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Measurement of temperature, velocity and water vapor concentration in a scramjet combustor based on near-infrared diode laser absorption

Fei Li[1], Xilong Yu[2], Hongbin Gu[3], Zhi Li[4],Lihong Chen[5], Xinyu Chang[6]
Key Lab of High Temperature Gas Dynamics, Institute of Mechanics,Chinese Academy of Sciences,
Beijing, China,100190

A multi-channel Tunable Diode Laser Absorption Spectroscopy (TDLAS) system was designed and constructed for flow parameters diagnostics in a scramjet combustor. Two fiber coupled distributed feedback (DFB) lasers with narrow line width were used to probe two H_2O absorption features (7185.597cm^{-1},7444.35cm^{-1}+7444.37cm^{-1}(combined)) by using direct absorption Time-Division-Multiplexing (TDM) strategy at a 4-kHz repetition rate. Laser light was split into five beams and transmitted across the test region. Two motorized precision translation stages were used to move the collimators during the test, so that the three beams located near the cavity and at the exit of the combustor can scan the cross sections respectively. Flow parameters could be obtained simultaneous which included average temperature, water vapor concentration and velocity at the entrance of the combustor, the distribution of temperature, water vapor concentration at a cross section near the cavity, the distribution of temperature, water vapor concentration and velocity at the exit cross section of the combustor. The parameters of the flow entering and exiting the combustor could be used to evaluate the performance of the direct-connected scramjet facility and the combustion efficiency of the combustor. The parameters at the cross section in the combustor could also be used to analysis combustion characteristics in the combustor.

Nomenclature

C = speed of light, m/s
R = intensity ratio
S = the line strength of the transition (cm^{-2}atm^{-1})
V = flow velocity, m/s
E_i'' = low state energy of the transition, cm^{-1}
θ = crossing angle between two beams in measurement test section
ν_0 = line-center frequency in absence of Doppler shift, cm^{-1}

I. Introduction

As a great potential technology for air-breathing hypersonic propulsion, scramjet has been developed over the past 40 years. In all the scramjet research challenges, the design of combustor is still the key one. Because combustion heat release distribution determines combustor performance and combustion efficiency is a critical problem for scramjet combustor performance evaluation, great efforts have been made to measure combustion efficiency and analyze heat release distribution. Static temperature, velocity and the concentration of combustion product are significant for diagnosing combustion efficiency. The distributions of these flow parameters are also

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[1] Assistant professor, Institute of Mechanics, CAS, email: lifei@imech.ac.cn
[2] Professor, Institute of Mechanics, CAS, email: xlyu@imech.ac.cn.
[3] Associate professor, Institute of Mechanics, CAS, email: guhb@imech.ac.cn.
[4] PHD student, Institute of Mechanics, CAS, email: lizhi@imech.ac.cn
[5] Professor, Institute of Mechanics, CAS, email: lhchen@imech.ac.cn, member AIAA
[6] Professor, Institute of Mechanics, CAS, email: xychang@imech.ac.cn, member AIAA

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very important for combustion heat release distribution estimation. So this paper focused on the measurement of these flow parameters in scramjet combustor by using near-infrared diode laser absorption diagnostics technology.

Recent advances in near infrared diode laser sources for telecommunication in room temperature, high speed computer networks and optical data storage applications were enabling a new generation of gas-dynamic and combustion-flow sensors based on laser absorption spectroscopy.[1-4] Near infrared absorption sensors were used successfully to provide in situ measurements in scramjet facilities.[5-7] But only few papers reported the TDLAS experimental results, especially about the flow velocity information. In this study, a multi-channel Tunable Diode Laser Absorption Spectroscopy (TDLAS) system was constructed to measure flow parameters in a direct-connected scramjet test facility fueled with ethylene. Many flow parameters were obtained simultaneous which included the distribution of temperature, water vapor concentration and velocity in the combustor. It demonstrated the capability of TDLAS in supersonic combustion research.

