Visualization of Supersonic Microjets Using LIF and MTV Techniques

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Abstract. Supersonic microjets issuing from a convergent rectangular nozzle whose height is 500 µm at its exit are visualized using the acetone-based PLIF (planar laser-induced fluorescence) and MTV (molecular tagging velocimetry) techniques. The jet Reynolds numbers are ranged between 200 and 7000 and the fully-expanded jet Mach-number is set to 1.5. The PLIF visualization results reveal that the jets spread abruptly at a certain location. Instantaneous MTV images are captured in the vicinity of the location where a jet spreads abruptly and the process of the jet collapse is successfully visualized. The distance between the nozzle exit and the jet-collapse location is estimated from each PLIF image. The distance is found to be constant for the Reynolds numbers higher than ~700 and to be inversely proportional to the Reynolds number for the numbers lower than ~700. Moreover, the distance changes abruptly at the Reynolds number of ~700.

1. Introduction

Recently, study on supersonic microjets has become important due to increase in engineering applications such as power generation [1], propulsion [2], cooling of MEMS component [3], laser cutting machine [4], micro pump [5], and so on. In order to improve the performance of a supersonic microjet for each engineering application, the detailed characteristics of this flow have to be understood. A relatively large number of studies have investigated supersonic microjets experimentally. However, there are no experimental studies on supersonic “rectangular” microjets beyond the researches of Lempert et al. [6] and Handa et al. [7].

Lempert et al. [6] created microjets with a convergent-divergent rectangular nozzle. They measured the jets’ velocity profiles using the MTV (molecular tagging velocimetry) technique for jet Reynolds numbers of ~200. They compared the measured profiles with profiles obtained by a direct simulation Monte Carlo (DSMC) method. Their experimental results agreed well with their simulation results. Using the MTV technique, Handa et al. [7] also measured the velocities in supersonic microjets issuing from a convergent-divergent rectangular nozzle. In their experiments, the Reynolds numbers were ranged between 154 and 5560. Their experimental results showed that the jets abruptly spread at a certain location owing to their collapse.

In spite of the above-mentioned studies on the rectangular supersonic microjets, we have no detailed description of microjet’s collapse. In the present study, the supersonic microjets issuing from
a convergent rectangular nozzle whose height is 500 µm at its exit are visualized using two techniques of PLIF (planar laser-induced fluorescence) and MTV techniques.

2. Experimental setup

A suction-type wind tunnel was used, and the working gas was nitrogen. Stored in a balloon made of vinyl chloride, the gas was supplied to a micronozzle. The gas was then accelerated by the nozzle and was discharged into the wind-tunnel vacuum chamber, which was evacuated by a vacuum pump. To visualize the microjets using the PLIF and MTV techniques, acetone was evaporated and mixed into nitrogen gas in the acetone seeder. By adding pure nitrogen gas to the nitrogen gas (containing acetone vapor) stored in the balloon, the seeding rate of acetone is set at less than ~3%.

Figure 1 shows the detailed structure of the nozzle, a symmetric convergent rectangular nozzle. The coordinate system used to analyze the results is defined in the left hand side of Fig. 1, where x and y are the streamwise and height coordinates, respectively, and the origin point O is located at the nozzle exit on the nozzle centerline. The nozzle was fabricated using electric discharge machining. The nozzle height at the exit is \( h_{\text{exit}} = 500 \mu m \). The nozzle width is 5000 µm; i.e., the width-to-height ratio (aspect ratio) is 10 at the nozzle exit.

Figure 1. Micronozzle.

The flow in the entrance region with a nozzle height of 18000 µm (Fig. 1) is almost stagnant. The pressures in this region were ranged between \( p_0 = 3 \text{kPa} \) and 90 kPa. The pressure in the wind-tunnel vacuum chamber was adjusted so that the nozzle pressure ratio (NPR) became 3.67. In general, the jet characteristics are discussed relating to the fully-expanded jet Mach number \( M_j \). This Mach number is calculated so that the gas is expanded fully from the stagnation pressure \( p_0 \) to the back pressure \( p_b \). The ratio \( p_0/p_b \) corresponds to the NPR. The value of \( M_j \) thus obtained is 1.5. The authors confirmed from the preliminary MTV measurements that all the visualized jets accelerated to the Mach numbers close to 1.5 at \( x/h_{\text{exit}} = 1.0 \). The nozzle pressure ratio is set within an accuracy of ± 0.5%. The stagnation temperature is maintained at 295 ± 4 K. The Reynolds numbers, which was calculated based on the variables at the nozzle exit, were ranged between \( Re_j \sim 200 \) and ~7000.

