The LIF Measurement of Interaction of Gas Jet Flow with Plane Wall under Low Pressure Conditions

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Abstract
Discharging gas jets in low-pressure conditions are interesting and important phenomena from an engineering point of view. For example they relate to the gas jet thruster for attitude control of artificial satellite, and gas purging method in the semiconductor technology. The jets, however, deform to the complicated shapes by interacting with solid walls. This paper deals with visualization experiments on the interacting jet and plane wall by applying LIF (Laser Induced Fluorescence) method using an Ar-ion laser. We have obtained a series of jet-wall interacting images at various distances.

Key words
Jet-wall Interaction, LIF (Laser Induced Fluorescence), Vacuum, Iodine, Ar-ion Laser

1. Introduction
Discharging gas flow interacts occasionally with neighboring solid structures such as plane or curved walls. This phenomenon relates to the aerospace jet which produces interference problems with solid structure in space. For this purpose, the distributions of jet flow parameters should be investigated to obtain more precise information about flow field.

The visualization of interacting rarefied gas flow has been carried out mainly by using the LIF (Laser Induced Fluorescence) method. The LIF measurement has high sensitivity and is suitable to measure the fields where temperature or density is changing significantly. In addition, it is possible to measure the flow field by using LIF method without causing turbulent flow, because it is a noncontact measurement method. However, it is not easy to obtain the physical values of the flow field quantitatively, because the fluorescence intensity depends both on density and thermodynamic state of iodine, and so on [1-6].

In this paper we have performed experiments on flow visualization, as a first step, by applying the LIF method on the jet-wall interaction. The Ar gas mixed with iodine (I2) was spouted out from a 1mm diameter circular hole into the low pressure air chamber on a flat plate as a free jet. The fluorescence intensity distribution related to the density distribution with assumption of constant temperature has been obtained in the interaction of flow field with solid wall.

We have obtained the images as the distribution of fluorescence intensity by a CCD camera of high sensitivity. In addition, we have obtained a series of images at various distances from free jet exit. Furthermore, we normalize these images and obtain the comparative and quantitative fluorescence intensity distribution for the flow parameters.

2. Experiment
2.1 Experimental apparatus and visualization
The experimental apparatus of LIF experiment is shown in Fig. 1. The Ar gas was mixed with iodine (I2) and guided through thin tube (inside tube diameter is about 4mm) and spouted out from the nozzle into vacuum chamber (the pressure in vacuum chamber $P_{cb}$ is approximately 0.2 ~ 0.3kPa) as discharging gas jets. During the gas jet discharging, the pressure ratio of the stagnation pressure $P_a$ by ambient pressure $P_{atm}$ was maintained approximately with the held 15. The $P_{atm}$ is fixed by the ability of rotary pump. We adjusted the pressure ratio that one or two barrel shock has occurred. The pressure fluctuation from rotary pump is negligibly small.

The nozzle details are shown in Fig. 4 and described in section 2.2. The interacting gas jet was irradiated with a sheet-shaped Ar-ion laser beam, and emitted the longer-wavelength fluorescence compared with the wavelength of Ar-ion laser (AUTEX, H800AMaFF7, max 1.1W). The Ar-ion laser wavelength varies from 457.9nm to 514.5nm. Where the power rate of the wavelengths of 488.0nm and 514.5nm accounted as 40-45%. As a result, the iodine molecules in the jets were excited by Ar-ion laser, and they generated the fluorescence [7]. The LIF images were taken with high sensitive CCD camera (HAMAMATSU, ORCA-ER-12AG, C4742-80), and the measured signals of stagnation and back pressure were sent to the oscilloscope. A band pass filter (CVI Melles Griot, F10-585.0-4-2.00) of 585nm center wavelength and FWHM of 10nm was fixed on the CCD camera. The CCD camera was set perpendicular to the laser sheet. Thus the arbitrary cross section image parallel or perpendicular to the interaction jet can be obtained by changing the model layout. We obtained the series images by using the pulse stage when gas jet was discharging. The image data were sent to a personal computer, and were processed to obtain the normalized or colored fluorescence intensity distribution from these images.

2.2 The experimental model and coordinate system
The coordinate systems with their origin at the center of nozzle exit are shown in Fig. 2 and Fig. 3. In our experiments we can obtain the two plane images, $x$-$z$ plane and $y$-$z$ plane by changing the model layout. The sheet shaped laser beam is kept parallel to $y$-axis, as shown in Fig. 2, to obtain $y$-$z$ plane images and kept parallel to $x$-axis, as shown in Fig. 3, to obtain $x$-$z$ plane images.
The nozzle shown in Fig. 4 is the axisymmetrical nozzle which has 1.0mm diameter exit circular hole. Based on diameter of the circular hole Re is equal to $1.82 \times 10^{-3}$ which is so small and the flow is laminar. We can change the length ($l$) from the bottom plane wall to the center of nozzle exit and the angle ($\theta$) between the bottom plane wall and the direction of nozzle. In this paper, we set the nozzle with $l = 2.0\text{mm}$ and $\theta = 30^\circ$, $45^\circ$. We set $\theta$ less than $90^\circ$ to observe the impinging jet diffusions. We carried out the other experiments using two different angles $\theta$, $30^\circ$ and $45^\circ$, the comparison of these experiments are discussed in this paper.

