Planar Laser-Induced Fluorescence (PLIF) Measurements of a Pulsed Electrothermal Plasma Jet

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The characteristics of a pulsed plasma jet originating from an electrothermal capillary discharge have been investigated using laser-induced fluorescence (LIF) measurement. Previous emission spectroscopic measurements of a 3.1 kJ plasma jet show that upstream of the Mach disk the temperature and electron number density are about 14,000 K and 10^{17} cm^{-3}, while downstream of the Mach disk the values are about 25,000 K and 10^{18} cm^{-3}, respectively. However, these values are based on line-of-sight integrated measurements that may be misleading. Hence, LIF is being used to provide both spatially and temporally resolved measurements. Our recent work has been directed at using planar laser-induced fluorescence (PLIF) imaging of atomic copper in the plasma jet flow field. Copper is a good candidate for PLIF studies because it is present throughout the plasma and has electronic transitions that provide an excellent pump-detect strategy. Our PLIF results to date show that emission measurements may give a misleading picture of the flow field, as there appears to be a large amount of relatively low temperature copper outside the barrel shock, which may lead to errors in temperature inferred from emission spectroscopy. In this paper, the copper LIF image is presented and at the moment, relative density of atomic copper, which is distributed in the upstream of the pulsed plasma jet, is discussed qualitatively.

Key Words : Plasma Jet, Planar Laser-Induced Fluorescence(PLIF), Barrel Shock

1. Introduction

There are a large number of practical engineering devices for which spatially and temporally resolved species concentration

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measurements are necessary to provide detailed understanding of the physical phenomena occurring. Such devices include laser ablation, (Erlich and Taso, 1989 ; Lyman, 1988 ; Estler et al., 1991 ; Mulser et al., 1973 ; Hopkins et al., 1983 ; Rohlfing, 1984) plasma coating, (Cho et al., 2001 ; Macek et al., 2001 ; Okuji ; Basner, 2000) laboratory burners, (Mcenally and Pfefferle, 1998 ; Arnold et al., 2000) automobile engines, (Case and Hofeldt, 1996 ; Zhao et al., 1992) and plasma-jet facility driven by high voltage discharge inside a small cavity. (Hankins et al., 1998 ; 1997 ; Gilligan et al., 1991 ; Kohel et

al., 1999) One technique which shows great promise as a diagnostic tool for measuring species concentration in such flow is the laser induced fluorescence spectroscopy. Radiation of laser is tuned to appropriate electronic transitions and thus atoms of vapor are excited. The vapor atomic density can then be estimated from the emitted fluorescence light. The method is known to be reliable for densities below 10^{11} cm^{-3} and for optical paths of several centimeters. For higher densities collisions among the particles and optical thickness limit the application. This technique has been discussed by a number of workers. Our Previous emission spectroscopic measurements of a 3.1 kJ pulsed plasma-jet, (Kohel et al., 1999) originating from an electrothermal capillary discharge, showed that the plasma-jet, which expanded rapidly into an atmosphere, is quite underexpanded and upstream of the Mach disk the temperature and electron number density are about 14,000 K and 10^{17} cm^{-3}, while downstream of the Mach disk the values are about 25,000 K and 10^{18} cm^{-3}, respectively. Our current work has been directed at using planar laser-induced fluorescence (PLIF) imaging of atomic metal vapor in the plasma-jet flow field. It is much interested in the spatial distributions of atomic metal vapor in the plasma-jet since it helps us much to understand the flow field structure and at our best knowledge, it is the first attempt of atomic PLIF measurement, which has enormous background emission due to hot plasma temperature (15,000 K~25,000 K). Atomic copper is used as a candidate for PLIF studies because it is present throughout the plasma and has electronic transitions that provide an excellent pump-detect strategy.