In the present study, the flow was visualized by the PLIF technique. The laser was a Nd:YAG laser (Spectra Physics, 170-10) operated with a fourth harmonic mode of 266 nm. Located in the central plane of the nozzle, the laser sheet was irradiated into the flow field parallel to the y-axis shown in the right hand side of Fig. 1. The incident laser energy was ~10 mJ. The resulting LIF signal was collected through a lens and was detected by the CCD camera with an image intensifier (Hamamatsu C7970). The image intensifier’s gate was set to be open during 50 ns. In a single experimental run, fluorescence intensity corresponding to 100 laser shots were integrated on the CCD camera (i.e., fluorescence intensity for one image corresponds to 100 laser shots). In a single experimental run, 50 to 400 images were captured and averaged.
The sensitivity of an image intensifier is not uniform over its output phosphor and the laser intensity is not uniform over the laser sheet. To take these into account, the measurement system was calibrated by filling the still nitrogen with a small amount of acetone in the expansion chamber. The captured PLIF image of the still nitrogen was used as a reference image to correct the image data.

Handa et al. [10] investigated the characteristics of acetone fluorescence intensity for pressures and temperatures lower than the atmospheric pressure and temperature, respectively. They determined the empirical constant appearing in the multi-step decay model proposed by Thurber et al. [11] so that it could be used in the low temperature and pressure ranges. According to the multi-step decay model having the empirical constant determined by Handa et al., the fluorescence intensity per molecule is almost constant within ±8%. Therefore, the fluorescence intensity is almost proportional to number density of the jet.

The MTV visualization system was the same as that used by Handa et al. [7]. In this system the acetone molecules seeded in the flow were tagged by a beam-shaped Nd:YAG laser operated with a fourth harmonic mode of 266 nm (Spectra Physics, 170-10) and the resulting fluorescence signal was detected by the CCD camera with an image intensifier (Hamamatsu C7772S). The image intensifier’s gate was set to be open during 20 ns. The time delay between tag and interrogation was controlled by the delay pulse generator (Stanford Research System, DG645) and was set to 400 ns.

In general, the spatial resolution of the image intensifier of an intensified CCD camera is lower than that of its CCD array. The spatial resolutions of the image intensifiers used in the present PLIF and MTV visualizations were estimated according to Lempert et al. [12]. The resolutions on the objective planes were 31 μm and 21 μm for PLIF and MTV visualizations, respectively.

![Figure 2. PLIF images. (a) Reₐ = 6810. (b) Reₐ = 3780. (c) Reₐ = 1510. (d) Reₐ = 757. (e) Reₐ = 568.](image)
3. Results and discussion
Figure 2 shows the PLIF images of microjets for $M_j = 1.5$. It is found that all the visualized jets in the figure spread abruptly at a certain location. Such abrupt jet spreading is generally seen in incompressible and compressible microjets. Gau et al. [13] visualized incompressible rectangular microjets using the smoke wire technique. They tested three rectangular micronozzles whose heights at the exit were 100 μm, 200 μm, and 500 μm, respectively. They observed that the jet spreads abruptly at a certain location, and this location shifted downstream with decrease in Reynolds number.

![Image of PLIF images](image1)

**Figure 3.** Instantaneous MTV images ($Re_j = 6810$).
(a) $x/h_{exit} = 2.0$. (b) $x/h_{exit} = 4.0$. (c) $x/h_{exit} = 5.0$. (d) $x/h_{exit} = 6.0$. 
By using MTV, Handa et al. [7] obtained the streamwise distributions of jet half-widths for the microjets issuing at \( M_j = 2.0 \) from a convergent-divergent rectangular nozzle, whose heights were 500 \( \mu \text{m} \) at its exit. In their experiments, the nozzle pressure ratio was set so that the jet was ideally expanded assuming the flow in the nozzle to be inviscid. They also observed that the jets spread abruptly at a certain location and this location also shifted downstream with decrease in Reynolds number. However, in the present visualization results of Fig. 2, the location where the jet spreads abruptly is almost constant for \( Re_j \geq 757 \) and shifts downstream abruptly between \( Re_j = 757 \) and 568.