II. Measurement Technique

The principle of TDLAS was presented in detail in Ref.3, Ref.8 and would be reviewed only briefly here. Absorption method is based on Beer-Lambert law. The spectral absorption coefficient of each translation is a function of temperature and species partial pressure, while the intensity ratio for two absorption lines can be found only the function of temperature. So temperatures may be inferred from the ratio of the measured line strengths of individual spectral features. Then partial pressure of the absorption species (H_2O in this paper) can be deduced from the integrated absorbance of either transition.

This is the tradition method called direct absorption strategy. Wavelength modulation spectroscopy with second harmonic detection (WMS-2f) is a derivative method of direct absorption spectroscopy. [9] It has the ability to significantly improve Signal-to-Noise Ratio (SNR) for weakly absorbing features,[6] and is commended for application in harsh, noisy environments such as scramjet combustor for its high SNR.

However, in this study, the two strong water absorption feature (as shown in Table 1), and long absorption length could provide the large absorbance level. So the SNR was high enough. Besides, in our experimental condition, the static pressure of the target flow was less than 0.3MPa, so wavelength scanned method was very suitable here. On the other hand, our experiments needed high measurement bandwidth (often more than 1kHz) and long term data recorder, the very high sampling frequency and high volume data of WMS-2f method were huge challenge for us. These made direct-absorption wavelength scanned method an ideal choice here, and the Time-Division-multiplexing (TDM) TDLAS strategy was employed for the benefit of calibration-free of the detectors.

Flow velocity is a very important parameter for combustion model evaluation and combustion efficiency calculation. It can be determined by measuring the Doppler frequency shift of the absorption peak of two beams.

$$\Delta \nu_{Doppler} = \frac{V}{c} \nu_0 \cos\theta \tag{1}$$

Where θ is the angle between the laser propagation and bulk flow directions; ν_0 is the line-centre frequency of the transition.[1,4]

Table1. Spectroscopy parameters of the transitions used in this study (based on Hitran2004)

Frequency ν_0 (cm^{-1})	Line strength S(T) at T=1000K ($atm^{-1}cm^{-2}$)	Low-state energy E'' (cm^{-1})
7185.597	0.0298	1045.058
7444.35	0.0099	1774.751
7444.37	0.0118	1806.670

The selection of absorption transitions is very important while the optimal selection can improve signal-to-noise ratio and measurement accuracy. A discussion of the strategy behind selection rules may be found in literature.[8] Spectral features used in this study and their parameters were tabulated in Table 1. Line strength S of these two spectral feature were validated in literature. [6] and their laboratory-validated parameters were used in this study. Fig 1 illustrated line strength of selected lines versus temperature. The strong absorption strengths of the line pair indicated the high SNR. The curve for temperature resolution about line pair strength ratio was given in Fig.2. It showed that the line pair has high sensitivity of temperature measurement in 500-2500K.

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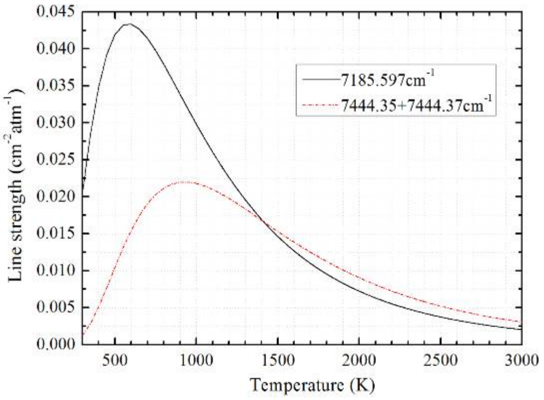

Figure 1. Line strengthen of selected water vapor absorption lines versus temperature

