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Quantitative Density Imaging of Subsonic Jet Using Planar Laser Induced Fluorescence of MEK

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Abstract— **Quantitative molecular density distribution of Methyl ethyl ketone (MEK) in turbulent nitrogen jet (Re≈2-3X10^3) was measured using PLIF technique. The tracer (MEK) was seeded in the nitrogen jet by purging through the liquid MEK at ambient temperature. Planar laser sheet from frequency quadrupled, Q-switched, Nd: YAG laser (266 nm) was used as an excitation source. Emitted fluorescence images of jet flow field were recorded on CMOS camera. To obtain quantitative density profile, the dependence of PLIF intensity on MEK partial pressure was employed. Thus an instantaneous quantitative density image of nitrogen jet, seeded with MEK was obtained.**

Keywords-PLIF;MEK;turbulent jet; concentration;

I. INTRODUCTION

Planar laser induced fluorescence (PLIF) is widely used gas flow visualization technique in fluid dynamics and combustion diagnostics. The technique is based on the observation of fluorescence from the fluorophore through the excitation of electronic energy levels that are usually populated in the UV-visible range. Since fluorescence intensity depends on the various molecular parameters such as concentration, pressure and temperature, this allows qualitative and quantitative measurements using PLIF. Among various tracers used, ketones are very popular organic carbonyls. Acetone is frequently used due to its high vapor pressure, low boiling point (56°c) and good fluorescent properties. Its absorption cross section extends from 225-320 nm. Löffler et al. (2010) studied acetone LIF in internal combustion engine and reported the calibration data for quantitative measurement of temperature and pressure [1-5].

Due to structure similarity, Methyl ethyl ketone (MEK) possesses physical and photo-physical properties like that of acetone. The following table 1 shows the similarity between the acetone and MEK.

TABLE I. THE PROPERTIES OF THE ACETONE AND MEK RELEVANT TO PLIF EXPERIMENTS.

Tracers	**Chemical formula**	**Boiling point (°C)**	**Vapour pressure at 20°C (mm of Hg)**	**Absorption wavelength range (λabs /nm)**	**Fluorescence wavelength range (λfl/nm)**
Acetone	(CH3(CO)CH3)	56.1	180	~225-320	~320-550
MEK	(CH3 (CO)CH2CH3)	80	100	~220-330	~350-550

In spite of these similar properties of MEK with acetone relevant to PLIF, MEK is very rarely used in these experiments. In the present work, dependence of MEK fluorescence excited by fourth harmonic of Nd:YAG laser on number density was investigated. The dependence of PLIF intensity on MEK partial pressure was employed to obtain quantitative density profile in nitrogen jet. A quantitative planar imaging of density distribution in fluid flow is very important in understanding the physics of turbulent processes. Understanding of turbulent flow is of great importance mainly due to its natural occurrence in many science and engineering applications. These applications include fluid mixing, combustion, chemical reaction, entrainment and jet noise generation in aerodynamics. The far field turbulence in water jets were studied by Dimotakis et al. [10-12], using PLIF of Rhodamine 6G and found large scale vortical structures in axisymmetric and spiral in nature.

Most of the turbulent jet flow contains both coherent structures and incoherent turbulence but formers are more significant. This is due to the major contribution in mass and momentum transfer is usually by coherent structures. One of the reasons for the formation of these structures is local instabilities in the flow. These structures are also important for understanding major problem of aerodynamic noise generation [4].

In this paper, we present the molecular density distribution measurement in turbulent nitrogen jet (Re≈2-3X10^3) seeded with MEK. The frequency quadrupled Q-switched Nd: YAG laser (266 nm) sheet was used as excitation source. Emitted fluorescence images were recorded for different MEK

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concentrations. The dependence of PLIF intensity on MEK vapor density was used to convert PLIF image of nitrogen jet into the tracer number density image on pixel by pixel basis. Thus instantaneous quantitative density images of nitrogen jet seeded with MEK was obtained.

II. THEORY

The cornerstone for number density measurement is linear dependency of LIF intensity on number density of the fluorescing tracer. For the molecules with broadband spectral absorption, fluorescence with the laser excitation can be modeled as in Eq. (1). For weak excitation (linear excitation regime) the fluorescence intensity S_f is given by the following equation

$$S_f \alpha n_{abs}(P,T)\sigma(\lambda,T)\Phi(\lambda,T,n_i) \qquad (1)$$

where n_{abc} is number density (/cm^3), σ is molecular absorption cross section of exciting species(cm^2/molecule), **Φ** is fluorescence quantum yield.

Local Reynolds number of the jet at the exit is given by the following equation [12]

$$\mathrm{Re} = \frac{\rho U d}{\mu} = \frac{Ud}{\upsilon} \qquad (2)$$

where ρ is the gas density (kg/m^3), μ is absolute viscosity (Pa. S), ν=μ/ρ is kinematic viscosity (m^2/s) of the gas. U is the exit velocity (m/s) and d is exit diameter (m) of the jet.

