Ambient Gas Entrainment into a Transient Gas Jet*

(Visualization of Surrounding Air Motion and Estimation of Entrainment Amount by Path Line Method)

Eiji TOMITA**, Yoshisuke HAMAMOTO**,
Hiroyuki TSUTSUMI** and Shiro TAKASAKI**

For the study of the combustion in a transient gas jet used in gas diesel engines, it is very important to investigate the entrainment process of the surroundings of the jet. In this study, a path line method utilizing a CCD random shutter camera with various shutter times was applied. Large ($40\ \mu\text{m}$), lightweight microballoon particles are used for scattering the path lines of the surroundings and fine particles ($0.75\ \mu\text{m}$) are used for visualizing the approximate shape of the jet. The transient gas velocity was also measured with a two-component laser Doppler velocimeter (LDV). Consequently, (1) the jet configuration and the entrainment process could be visualized simultaneously, and (2) this path line method was found to be very useful for estimating the air mass entrained because of the good agreement with the values obtained using LDV.

Key Words: Jet, Unsteady Flow, Flow Visualization, LDV, LDA, Entrainment, Transient Gas Jet, Path Line Method

1. Introduction

For the study of the combustion in a transient fuel gas jet used in gas diesel engine or direct injection stratified charge spark-ignition engine, it is very important to investigate the entrainment process of the ambient air into the jet. In a gas diesel engine or direct injection stratified charge spark-ignition engine, a fuel gas is injected for a short time into the cylinder of the combustion chamber. It is very important to investigate the properties of the transient gas jet in order to reduce the exhaust emission and to increase thermal efficiency.

Many studies^{(1),(2)} have been conducted on the steady jet, whereas only a few have been made on the transient gas jet. The properties of a turbulent jet upon injecting helium or hydrogen were investigated by Tanabe et al.⁽³⁾⁻⁽⁶⁾ in detail. The velocity field of an air jet was measured by Witze⁽⁷⁾. The penetration and

the inner structure of a jet were investigated by Sugita et al.^{(8),(9)} The structure of a colored water jet containing NaCl was investigated by Shiragashi et al.⁽¹⁰⁾ The penetration of a jet was investigated by changing the injected and ambient gases by Hamamoto et al.⁽¹¹⁾ The properties of a methane jet were studied and applied to a gas diesel engine by Komoda et al.⁽¹²⁾ The concentration distributions of hydrogen and methane jets were measured with a laser interferometer by Hamamoto et al.⁽¹³⁾ and with an infrared absorption method by Tomita et al.⁽¹⁴⁾

The above studies emphasized the jet itself and its inner structure. The entrainment process is also of primary importance when the combustion process is considered. Ricou and Spalding studied the entrainment rate of ambient air into a steady gas jet⁽¹⁵⁾. The interaction between the gas flow and the mixing process was investigated by measuring the velocity and the concentration simultaneously in the case of low Reynolds number by Takagi et al.⁽¹⁶⁾ Using a laser sheet method, the steady jet as a whole was visualized by Long et al.⁽¹⁷⁾, turbulent eddies of the jet were visualized by Dahm and Dimotakis⁽¹⁸⁾ and the entrainment process was discussed by Shioji et al.⁽¹⁹⁾

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** Dept. of Engineering, Okayama University, Tsushima-Naka 3, Okayama 700, Japan

However, there are few works on the gas flow or entrainment of ambient air except for the transient spray^{(20)–(24)}.

In this study, a transient free turbulent gas jet was formed by sudden injection into the ambient quiescent air under atmospheric pressure and room temperature and the ambient air motion was visualized by a laser sheet method. The mass of air entrained could be obtained from the path lines during a certain shutter time of a CCD camera. The amount of the air was compared with that determined from LDV measurement and the validity of this path line method was discussed.

2. Measurement Method

Air was injected into ambient quiescent air of atmospheric pressure and room temperature (297 K) in a large cubic vessel (one span=350 mm) for 11.5 ms. The electromagnetically controlled injector shown in Fig. 1 (hole diameter=0.82 mm) was connected to a tank with 494 kPa pressure.