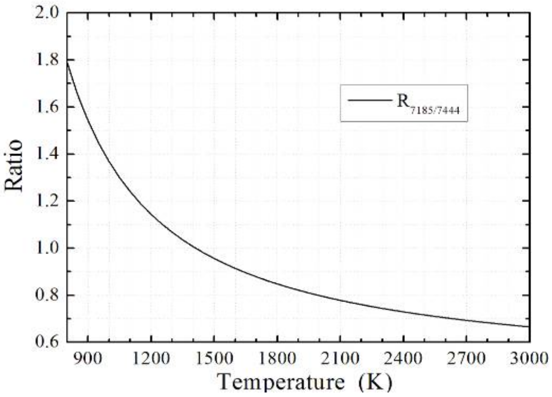

Figure 2. Temperature dependence of selected line pair strengthen ratio

III. Experimental Setup and Design

Direct-connected scramjet test facility was a very important facility for supersonic combustion research. A schematic of the facility was shown in Fig 3. The flow was heated by hydrogen/oxygen combustion in a vitiator.[10] Oxygen was added to replenish that which was burned in the vitiator. The high pressure flow was expended to Mach 1.8 where it entered a model scramjet combustor. C_2H_4 was injected into and burned in a cavity-based flame holder. The wetted surface area was 40mm*85mm.The design parameters of the supersonic flow entering into the combustor were shown in table 2.

Table 2. Operation parameters of facility in this study

Mach number [-]	Total temperature [K]	Total pressure [MPa]	Flow rate [kg/s]
1.8	950	0.6	1.8

Figure 3 was schematic diagram of the multiplexed diode laser sensor system for combustion efficiency measurement in scramjet. The system composed of two independently operated DFB diode lasers (products of NTT Corporation) probe two H_2O absorption features (7185.597cm^{-1},7444.35cm^{-1}+7444.37 cm^{-1}(combined)) individually. The line width of lasing wavelength of lasers was less than 10MHz. The ramp signal from Signal generator(Model:Tektronix AFG3022) was injected into combination diode/TEC controller (model ITC502, Thorlabs INC.) and lasing wavelength was tuned over the desired transition with the repetition rate of 4kHz.

Laser light was split into 6 parts using a single-mode fiber coupler (2×6) designed for the near infrared. The first one was delivered to a Fabry-Perot interferometer for relative frequency measurement of the laser as it was scanned. Other five parts were transmitted across the test region using collimators. Fig.4 showed the location of the five laser beams in combustor. For combustion efficiency diagnostic, the flow parameters before and after combustion should be measured. So two beams (beam 4 and beam 5)were set at the entrance of the combustor with 60° angle, beam 1 and beam 2 were set at the exit of the combustor with 45° angle, while beam 3 was perpendicular to the window fixed in side wall.

On the other side five collimators with larger numerical aperture (NA) were used to collect the transmitted beam into multimode fibers. Five convex lenses were used to focus the light out of the multimode fiber onto individual InGaAs detectors with 2-mm diameter sensitive area. A Tektronix high dynamic oscillationscope was employed for data record. Nitrogen purge chambers were utilized to eliminate environmental water interference in the free space light path. The beam steering caused by the vibration and the turbulent flow field within the test region was the biggest problem to obtain the light intensity accurately. So a lot of effort was taken to eliminate it, such as collimators with larger numerical aperture and high scanning rate. A post processing routine was used to perform the fits to Voigt line profile. Then the integrated absorbances of the two absorption lines were deduced.[3,11]