2. Experimental Methods

The detailed schematic description of the pulsed plasma-jet facility is shown in Fig. 1(a) and it is well illustrated in our previous work, so only brief description will be given here. The capillary plasma source is driven by a pulse-forming network (PFN), consisting of a 251 μF capacitor charged to a maximum of 5.0 kV (3.1
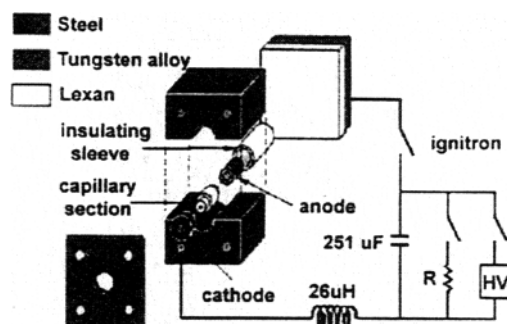

Fig. 1(a) Schematic diagram of experimental setup for pulsed plasma jet facility
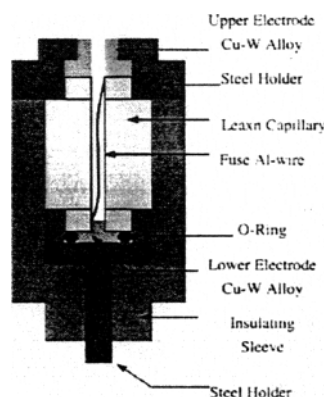

Fig. 1(b) Detailed description of the capillary and the zirconium (copper-Tungsten Alloy) electrodes

kJ) and a 26 μH inductor. The capillary is made of polycarbonate (Lexan, $C_{16}H_{14}O_3$). It is 3 mm in diameter and 30 mm long and is open at one end only. Aluminum fuse wire (64 μm diameter) was used between two electrodes to initiate the discharge. In order to resist the erosion, the electrodes were constructed with inserts made of a copper-tungsten alloy (30% Cu, 70% W). The detailed description of capillary and the electrodes are shown in Fig. 1(b). The discharge is initiated with a thin aluminum fuse wire and ablation and initiation of material from the capillary surface sustains the discharge. The resulting plasma rapidly expands from the open end of capillary and issues into room air. The peak current through the plasma jet is approximately 4.6 kA for an initial capacitor voltage of 5 kV (discharge energy 3.1 kJ), and

Fig. 2 Typical schlieren image of the freely expanding pulsed plasma jet for initial charging voltages of 3.0kV

Fig. 3 Atomic copper energy level diagram

Fig. 4 Schematic diagram of experimental setup for copper laser-induced fluorescence(LIF) measurement

the discharge duration is approximately 250 μs.

3. Schlieren Imaging of the Pulsed Plasma Jet

Schlieren imaging is a well-established technique that enable the visualization of index-of-refraction gradients in a flow field. Since the general experimental setup for Schlieren imaging is well known that only brief description is provided here. The second harmonic (532 nm) of a pulsed Nd:Yag laser was used as a light source. The pulse duration is 10 ns, which is sufficient to freeze the motion of the flow. To improve image quality the beam was spatially filtered by passing it through a 25×microscope objective lens, which focused the beam onto a 25 μm pinhole. The laser pulse was attenuated (to about 5 μJ per pulse) by reflecting it from three glass flats to avoid burning the pinhole. The spatial filter was placed at the focus of the concave mirror, so that the working section (i.e., plasma jet facility) was illuminated uniformly by a collimated beam of light. Figure 2 shows a typical Schlieren image of the freely expanding pulsed plasma jet for initial charging voltages of 3.0 kV. The blast wave development is an unsteady process comparable to the shock propagation from the open end of a shock tube or from the barrel of a rifle. (Klingenberg and Heimerl, 1992) As in the shock tube flow, a nearly spherical shock wave develops, and the flow expansion is initially restrained by the outer blast w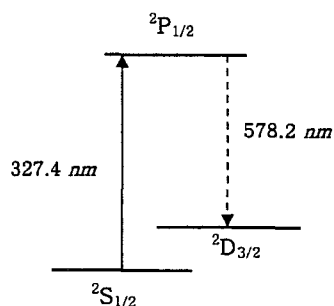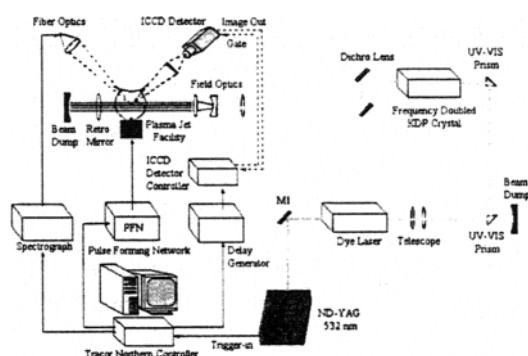ave. It is interesting that the index-of-refraction gradients are so large across the blast wave that they completely mask the barrel shock that exists inside it.