Figure 2 shows a schematic diagram of the experimental apparatus and optical arrangement. A beam from an argon ion laser with power of five watts was flattened into a sheet by cylindrical and convex lenses. The laser sheet was passed through the sections including or perpendicular to the jet axis. The image of the jet and the surroundings was taken with a CCD random shutter camera based on a trigger signal and an electric shutter. The thickness of the sheet was

Fig. 1 Schematic diagram of nozzle exit

Fig. 2 Schematic diagram of experimental apparatus and optical arrangement for taking photographs of ambient air including jet axis

about 3 mm in most cases except for a special one which is discussed in Section 3.1. Microballoons of mean diameter 40 μm and specific gravity 0.04 g/cm^3 were seeded in the vessel. Fine particles of boron nitride (BN) of diameter was 0.75 μm and specific gravity 2.26 g/cm^3 were set in the small chamber before the nozzle exit as shown in Fig. 1.

Before air was injected from the nozzle, BN particles were seeded in the air in advance. The shutter of the CCD camera was open within any period from (or before) the initiation of the injection by the trigger signal. The path lines of the microballoons were visualized and the approximate flow patterns were obtained. After the image was frozen by the controller into the frame memory with 512×512 pixels and 256 gray levels, the image was processed by a personal computer.

The velocity of ambient air was measured with an LDV. Argon ion laser was used as the light source, and two-component velocity was measured by three beams with two wavelengths of 488 and 514.5 nm. The cross-sectional angle was 0.164 radian, the lengths of the intersection region for axial and radial directions were 0.97 and 1.02 mm, and the diameters were 79 and 83 μm , respectively. The forward-scattering LDV system with a frequency shifter (Bragg cell type) was chosen for high S/N ratio and for determining the flow direction. Smoke from incense sticks was used as seeding particles for LDV. The origin of the coordinate system is the nozzle exit, and the jet axis direction is denoted by x , the radial direction by r , the tangential direction by θ and the upper side of the nozzle in Fig. 1 is $\theta = \pi/2$ radian. The jet axis was decided after determining the velocity distribution. The measurement locations were $3.3 \leq r \leq 19.0$ mm at $x = 10$ mm, and $14 \leq r \leq 18$ mm at $x = 50$ mm in $\theta = 3/2\pi$ radian.

3. Visualization of Ambient Air Motion

3.1 Ambient air flow around jet

Microballoon particles were seeded in ambient quiescent air in the vessel. The shutter of the CCD camera was open during 2, 4, 6, 8 and 10 ms from the initiation of the injection. Figure 3 shows examples of the images in the $x-r$ section, where $t = 0 \sim 2$ ms means the period from 0 to 2 ms. The jet appeared as a white cloud in Figs. 3(a) to (d) because boron nitride (BN) particles were seeded in the injected air. The intensity of the cloud differed depending on the amount of BN particles. Figures 3(d) and (e) also show the images for $t = 0 \sim 10$ ms, but the magnitude of the pictures differs from that in Fig. 3(c). Ambient air motion was slight at $t = 0 \sim 2$ ms as shown in Fig. 3(a). At $t = 0 \sim 4$ ms and $t = 0 \sim 10$ ms (Figs. 3(b)

and (c)), ambient air is entrained normal to the jet boundary near the upstream region as indicated by "a" in Fig. 3(c). The ambient air away from the jet axis moves outside of the jet and against the jet direction when the jet approaches the air and it is

entrained after passing through the unsteady part of the jet. Thus, the path line away from the jet axis appears like the letter "U" in the region near "c" in Fig. 3(c). The path line appears like the letter "I" in the region upstream of the jet near "a" in Fig. 3(c) and the letter "J" in the region near "b".

On the other hand, the particles ahead of the front part of the jet move toward the downstream region. It could not be judged from these path lines whether the ambient air was pushed away by the jet front or it was entrained from the jet front. Figure 3(e) shows an example of the image of the lower half side of the jet and ambient air; however, the jet boundary was not clear because BN particles were not seeded in the jet in this case.

The cross-sectional images perpendicular to the jet axis are shown in Fig. 4. Figure 4(a) shows an example of the image at $x=10$ mm and time from -2 ms to 8 ms after the initiation of the jet injection (shutter time = 10 ms). The start location of the path line seems to broaden owing to the blooming phenom-

(a) $t=0\sim 2\text{ms}$

(b) $t=0\sim 4\text{ms}$

(c) $t=0\sim 10\text{ms}$

(d) $t=0\sim 10\text{ms}$

(e) $t=0\sim 10\text{ms}$

Fig. 3 Examples of images of path lines from initiation of jet injection (cross sectional image including the jet axis)

(a) $x=10\text{mm}$, $t=-2\sim 8\text{ms}$ (b) $x=50\text{mm}$, $t=0\sim 10\text{ms}$

Fig. 4 Examples of images of path lines (cross sectional image perpendicular to the jet axis)

non, because the microballoons are motionless before the jet injection. Some particles have been entrained into the jet. It can be seen from Fig. 4(a) that the ambient air is entrained axisymmetrically before the entrainment into the jet and that it flows randomly after that. Figure 4(b) shows an example of the image at $x=50\text{mm}$ and the shutter time is 10 ms after the initiation of the jet injection. The width of the laser sheet was set to 6 mm only in this case in order to prevent particles from deviating from the laser sheet. The ambient air moves outside the jet at first and it is entrained into the jet after the unsteady part of the jet passes. It is found from Fig. 4(b) that the air flow is axisymmetric far from the jet.

