedure. The lifted flame (i.e. OH radicals) exist at locations just above the fuel pattern, $x/d > 8$, shown in Figure 3.

A comparison of the images and radial profiles in Figure 3 shows that the spreading angle of the fuel rich zone is larger for the larger fuel mass flow rate. This is believed to be due to the increased heat addition to the flow field for the large fuel flow rate which adds more volume expansion and increases the blockage effect of the flame. The flow blockage decelerates the supersonic coflow air which then reduces the velocity difference across the shear layer of the jet and coflow streams. The final result is the wider shear layer at the higher fuel mass flow rate which is evident in Figure 3a.

The images in Figures 3a and 3b show evidence of strong recirculation zones in the vicinity of the jet exit, $x/d < 1.0$. Fuel is observed radially along the base of the bluff body from the jet core to the coflow air stream. At $x/d = 6.7$, the radial profiles display secondary maximums. These features are the result of fuel in the recirculation zone being convected downstream by the supersonic coflow air. An instantaneous acetone PLIF image is displayed in Figure 4. In this image, the symmetric peninsulas of fuel which produce the secondary maximums in the mean radial profiles are clearly evident. Also evident are the regions of high fuel concentration which are immediately adjacent to the supersonic coflow. The acetone PLIF images suggest that fuel is being engulfed into the supersonic coflow and convected downstream where it later reacts as a premixed gas or it flows past the flame without reacting and out of the combustor.

PLIF images of the OH radical produced in the reaction zone of the supersonic flame were recorded at 5 axial locations which covered the viewing area of the combustor. Figures 5a and 5b display the mean of 100 OH PLIF images at each vertical viewing position. During the acquisition of the images the viewing regions were slightly overlapped. A comparison of the mean intensity from the overlap regions provided a scale factor which accounted for differences in camera gain and collection optics solid angle at each vertical position. These scaling factors were applied to the OH images to provide a good estimate of the OH LIF intensity at the downstream locations.

The images presented here do not account for attenuation of the laser sheet due to absorption by the OH radical. It was decided not to correct for absorption since such a correction requires some speculation about either OH concentration or flame symmetry. The absolute magnitude of the OH signal was not of primary interest; instead OH is used only to define the reaction zone location and structure.

Figure 5b, the smaller of the two flames (fuel mass flow rate = 0.95 g/s), vividly displays how the flame develops an open tip which is contrary to a classic nonpremixed overventilated flame. This is also true of the larger flame displayed in Figure 5a, however it is not fully evident from the image because the flame extends beyond the viewing region of the combustor. At x/d=34, Figures 5a and 5b show that regions of high OH concentration are observed outside of the main OH feature. The knowledge gained from the acetone images suggest that these islands of OH outside the main flame structure are due to the reaction of pockets of premixed fuel and air which have been convected downstream from the bluff body region. These exterior reactions are more evident in the larger flame which occupies more of the combustor volume therefore making it more difficult for unburned fuel to escape the combustor. The increase in flame surface area increases the level of flame and unburned gas interaction as demonstrated by Gaston et al[4].

## Conclusions

The results of the sampling measurements in the supersonic combustor show that the combustion efficiency increases as the fuel mass flow rate is increased. It was previously suggested that larger flames resulting from larger fuel mass flow rates would increase flow blockage and heat addition, therefore decreasing the possibility of unburned fuel escaping the combustor. The PLIF images of fuel mixing and the reaction zone lend information in support of the previous claim and provide further insight into how the unburned fuel escapes the combustor. The acetone PLIF images of fuel mixing show that significant amounts of fuel are engulfed by the supersonic coflow air and convected downstream before reacting. The resulting pockets of premixed fuel and air react at further downstream locations or escape the combustor without reacting by flowing around the flame. The OH PLIF images display exterior islands of significant OH concentration which suggest that pockets of premixed gas react at downstream locations. The high fuel mass flow rate flame has a greater occurrence of these exterior reactions. Near the combustor exit the premixed pockets of gas must flow between the combustor walls and the flame. Therefore, escape of unburned fuel is less likely for the large flames.