3. Results and Discussion

3.1 Visualization image

We obtained the series of images in $x$-$z$ plane and in $y$-$z$ plane. The specific original visualization images from obtained the series of images were shown in Fig. 5 ~ Fig. 7. In this research, the size of images that we obtained is 14.7mm in height and 80.0 mm in width.

We define new $X_{30}$ and $X_{45}$ axis as parallel to $x$ axis with their origin at the point that gas jet impinging. The $X_{30}$ and $X_{45}$ were the distance from impinging point that the gas jet impinging in experiments of $\theta = 30$, $45^\circ$ respectively and represented in

$X_{30} = x - 3.5$

$X_{45} = x - 2.0$

Figure 5(a) and Fig. 5(b) show the visualization images at $x$-$z$ plane irradiating the $y = 0$ line (coinciding the center of the nozzle exit point) with laser sheet, $\theta = 30^\circ$, $45^\circ$. Figure 5(c) shows the visualization image, $\theta = 0^\circ$ for reference.

Figure 6(a) and Fig. 6(b) are the visualization images at $y$-$z$ plane irradiating the $X_{30} = 0\text{mm}$ and $X_{45} = 0\text{mm}$ line (encompassing the gas jet impinging point) with laser sheet, $\theta = 30^\circ$, $45^\circ$.
3.2 Discussion for fluorescence visualization results

3.2.1 Image processing

To visualize the images with bright clarity, the fluorescence intensity distribution has been normalized with a criterion value, I₀. Furthermore, threshold levels are decided for normalized value I* = I/ I₀ (I, value of any pixels) and the pixel that has fluorescence intensity, I* is denoted in different color coding in accordance to the threshold levels. In this paper, we defined I₀ as the average fluorescence intensity of the image before the jet discharges and denoted it with different color coding according to Table 1 and Table 2.

In this paper we will discuss y-z plane images mainly. Thus, we colored up y-z plane images as shown in Fig. 8 and described previously each figure is adjusted into two parts. The upper images in each figure are adjusted according to the Table 1 color coding system and lower one is adjusted according to Table 2 color coding system. The Table 1 is the color coding in order to visualize the pattern of the interacting flow. Thus, in upper images of Fig. 8, the relative intensity of fluorescence is unclouded more than Fig. 6 and Fig. 7, and the shapes and characteristics of interacting flow can be figured out. In particular, we deal with the field that have I* 1.4 of normalized fluorescence intensity in the images. The lower images of Fig. 8 colored according to Table 2 show the field that has I* 1.4 in normalized fluorescence intensity with bright clarity. Here we will discuss in detail two area surrounded by a box as shown in Fig. 8 lower part and compare it with other images with same color coding system. The white brighted area here we will define it as “analysis field” and is denoted by S*.

We analyze the part of box-surrounded image in all images assuming the symmetry of interaction gas jet with ignoring the strong light that is considered the reflection light of nozzle locating near the center of visualization images.

The “analysis field” and center jet are connected in Fig. 8(c) though these are separated in Fig. 8(d). From here own wards, the jets separated from impinging are diffuse independently. In fact the center jet is not diffuse in y direction.

Table 1 Upper images color coding

<table>
<thead>
<tr>
<th>I*</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 &gt; I*</td>
<td>Dark red</td>
</tr>
<tr>
<td>1.1 &gt; I*</td>
<td>Dark yellow</td>
</tr>
<tr>
<td>1.2 &gt; I*</td>
<td>Light yellow</td>
</tr>
<tr>
<td>1.3 &gt; I*</td>
<td>White</td>
</tr>
<tr>
<td>1.4 &gt; I*</td>
<td>White</td>
</tr>
<tr>
<td>I* ≥ 1.4</td>
<td>Light yellow</td>
</tr>
</tbody>
</table>

Table 2 Lower images color cording

<table>
<thead>
<tr>
<th>I*</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>I* &lt; 1.4</td>
<td>Black</td>
</tr>
<tr>
<td>I* ≥ 1.4</td>
<td>White</td>
</tr>
</tbody>
</table>
3.2.2 Image-processed area of interaction

Before discussion, some parameters are defined. The close up image is shown in Fig. 9. The $S^*$ is defined as the “analysis field” area normalized from nozzle exit area. In addition, the $D$ and $H$ are defined as shown in Fig. 9 assuming the “analysis field” regarded as an elliptical.