4. Cu-PLIF Imaging Setup

4.1 Cu Atom Laser-Induced Fluorescence (LIF)

Figure 3 displays an excitation scan of the $^2S_{1/2}$ → $^2P^0_j$ transition in copper atom as well as an abridged Cu(I) energy level diagram. Atomic copper is excited from the ground state ($^2S_{1/2}$) to the two spin-orbit levels of the ^2P_j state at the energy (wavelength) of 30,544.051 cm^{-1} (327.396 nm). For this scan fluorescence was detected at 578.4 nm to the $^2D_{3/2}$ level. Copper is chosen as the target material for these studies because the spectroscopy of Cu is relatively well understood. The experimental configuration of Cu-PLIF imaging is displayed in Fig. 4. In this study, at a variable of time delay after the plasma jet
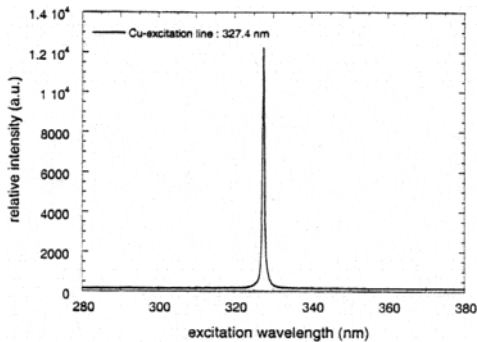
Fig. 5 Laser exciting line from the frequency doubled crystal of the dye laser. The peak intensity wavelength is $327.4 nm (^2S_{1/2} \rightarrow {}^2P^0_{1/2})$

initiated, the Nd:Yag pumped laser was fired. The second harmonic (532 nm) of a pulsed Nd:Yag laser was used as a pumping source and the pulse duration was 10 ns, which is sufficient to freeze the motion of the jet flow. For Cu atom detection, DCM dye was used in methanol solvent and the fundamental beam at approximately 655 nm from the DCM dye is frequency doubled in a KDP crystal to produce radiation in the vicinity of 327. 4 nm. In order to filter out further two dichrolenses were employed. The excitation wavelength of the laser was adjusted using a laser spectrometer and simultaneously checked by means of spectrograph (Tracor-Northern TN-6500 spectrometer) equipped with a fiber optics. A typical example of copper excitation line from the output of KDP crystal is shown in Fig. 5. The available peak energy from the excitation line was more than 6.5 mJ in the ultraviolet. In order to visualize upstream the Mach disk of the plasma jet (i.e., from the exit bore to Mach disk location) the excitation beam was converted to sheet of light by using appropriate field optics. The sheet of light is approximately 19 mm high and 300 μm thick and passes through the center of plasma jet apparatus. The excitation beam was bounced back by a retro-mirror to increase excitation photons within the plasma jet. The plasma jet facility is externally synchronized with the laser and the Cu planar laser induced fluorescence (PLIF) image was obtained at 104.5 μs after the plasma jet initiation. The plasma jet apparatus was charged to 3. 0 kV for copper PLIF imaging throughout the

experiment and aluminum fuse wire was used instead of copper, since it was observed that from the previous experiment lots of neutral copper atoms comes from the exploding copper fuse wire, increasing the unwanted background emission. In order to reduce the enormous background emission from the hot thermal plasma jet, it is necessary to minimize the ICCD camera gate pulse width (≈ 24 ns) and a copper fluorescence line filter (i.e., central wavelength, λ_c, is 578.2 nm with bandwidth of 2.0 nm, Model F1. 5-578.0-4 from CVI laser) was used in front of the ICCD camera (Princeton Instruments ICCD-576,576 × 384-pixel resolutions). In this study, the Cu-PLIF imaging experiments is required that the laser be fired at an arbitrary time after the initiation of the plasma-jet discharge. The laser used is inherently operated at 10 Hz and thus cannot be easily fired at an arbitrary time after plasma-jet initiation. Moreover, the Q-switch of the laser is fired at 165 μs after the lamp signal. In order to resolve this problem we devised specific trigger generator, which can provide firing signal for the plasma-jet and time variable delay trigger pulse for the laser Q-switch as upon the input of laser lamp trigger. The ICCD camera was synchronized with the laser to insure that a laser pulse occurred during the 24 ns gate width (i.e. integration time) of the camera. With this configuration, only one image was taken per plasma shot, because the dye laser could deliver one single pulse per discharging period of plasma jet. Since the copper fluorescence is collected during very short time of ICCD gate pulse width (≈ 24 ns) caution should be provided to avoid any noise in the measurement. In order to check whether the laser excitation beam falls within the gate pulse width, a high-speed digital oscilloscope was employed to monitor both the laser excitation line and ICCD gate pulse width signal, simultaneously.