Corresponding to \( x/h_{\text{exit}} = 2.0, 4.0, 5.0 \) and 6.0, MTV images captured for \( Re_j = 6810 \) are shown in Fig. 3(a)–(d). In each figure, the image on the left end is the averaged image. The other four images are representative instantaneous images. Although shot noise degrades instantaneous images, the four interrogated line profiles have almost the same shape for \( x/h_{\text{exit}} = 2.0 \) (Fig. 3(a)). However, the profile fluctuates up and down for \( x/h_{\text{exit}} = 4.0 \) and 5.0 and the degree of the fluctuation at \( x/h_{\text{exit}} = 5.0 \) is higher than that at \( x/h_{\text{exit}} = 4.0 \). These imply that the jet might flap and the degree of flapping motion grows along the flow’s path. At \( x/h_{\text{exit}} = 6.0 \), the profiles of instantaneous interrogated lines are considerably different from the profile of averaged line. This implies that the jet collapses immediately downstream from at \( x/h_{\text{exit}} = 5.0 \) as a result of the growth in flapping motion. Owing to such jet collapse, large-scale structures might be produced. It is considered that the undulations seen in profiles in Fig. 3(d) might be attributed to such large-scale structures. The process of the jet collapse shown in Fig. 3 is quite similar to that observed by Handa et al. [7] who captured the MTV images of microjets issuing from the convergent-divergent rectangular nozzle although the Reynolds-number dependences of the shift in jet collapse location are different between the presently (convergent nozzle) and previously (convergent-divergent nozzle) visualized microjets.

The jet collapse length, which is defined as the distance between the nozzle exit and the location where the jet abruptly spreads, is estimated from each PLIF image (the location is denoted by an arrow in each image) and plotted against the jet Reynolds number \( Re_j \) as shown in Fig. 4. In the figure, the collapse length estimated from the macrojet data measured by Walker and Thomas (\( M_j = 1.49 \)) [14] is also plotted. The jet tested by them is underexpanded although it issued from the convergent-divergent nozzle. It is found from the graph that the collapse length normalized by the nozzle exit height, i.e., \( L_c/h_{\text{exit}} \), is constant for \( Re_j > \sim 700 \) and the length is inversely proportional to \( Re_j \) for \( Re_j < \sim 700 \). In addition, the collapse length changes abruptly in the vicinity of \( Re_j \sim 700 \). The uniformity of the collapse length for \( Re_j > \sim 700 \) intimates that the length depends only on the jet Mach number; i.e., the length seems independent of the nozzle shape as long as the jet is underexpanded.

![Figure 4. Plots of jet collapse length vs. Reynolds number.](image-url)
Gau et al. [13] visualized subsonic incompressible microjets by the smoke-wire technique. Their visualization results also showed that the jets spread abruptly at a certain location. They also plotted the jet collapse length (normalized by the nozzle exit height) vs. the jet Reynolds number $Re$. Their plots showed that the jet collapse length was inversely proportional to the Reynolds number over the entire Reynolds number range that they tested; i.e., no abrupt change in the collapse length was seen in their plots. This is why the relationship between the collapse length and Reynolds number shown in Fig. 4 is peculiar to underexpanded microjets.

4. Conclusions
Supersonic microjets issuing from a rectangular convergent nozzle whose height was 500 µm at its exit was investigated using the acetone-based PLIF and MTV techniques. The jet Reynolds numbers was ranged between 200 and 7000 and the jet Mach number was set to 1.5. The PLIF visualization results revealed that the jets spread abruptly at a certain location owing to jet collapse and the jet-collapse process was successfully observed in the instantaneous MTV images. The distance between the nozzle exit and the jet-collapse location was estimated from each PLIF image. This distance was found to be constant for the Reynolds numbers higher than ~700 and to be inversely proportional to the Reynolds number for the Reynolds numbers lower than ~700. Furthermore, the distance changed abruptly at the Reynolds number of ~700.

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