The relationships between the $S^*$ and $X_{30}$ or $X_{45}$ are shown in Fig. 10. The $X$ axes $X_{30}$ and $X_{45}$ are hereinafter collectively called $X$.

In the result of $\theta = 45^\circ$ the $S^*$ has locally maximum value at $X = 3$ mm and decreases with increasing $X$ until $X = 5$ mm, but the $S^*$ increases rapidly over $X = 5$ mm. In the result of $\theta = 30^\circ$ the $S^*$ has locally maximum value at $X = 4$ mm and $S^*$ does not have the rapid increasing point in comparison with the result of $\theta = 45^\circ$. However, the result of $\theta = 30^\circ$ has the -5.7 gradient between $X = 4$ mm and 5 mm and the -3.0 gradient between $X = 5$ mm and 6 mm. Thus, $S^*$ of $\theta = 45^\circ$ and $30^\circ$ indicates different rise and fall in a similar vein and the $S^*$ of $\theta = 45^\circ$ escalates in more small $X$ than $\theta = 30^\circ$.

Here, the relationships between the $W$ and $X$ are shown in Fig. 11 and the relationships between the $D$ and $X$ are shown in Fig. 12. The behavior of the $D$ in Fig. 11 discriminates the result of $\theta = 45^\circ$ from $\theta = 30^\circ$ as compared to the $H$ in Fig. 12. Thus in Fig. 11, the $D$ implicates the $S^*$ because the $D$ in $\theta = 45^\circ$ has local minimum point at $X = 5$ mm same as the $S^*$ shown in $\theta = 45^\circ$ in Fig. 10.

As whole we consider that the difference of angle influences the $y$ (width) direction more than $z$ (height) direction. In the result, we consider that the difference of $S^*$ behavior results due to the difference in angle.

3.2.3 Movement of center of “analysis field”

The intersection point of major and minor axes, $C$ ($y_c$, $z_c$) is defined as the center of “analysis field”. The relationships between the $C$ ($y_c$, $z_c$) and $X$ are shown in Fig. 13 and Fig. 14. The Fig. 13 represents the location of $C$ ($y_c$, $z_c$) along the $y$ coordinate ($y_c$) and Fig. 14 represents the location of $C$ ($y_c$, $z_c$) along the $z$ coordinate ($z_c$). In Fig. 14 the results of $\theta = 45^\circ$ overlap on $\theta = 30^\circ$ same as in Fig. 12. However, in Fig. 12 the $y_c$ of $\theta = 45^\circ$ moves at than the $y_c$ of $\theta = 30^\circ$ along the $y$ axis direction over $X = 2.0$ mm. Thus the moving distance of interaction gas jet changes along the $y$ axis direction longer than $z$ axis direction between the results of $\theta = 30^\circ$ and $45^\circ$ further apart 3.2.2.
4. Conclusion

In this study we have performed the experiments of the interaction of gas jet flow with a plane wall under low pressure conditions by applying the iodine LIF measurement and obtained some series of visualization images. The shapes and characteristics of interaction flow have been figured out from that visualization images. Accordingly we figured out that the center jet is not diffuse to y direction. In addition, we analyze the visualization images and figure out that the difference of angle between plane wall and gas jet contributes in y axis direction more than z axis direction. Future research activity will be devoted to obtain the longer X visualization images and analysis.

Nomenclature

\( P_{cb} \): the pressure in vacuum chamber
\( P_{st} \): the stagnation pressure
\( x, y, z \): one of the variable number in coordinate system
\( l \): the length from the bottom plane wall to the center of nozzle exit
\( \theta \): the angle between the bottom plane wall and the direction of nozzle
\( X_{30} \): the distance from impinging point that the gas jet impinging in experiments of \( \theta = 30^\circ \)
\( X_{45} \): the distance from impinging point that the gas jet impinging in experiments of \( \theta = 45^\circ \)
\( X \): the variable number assembling the \( X_{30} \) and \( X_{45} \)
\( I \): a value of any pixels
\( I_0 \): a criterion \( I \) value
\( I^* \): the \( I \) value normalized by \( I_0 \)
\( S^* \): the “analysis field” area normalized from nozzle exit area

\( D \): the major axis length assuming the “analysis field” regarded as an ellipse
\( H \): the minor axis length assuming the “analysis field” regarded as an ellipse
\( C (y_c, z_c) \): the location of the center of the “analysis field”
\( y_c \): the location of the center of the “analysis field” along the y coordinate
\( z_c \): the location of the center of the “analysis field” along the z coordinate

References