3.2 Visualization near unsteady part

Figure 5(a) shows an example of an image of which the shutter time was from 5 to 7 ms ($t=5\sim 7\text{ms}$) during 2 ms under the condition of many microballoon particles exist in the ambient air. Two axisymmetric eddies on both sides of the jet axis could be observed near the unsteady part of the jet. In other

(a) $t=5\sim 7\text{ms}$ (b) $t=5\sim 7\text{ms}$

Fig. 5 Examples of visualization of eddies in the unsteady part of the jet

runs of the experiment, the two eddies were not always axisymmetric and sometimes they were not so clearly visible. When the shutter time was chosen as 10 ms (cf. Figs. 3(c) and (d)), the eddies shown in Fig. 5(a) could not be observed. In general, the time scale of the flow is less restricted than the observation period of the shutter time. Figure 5(b) shows the image with the same shutter time as in Fig. 5(a) under the conditions of BN particles in the jet and few microballoon particles in the ambient air. The path lines upstream of the eddies ($x\approx 60\text{mm}$) were longer than other parts of the ambient air because the air was strongly entrained here. Of course, the gas moves very fast after the air is entrained into the jet.

4. Mass of Ambient Air Entrained

Fine particles of BN were mixed in the jet for taking images of path lines while they were not mixed in the LDV measurement. In order to investigate the effect of the existence of fine particles of BN seeded in the jet on the entrainment of the ambient air into the jet, the axial and radial velocities, u and v , were measured both without and within BN particles at the locations of $x=10\text{mm}$, $r=7\text{mm}$ and $\theta=3/2\pi$ radian.

As a result, it was found that there was almost no effect of the existence of BN particles because both velocities were almost the same as shown in Fig. 6, where $\bar{u}$ and $\bar{v}$ denote ensemble averaged velocity.

4.1 Mass of ambient air entrained from upstream of the jet

Axial and radial velocities, u and v , were determined by LDV measurement at $x=10$ mm and $3.3 \leq r \leq 19.0$ mm. Figure 7 shows ensemble averaged velocities of $\bar{u}$ and $\bar{v}$. After the values of $\bar{u}$ show minimum values (opposite direction toward the progress of the jet) during $0.4 \sim 0.8$ ms their direction is changed, and they gradually approach constant values thereafter (same direction toward the progress of the jet). In the radial direction, air is entrained into the jet after being pushed toward the outside of the jet at $t \leq 0.3$ ms. Movement of the ambient air far from the jet is retarded after the initiation of the jet injection because of the unsteadiness of the jet.

Fig. 6 Effect of existence of BN particles seeded in the jet on velocity of ambient air

Fig. 7 Axial and radial velocities $\bar{u}$ and $\bar{v}$

The air mass which passes through the cylindrical surface of radius r per unit length of axial direction, namely, the rate of the passing air mass, $\dot{m}_p (= -2\pi\rho r\bar{v})$, is obtained, where ρ is the density of the ambient air, and the value of $\bar{v}$ is calculated from smoothing the velocity by the running average method. As shown in Fig. 8, the value of $\dot{m}_p$ reaches a steady state with time from the jet injection and shows a constant value near the jet boundary while becoming smaller with increasing radius.

Next, the air mass entrained is estimated from the path lines as follows. For example, in the path line image shown in Fig. 4(a), the coordinates of maximum and minimum radius locations of a path line which is not entrained into the jet are determined. From one path line, the passing air mass per unit length in the axial direction through the cylindrical surface of radius r_e is calculated by Eq. (1), as shown in Fig. 9.

$$\dot{m}_p = \rho\pi(r_m^2 - r_e^2) \quad (1)$$

This equation represents the mass of air surrounded

Fig. 8 Rate of passing air mass, $\dot{m}_p$, obtained from LDV data at $x=10$ mm

Fig. 9 Radius of start location, r_s , radius of final location, r_e and maximum radius of particle, r_m

by two cylinders of radii r_m and r_e with the same axis passing through the cylindrical surface of radius r_e . The path line represents the letter "I" near $x=10$ mm as shown in Fig. 3(c) (indicated by "a"). Then, most particles move within the width of the laser sheet (3 mm) as shown in Fig. 4(a).