III. EXPERIMENTAL

A. PLIF

Fig. 1 shows experimental setup used for PLIF imaging. In this setup, laser beam of 266 nm wavelength from Nd:YAG laser(Model LAB190) was transformed into a planar sheet using a cylindrical lens. Cylindrical plano-convex lens (width 2 cm, length 5 cm) of focal length 5 cm, in combination with a spherical plano-convex lens of focal length 70 cm can transform 4 mm diameter laser beam into a planar sheet of width 5 cm and thickness 15 µm. Jet exit diameter was 2 mm and axial velocity profile is shown in figure 2. Nitrogen was purged through the MEK and directed to the jet. The resulting MEK fluorescence image was captured on a Sony camera (Model-HDR-550XR) with CMOS sensor. The linear fluorescence regime was ensured by keeping incident laser energy well below the saturation intensity for MEK.

B. Calibration

For LIF dependency studies and calibration, a zincated steel chamber attached with a digital pressure gauge is locally fabricated and is shown in the figure 3. Zincated steel gas cell measuring 30 cm end to end and having four quartz windows of 2.5 cm diameter at the centre of the cell was used for these experiments. Two diametrically opposite quartz windows were used for entry and exit of laser sheet. Initially chamber was evacuated using rotary vacuum pump and MEK vapor pressure was varied from 10 torr to 90 torr and resulting PLIF images were recorded. Figure 4 shows the calibration plot used for converting gray scale intensity in to density image.

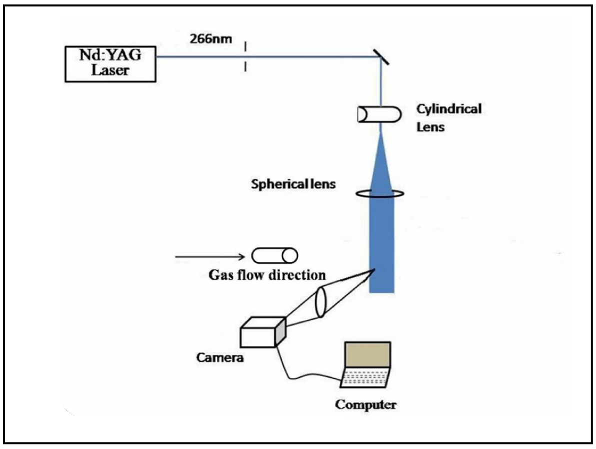

Figure 1. Experimental arrangement for LIF gas flow visualization.

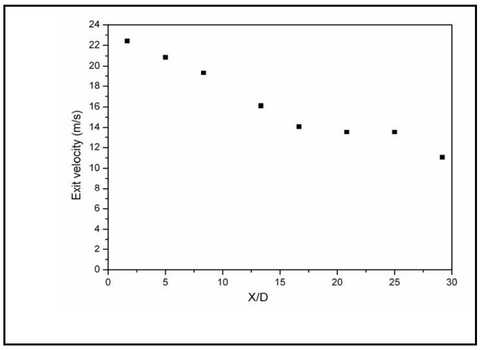

Figure 2. Axisymmetric velocity profile from the jet exit.

Figure 3. Calibration gas chamber with pressure gauge. .

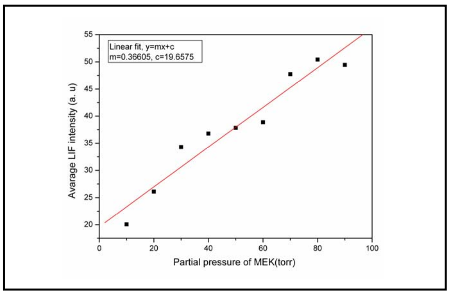

Figure 4. Gray scale LIF intensity averaged over image area as a function of MEK partial pressure from as chamber.

IV. Result and Discussion

Figure 5 shows PLIF gray scale intensity image for the jet with stagnation pressure of 1.5 bar. The PLIF raw images obtained on digital CCD/CMOS sensor usually have many imperfections in image acquisition systems, for example defective pixels, low light or uneven illumination etc. Thus there is need for image processing to correct for such a defects and increase the contrast of the image [7]. The image processing was carried out using code written in MATLAB. Initially the defected pixel values were identified by sudden decrease in the intensity value and compensated by averaging. The next step involves smoothing the image by convolving with a Gaussian filter. The Gaussian filter in vertical and horizontal direction makes use of two dimensional Gaussian function given by the following equation.

$$G(x,y) = \frac{1}{2\pi\sigma^2} e^{\frac{x^2+y^2}{2\sigma^2}} \quad (3)$$

Here there are two free parameters which can be varied size of the discrete kernel and the value of σ which is standard deviation of the Gaussian function. Kernel size (6X6) and σ was kept 1 for the all processed images.

Further the analysis of flow PLIF image for the Reynolds number 2-3x10^3 shows that the arrow head shaped coherent turbulent structures are present even at low Reynolds number. These coherent structures are found to be non-overlapping with separate boundaries. There is a clear distinction between laminar region and turbulence with coherent structures and incoherent instabilities.