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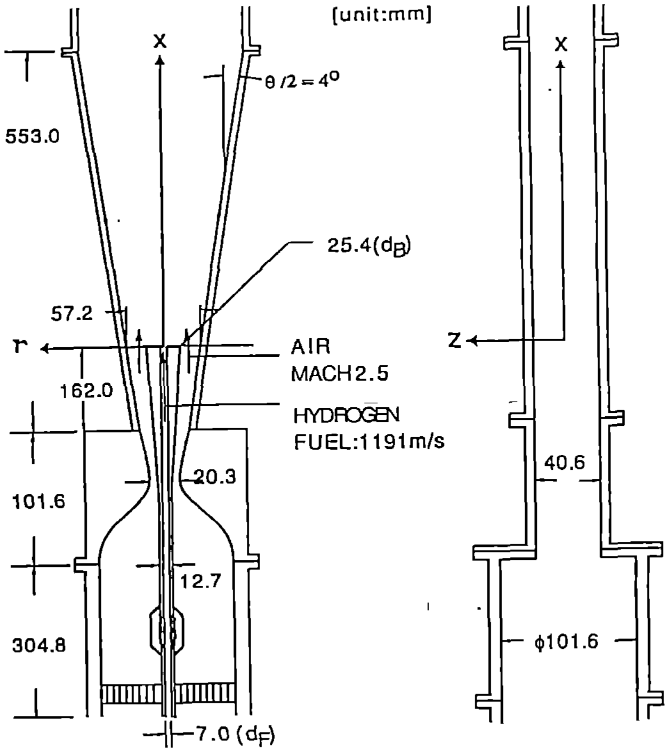



**Figure 1.** Diagram of the supersonic combustor

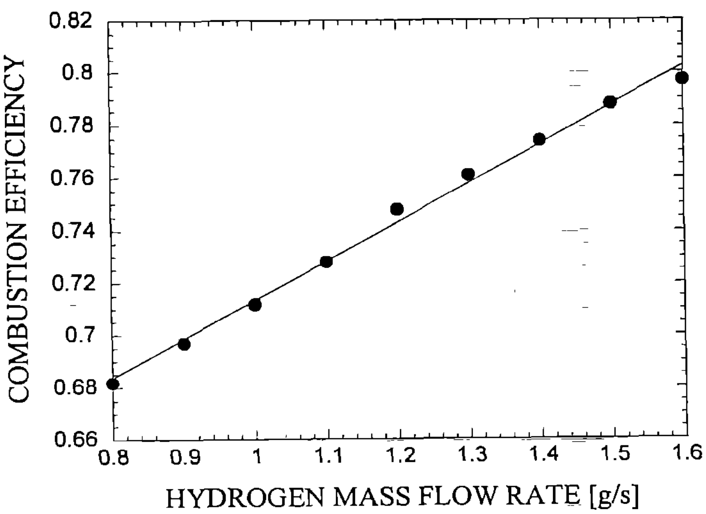



**Figure 2.** Combustion efficiency from the sampling probe measurements at 2 meters downstream of the combustor.

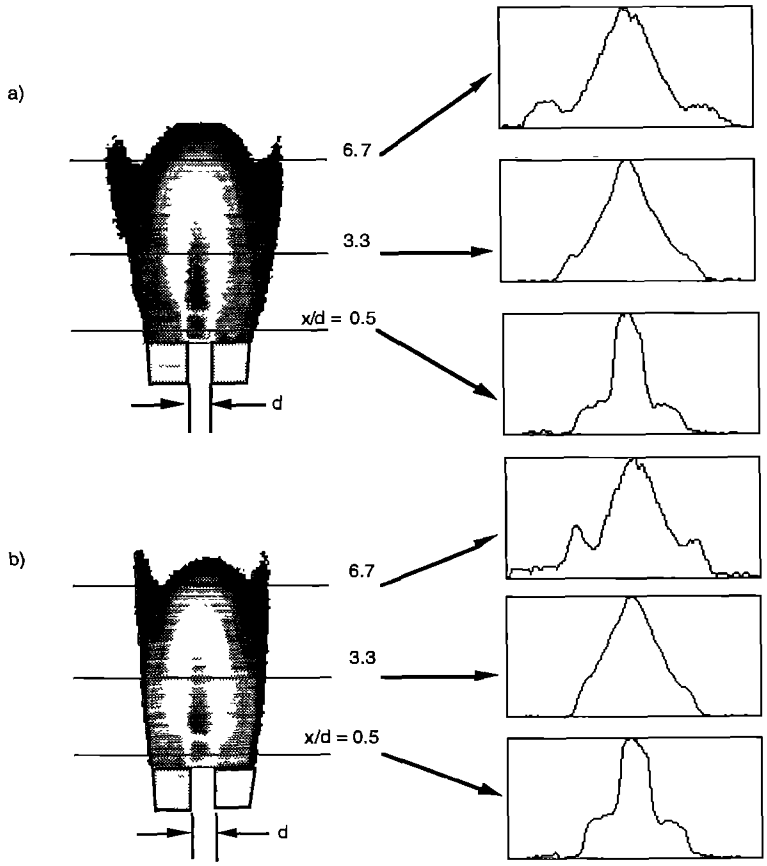



**Figure 3.** Mean PLIF images of acetone seeded in the fuel stream. Fuel mass flow rates are: a) 1.4 g/s, b) 0.95 g/s. Radial profiles at 3 axial locations are to the right of each image.