Figure 10 shows the mass of air passing through the cylindrical surface of radius r_e . The integrated values of m_p obtained from the radial velocity by LDV from the initiation of the jet injection to time t are also plotted in Fig. 10. Both values of m_p agree with each other. The value of m_p becomes constant at smaller r_e . The mass of air entrained, m_{es} , is defined as the constant value of m_p as shown in Fig. 10.

4.2 Mass of air entrained from downstream

For example, the passing air mass through the surface surrounded by the radius r_e , m_p , is obtained at

Fig. 10 Comparison of passing air mass from this path line method ($r-\theta$ section) with that from LDV

Fig. 11 Comparison of passing air mass from this path line method ($r-\theta$ and $x-r$ sections) with that from LDV

$x=50$ mm from the path lines in the $r-\theta$ section perpendicular to the jet axis as shown in Fig. 11 by solid circles. These data could be obtained only at $t=0\sim 10$ ms, while they could not be obtained from the path lines in the $r-\theta$ section under other conditions indicated in Fig. 11. When r_e is less than r_s , the passing air mass, m_p , can be determined from both the $r-\theta$ and the $x-r$ planes as shown in Fig. 12(a). However, when r_e is equal to or greater than r_s as shown in Fig. 12(b), it can be determined only in the $x-r$ plane and not in the $r-\theta$ plane because the location of r_e cannot be determined.

The passing air mass, m_p , is calculated from Eq. (1) by utilizing the image in the $x-r$ section as shown in Fig. 3(e) and reading out the location from path line of the letter "U" in the ranges of $45\leq x\leq 55$ mm and $8\leq r\leq 22$ mm. These results are shown in Fig. 11 at open circles. The results obtained from the two methods mentioned above show good agreement at $t=0\sim 10$ ms. Moreover, the passing air mass from the LDV data agrees well with that from this path line method.

At $x=50$ mm, the passing air mass, m_p , does not become constant near the jet boundary because of the strong effect of the unsteadiness. The maximum value of m_p in r_e is determined as the mass of air entrained, m_{es} .

4.3 Traceability of particles

The traceability of the microballoons in the fluid motion was examined for both impulsive and periodic changes in the fluid velocity⁽²⁵⁾. The characteristic lag time constant is 0.15 ms for impulsive change at the representative velocity of 1 m/s. For example, the periodic change in ambient air flow was less than about 200 Hz at $x=50$ mm and $14\leq r\leq 18$ mm as

Fig. 12 Relation among start radius, r_s , final radius, r_e and maximum radius r_m

Fig. 13 Axial and radius velocities, $\tilde{u}$ and $\tilde{v}$

shown in Fig. 13. The frequencies for the amplitudes of 0.97 and 0.99 are about 200 and 100 Hz when the fluid oscillates. When a particle moves along a straight line, the particle can be traced with higher response judging from the result from Fig. 10. Thus it is considered that the microballoon particles can follow the fluid motion sufficiently well. Of course, the particles do not follow the fluid motion with high frequency such as turbulence, and only the mean flow can be observed. Therefore, it is useful to investigate the entrainment motion of the ambient air because it does not have such high-frequency components in the ambient air flow.

4.4 Resolution of this path line method

For example, one pixel in the image shown in Fig. 4(a) corresponds to $67\text{ }\mu\text{m}$. If the start and end locations are misread for each pixel in the direction of $\pi/4$ radian, the maximum error in the value of m_p from Eq. (1) is about $\pm 3\%$ at $t=0\sim 10\text{ ms}$. In order to improve the resolution, path lines in the image should be taken longer or a higher resolution CCD camera should be used.

5. Conclusions

A transient gas jet was formed by injecting air into an ambient quiescent air. The entrainment of the ambient air into the jet was investigated. The main results are as follows:

(1) A laser sheet was passed through a jet, of which section was perpendicular to the jet axis or including the jet axis. The jet configuration was visualized by adding fine particles to the jet. The

entrainment motion into the jet was visualized by investigating the path lines of lightweight and large particles with various shutter times of a CCD random shutter camera.

(2) The mass of air entrained into the jet as determined by this path line method agreed well with that determined from LDV measurement. It was found that this method was easy and useful for studying the entrainment of ambient air into the jet.

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