The fluorescence light was observed at 578.213 nm at an angle of 90° with respect to the incoming laser beam and was collected by an intensified CCD camera fitted with a 105 mm focal length (AF Micro Nikkor) camera lens operated at $f/2.8$. By this choice of the
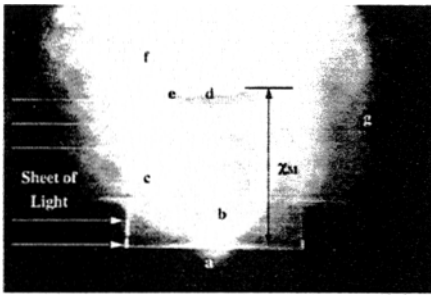
Fig. 6 Visible emission imaging from the pulsed plasma jet discharged with 3.0 kV. The image was taken at $105\mu s$ after the start of initiation a : Bore exit, b : Mach cone, c : Barrel shock, d : Mach disk, e : Triple point, f : Slip surface, g : Contact surface, respectively
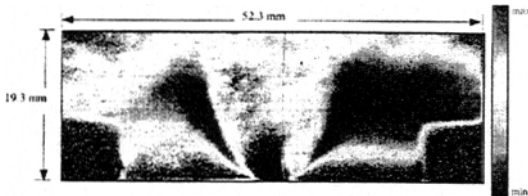

Fig. 7 Typical Cu-PLIF image averaged and background subtracted with 17 images. The excitation laser beam is passing from the left to right hand side

fluorescence transition, problems associated with stray light and scattering from macro particles that would arise from observation of the resonance line could be avoid. The acquired Cu-PLIF images were transferred to computer memory and written to disk for further analysis.

5. Results and Discussions

Figure 6 shows the visible emission imaging from the pulsed plasma jet, discharged with 3.0 kV. The image was taken at 105 μs after the start of initiation. As shown in the figure, expansion waves at the bore exit travel to the jet boundary where they are reflected to form weak compression waves, which then coalesce into the barrel shock. The barrel shock undergoes an irregular reflection and, in the triple-point downstream from the exit bore, the reflected shock, Mach disk, and slip surface are formed. (Liepmann and

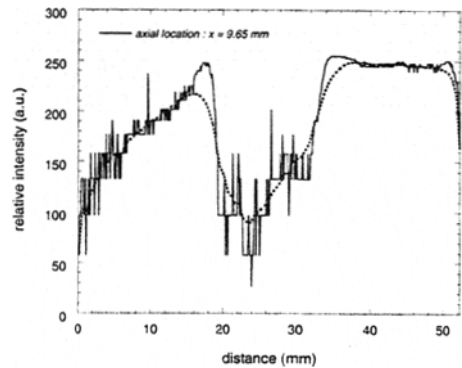Fig. 8 Relative intensity contour maps of the Cu-fluorescence

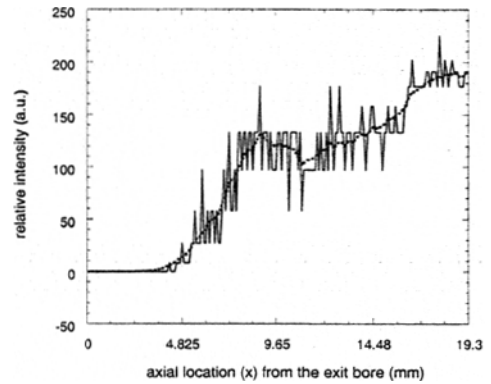Fig. 9(a) Cu-fluorescence intensity distribution across the barrel shock

Fig. 9(b) Cu-fluorescence intensity distribution along the axial location (χ) from the exit bore