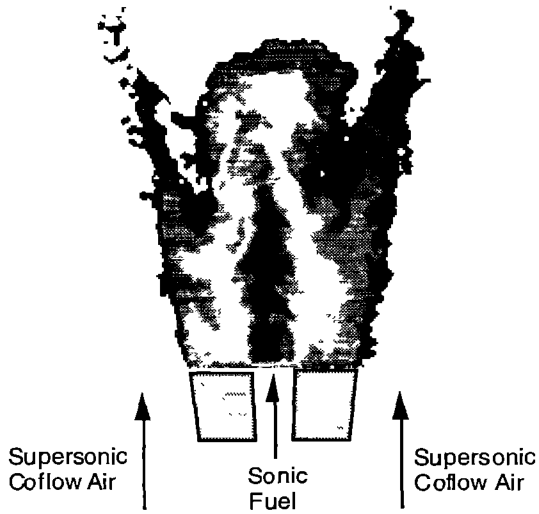
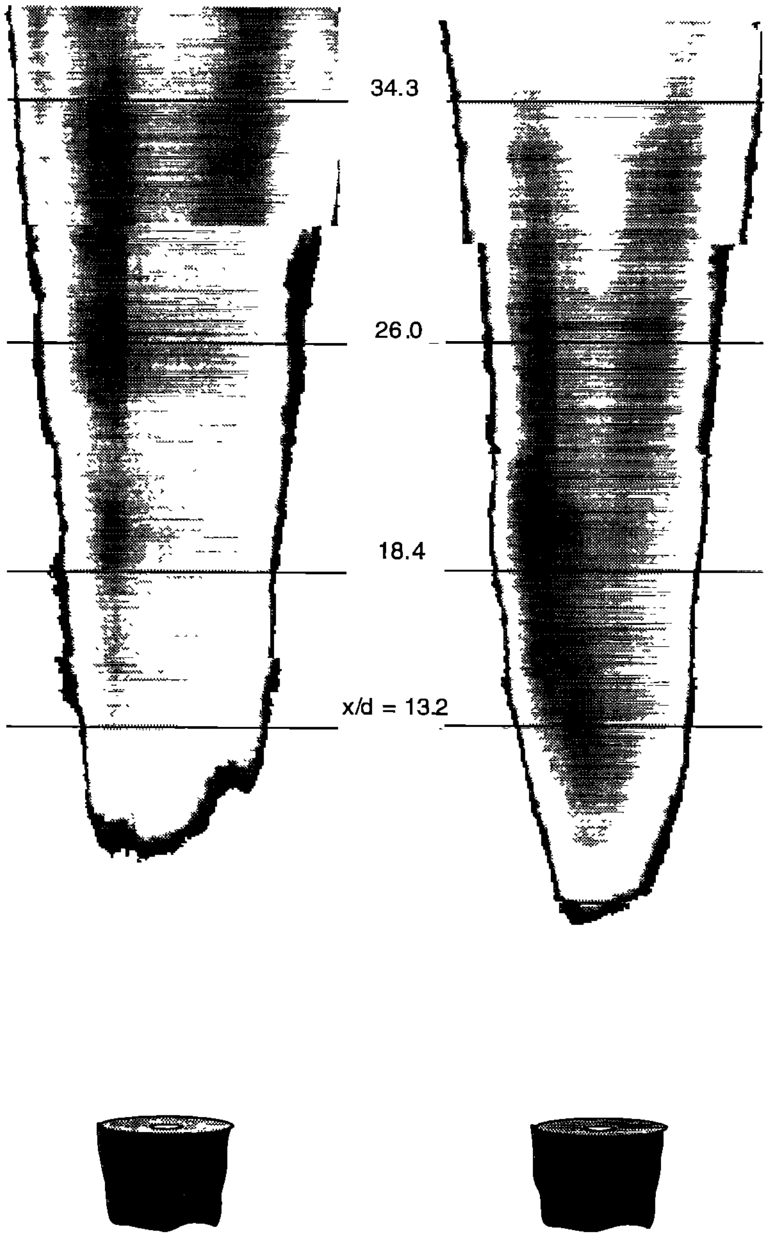



**Figure 4.** Single shot PLIF image of acetone seeded in the fuel stream. Fuel mass flow rate is 1.4 g/s.




a) b)

**Figure 5.** Mean PLIF images of the OH radical produced in the reaction zone of the lifted supersonic flame, a) fuel mass flow rate = 1.4 g/s, b) fuel mass flow rate = 0.95 g/s.