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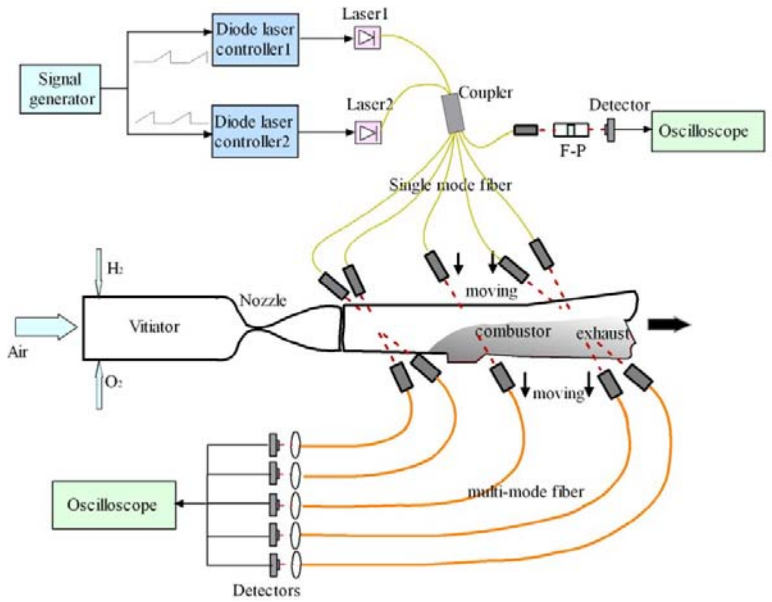

Figure 3. Schematic diagram of the multiplexed diode laser sensor system for combustion efficiency measurement in scramjet

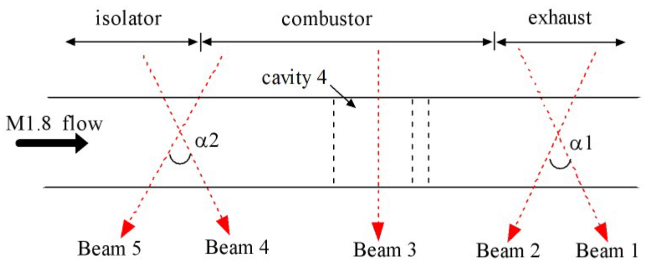

Figure 4. Schematic diagram of laser beams collocation (planform)

Because the two-dimensional cavities and parallel fule injection holes were arranged in the top wall, parameters along the height of the cross section at the exit should be heterogeneous while approximate uniform along the light of sight. One motorized precision translation stage was used to scanning measure the cross section at the exit of the combustor 600mm away from the injection holes of ethylene. Another one was used to move beam 3 for scanning measure the cross section near the cavity in the combustor. The moving velocity of the translation stages were about 100mm/s and 60mm/s respectively, so the parameters distribution of the cross sections could be obtained in one test.

IV. Results and Data Analysis

A. Parameters of flow entering the combustor

The measured flow static temperature, water vapor partial pressure and velocity were presented in Fig.5. Because of the uniform-flow, the measurement result along the light path at the center position of the flow channel could be treated as flow parameter entering the combustor.

The average temperature, water vapor partial pressure and velocity were 582.6K, 0.101atm, 862.3m/s respectively. Static pressure of the flow was 1.08atm which was measured by the pressure transducers fixed at the wall. Comparing with the operating parameters of this facility, the difference of temperature was less than 9.4K (1.6%), the difference of H_2O partial pressure was less than 0.0038atm (3.7%), and the difference of velocity was less than 24.3m/s (2.8%). The measurement result coincided well with the design parameters which shown great capability of this TDLAS system. Parameters fluctuation could be found in Fig.5, but maxium fluctuation was less than 2.9% which also showed great heater performance of this facility.