Roshko, 1957 ; Crist et al., 1966 ; Abbett, 1971 ; Eggins and Jackson, 1974) In the shock bounded, highly underexpanded jet flow region $(\leq x_M)$, the flow is characterized by relatively high Mach numbers, low pressure, and low temperatures. Across the Mach disk $(\geq x_M)$, the flow is decelerated to subsonic velocity, the pressure rises suddenly to atmospheric pressure or above, and

the temperature increases due to shock heating at the Mach disk. (Liepmann and Roshko, 1957; Crist et al., 1966; Abbett, 1971; Eggins and Jackson, 1974)

Figure 7 shows the copper laser induced fluorescence (LIF) image in the 3.0 kV plasma jet discharge and its relative fluorescence contour map was shown in Fig. 8. The LIF signal is generated by $^2S_{1/2} \rightarrow {}^2P^0_{1/2}$ (327.396 nm) laser excitation in the atomic copper and the fluorescence signal was obtained in the copper atomic transition between $^2P^0_{1/2}$ and $^2D^0_{3/2}$ (578. 213 nm). The filed of view of the fluorescence image is 19.3 $mm \times 52.3$ mm and the image is background subtracted, and averaged with 17 individual images. The laser excitation beam is passing through from the left to right hand side of the plasma jet in the figure. As shown in the PLIF image, the fluorescence intensity of the underexpanded jet flow region is relatively weaker than that of outer regions of the plasma jet. This phenomenon is well illustrated in Fig. 9 (a), where intensity distribution of Cu-fluorescence across the barrel shock was made at the axial location, $\chi \approx 9.65$ mm, from the exit bore of the plasma jet. Surprisingly, the fluorescence image is quite different from the visible emission image shown in Fig. 6, which shows strong intensity inside the barrel shock regions. One possible reason could be due to the collective sum of emissions of thermally exited species existing in the hot plasma jet. It seemed to be reasonable since our previous measurements showed that, in the shock bounded region, the population temperatures are relatively high (i.e., $\approx 14,000$ K) and the electron number density is order of 10^{17} cm^{-3}. In additions, it was observed that there were many different species in the plasma jet. The fluorescence intensity outside of the barrel shock is much higher than that of the inside barrel shock. Since the hot thermal plasma is initiated with high voltage discharge between two electrodes, clearly the upper electrode [shown in Fig. 1(b)] of the capillary is ablated by the sustained hot thermal plasma. Most of the ablated copper atoms remained at the outer surface of the charge and forms a relatively thick shear layers in the

plasma jet, which we believed to be the barrel shock. Copper atoms in the shear layer could not penetrate into the barrel shock (or Mach disk) because of high pressure and high density inside; instead they are diffused into outer regions of the shear layer and cooled down. Therefore, it seemed to be obvious that there are plenty of neutral copper atoms outside of the barrel shock. Moreover, the regions of right hand side of the plasma jet are seemed to have much copper density than that of left hand side. This is due to the enhanced excitation beam reflected from the retro-mirror located at near plasma-jet facility. The axial fluorescence intensity distribution is shown in Fig. 9(b). As shown in the figure, the intensity increases continuously as the axial location (χ) moves up from the exit bore, and reaches to a maximum value approaching to Mach disk location (χ_M). In the previous study both the population number density and the temperatures are abruptly increased across the Mach disk location. Therefore, it is clear that accelerated species from the exit bore is decelerated at the vicinity of the Mach disk location, and stratified to form relatively dense species concentration. As a result, atomic copper density is relatively higher than other interior parts of the plasma jet.

6. Conclusion

In the present work, laser-induced fluorescence (LIF) technique was employed to qualitatively measure the spatial distribution of neutral copper atoms in the underexpanded upstream of freely expanding electro-thermal pulsed plasma jet. Obtained Cu-PLIF image is quite different from that of the visible emission. Results showed that most of the ablated copper atoms formed thick shear layers in the plasma jet and diffused into an environment. Moreover, the copper atoms in the shear layer are believed mainly due to the ablation of the upper cathode electrode. On the other hand, it is believed that the copper atoms observed in the underexpanded zone is mainly due to lower part of electrode, which is plumed and ionized by the arc plasma jet. At the underexpanded zone, since the accelerated copper

atoms were decelerated and stratified near the Mach disk location, where a strong shock boundary layer had formed, relatively dense distributions of atomic copper were observed. Only qualitative measurements were provided in the current study, therefore, in order to get quantitative measurements further research is required.

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