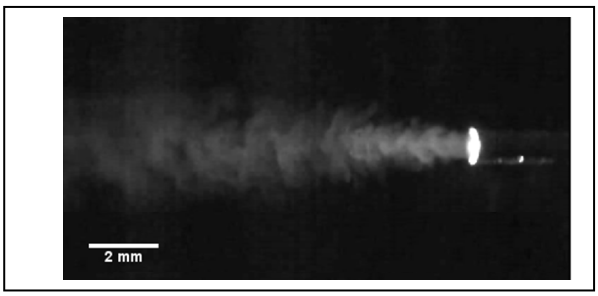

Figure 5. The gas phase MEK PLIF gray scale image of nitrogen jet purged through MEK.

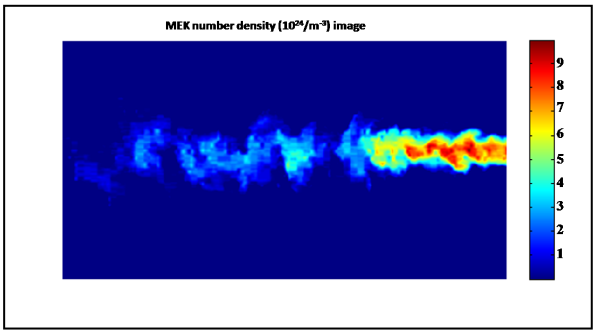

Figure 6. The MEK number density (x10^{24} cm^{-3}) image in nitrogen jet.

Based on the linear dependence on the concentration from eqn.(1) the PLIF intensity image was successfully converted to density map. Figure 6 shows density profile for the same intensity image as in figure 5. From these images it is clear that MEK seeded in the flow behaves similar to the bath gas. This is due to the number density distribution in the flow is similar to the main stream of the jet.

V. Conclusion

MEK seeded turbulent flow from subsonic jet was imaged using PLIF technique. Gaussian image processing was used to improve the PLIF image quality. Thus obtained PLIF intensity images were converted in to number density profile of MEK using MATLAB program. In a turbulent flow coherent arrowhead shaped structures were observed even at low Reynolds numbers of the order of 10^3. These structures are found to be more axisymmetric than spiral in nature. The proposed technique of using MEK seeded LIF imaging can be extended to study the chemistry of hypersonic flows.

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References

[1] Schulz C. and Sick V., "Tracer-LIF diagnostics: quantitative measurement of fuel concentration, temperature and fuel/air ratio in practical combustion systems." Prog. in Energy and Combustion Sc., vol. 31, pp. 75–121, 2005.

[2] Loffler M., Beyrau F. and Leipertz A., "Acetone laser-induced fluorescence behavior for the simultaneous quantification of temperature and residual gas distribution in fired spark-ignition engines." Appl. opt., vol. 49(1), pp. 37-49, 2010.

[3] Thurber, M.C. and Hanson, R.K.,"Pressure and composition dependences of acetone laser-induced fluorescence with excitation at 248, 266, and 308 nm." Appl. Phy. B, vol. 69, pp. 229–240, 1999.

[4] Thurber, M.C. and Hanson,R.K.,"Simultaneous imaging of temperature and mole fraction using acetone planar laser-induced fluorescence." Exp. Fluids, vol. 30, pp. 93-10, 2001.

[5] Lozano A., Yip, B. and Hanson, R. K., "Acetone: a tracer for concentration measurements in gaseous flows by planar laser-induced fluorescence." Exp. Fluids, vol. 13, pp. 369-376, 1992.

[6] Koch, J.D. and Hanson, R.K.,"Temperature and excitation wavelength dependencies of 3-pentanone absorption and fluorescence for PLIF applications." Appl. Phys. B., vol. 76, pp. 319–324, 2003.

[7] Solomon, C. and Breckon, T., "Fundamentals of image processing a practical approach with examples in matlab" A John Wiley & Sons, Ltd.,UK, 2011.

[8] Siddhartha S. S., Narasimha R., Basu A.J., and Kailas S.V. , "Coherent structures in numerically simulated jets with and without off-source heating " Fluid Dynamics Research, vol. 26, pp. 105–117, 2000.

[9] Fazle Hussain A. K. M.,"Coherent structures and turbulence" J. Fluid Mech., vol.173, pp. 303-356,1986.

[10] Paul E. Dimotakis, Richard C., Miake-Lye and Dimitris A. Papantoniou, "Structure and dynamics of round turbulent jets" Phys. Fluids, vol. 26(11), pp. 3185–92, 1983.

[11] Paul E. Dimotakis , "The mixing transition in turbulent flows" J. Fluid Mechanics, vol. 409, pp. 69–98, 2000.

[12] Paul E. Dimotakis, "Turbulent mixing" Annu. Rev. Fluid Mech., vol. 37,pp. 329–356 , 2005.