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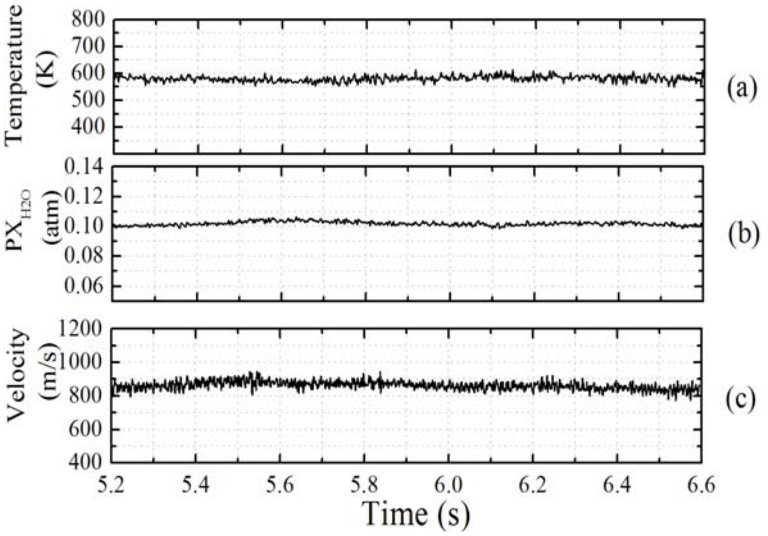
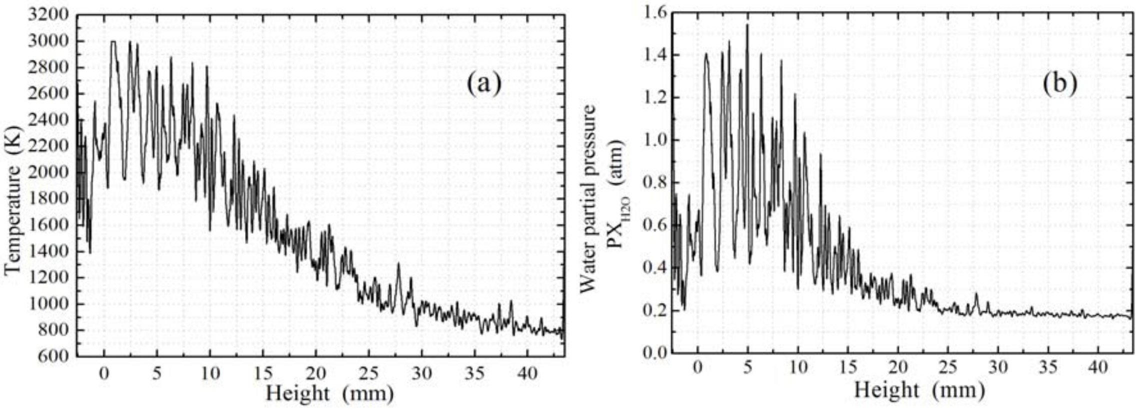


Figure 5. Temperature (a) , water partial pressure (b) and velocity (c) versus time at the entrance of the first combustor; 4-kHz measurement bandwidth filtered to 1 kHz in this plot

B. Temperature and water vapor partial pressure distribution near cavity

Figure 6 represented the temperature and water partial pressure distribution on the cross section near the cavity. The height of the cross section was 60mm while the zero point of x-coordinate was corresponding to the top wall. Because of the limitation of the window, only region -2.5mm to 43.5mm away from the top wall was measured while minus position meant beam located in cavity.

In this case, the fuel was C_2H_4 which was injected 250 mm upstream the cavity and the fuel to oxygen equivalence ratio was 0.36. Hydrogen (equivalence ratio about 0.03) was injected as pilot gas 60 mm upstream the cavity.



(a)Static temperature distribution **(b) Water vapor partial pressure distribution**

Figure 6. Distribution along vertical location near the cavity

As shown in Fig.6 (a), temperature was high near the cavity and gradually decreased away from the top wall. The maximum temperature and water partial pressure occurred in the cavity shear layer (0-10mm). It meant that there had intensive combustion there. Combustion instability was a common phenomenon in scramjet combustor, and could be found in Fig.6. At the fix position in the cavity shear layer, the high static temperature was more than 2800K， which should be coursed by intensive combustion upstream and the low static temperature was about 2100K which meant higher flow velocity and less combustion upstream. Considering about the speed of the motorized precision translation stage, frequency of combustion instability could be obtained which was about 100Hz.

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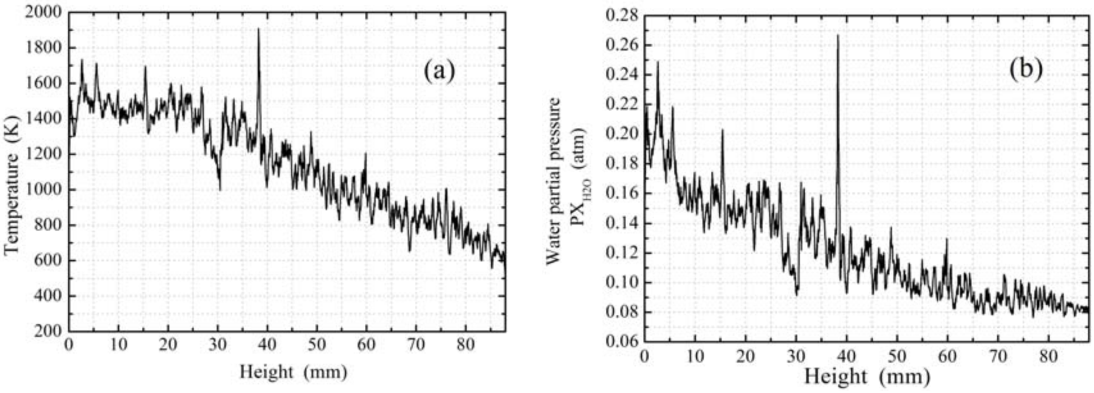
At the position 30-43.5mm, temperature and water partial pressure were almost stable, water vapor concentration was almost the same as the entrance. Because of the cavity and the fuel injector were only at one side, it can be considered that the influence range of combustion was only half the height of the section. In this area static temperature was about 800K, it was far more than the static temperature at the entrance that meant the low velocity there. If the flow in this region could be assumed to be isentropic, local Mach number could be deduced from the local static temperature and the total temperature at the entrance, which was about 1.1.

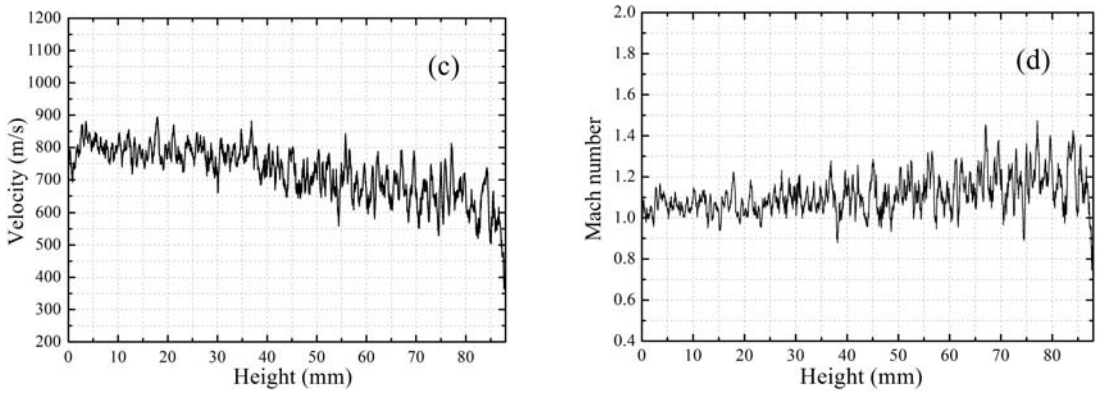
Water vapor partial distribution shown that water vapor decreased rapidly away from the upside wall to 15mm, while decreased slowly between 15-30mm. But temperature extension was larger than it. It indicated that combustion only happened in the cavity and the near wall region. Emission, convective heat transfer and diffusion made the influence range of the combustion extend to the center of the flow. The highest static temperature of the flow was nearly 3000K, which meant the combustion of the pilot hydrogen in the shear layer.

C. Parameters of flow at the exit the combustor

Figure 7 representd the flow parameters distribution on the cross section at the combustor exit. It was measured using beam 1 and beam 2. The height of the cross section was 88mm while the zero point of x-coordinate was also corresponding to the top wall. As shown in Fig.8(a)and Fig.8(b), temperature and water vapor partial pressure were high near the wall and gradually decreased away from the top wall.



(a) static temperature distribution **(b)water vapor partial pressure distribution**



(c)velocity distribution **(d) Mach number distribution**

Figure 7. Parameters distribution along vertical location at the combustor exit

Maximum values of temperature and water partial pressure were shown near the top wall which were about 1500K, 0.2atm respectively. While the value near the bottom wall were 650K and 0.085atm. The wall static pressure on the bottom wall was about 0.96atm. So the water vapor concetration in the flow near the bottom wall was about 8.8%. It was very close to flow parameter at the entrance of the combustor. This suggested that there was no

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combustion near the bottom wall in the whole combustor. Static temperature distribution showed that temperature decreased slowly from the top wall to 35mm, while decreased rapidly between 35 and the bottom wall. So in combustor, combustion mostly happened in the rang of 0-35mm region. Emission, convective heat transfer and diffusion made the influence range of the combustion extend to the whole section. It was different from Fig.6 where combustion influence only extended to the center of the flow. So between beam 3 and beam 2, combustion extension expanded deeply into the flow center.

Figure 7(c) and Fig.7(d) represented the velocity and Mach number distribution on the cross section at the combustor exit.Velocity was obtained using the frequency shift of the absorption profile of beam1 and beam2. Velocity was almost linear distribution along vertial location in the range of 820m/s-600m/s. Maximum velocity occured near the top wall which had a divergence angle. Mach number was deduced from the local static temperature and velocity. Mach number along vertial location changed slowly from 1.05 to 1.2 along vertial location.

Once the temperature and velocity distribution were obtained, combustion efficiency could be deduced with adiabatic assumption and the correction of surface heat transfer evaluation.[11] Another method for combustion efficiency calculation was considering the fuel consumption by using the ratio of fuel taking part in the reaction and the total fuel injected into the combustor. So water vapor partial pressure distribution and wall static pressure were useful. If we assumed that all the pilot hydrogen take part in the combustion completely, then the combustion efficiency of C_2H_4 could be obtained using Fig.5 and Fig.7. In this case, it was about 0.74.

V. Conclusion

A 5-beams Tunable Diode Laser Absorption Spectroscopy (TDLAS) system was designed and constructed diagnosing flow parameters in a scramjet combustor. Measurement repeat rate of each beam was up to 4kHz. Direct absorption Time-Division-multiplexing (TDM) strategy was used to simultaneous measure temperature, water partial pressure and velocity without complicated calibration of detectors. Many flow parameters were obtained simultaneous which included average temperature, water vapor concentration and velocity at the entrance of the combustor, the distribution of temperature, water vapor concentration at a cross section near the cavity, the distribution of temperature, water vapor concentration and velocity at the exit cross section of the combustor.

Because of the two-dimensional constrution of the combustor, flow parameters would be non-uniform along the vertical postion of the cross section. So parameters distribution were measured in one test using two motorized precision translation stages. The results were very useful for estimation of combustion mode and heat release region in combustor. Combustion efficiency was calculated by using the parameters of the flow entering and exiting the combustor.

The high signal to noise ratio showed the great potential of this TDLAS system in harsh, noisy environments. Well designed absorption systems can be used to study combustion structure in combustor, high-frequency pulse combustion in cavity, combustion heat release distribution and total combustion efficiency evaluation at the end of the exhaust nozzle. As spatial resolved temperature measurement capability developed combining with its high time response character, absorption technique will advance the research of supersonic combustor design.[12,13]

Acknowledgments

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