Flow Structure of a Round Jet with Side-Jet Formation

Kenta Kawabe and Akinori Muramatsu

Abstract When a low density fluid, such as hot air and helium gas, is discharged from a round nozzle, side jets are generated in the initial region of the jet. These radial ejections of the jet fluid are called *side jets*. The side-jet formation is estimated by the issuing conditions of the jet flow. The issuing conditions are mainly density ratio between the jet fluid and the ambient fluid, velocity profile and issuing speed at the nozzle outlet. However, a process of side-jet formation has not been revealed even now. In present work, we focused on the flow visualization of a gaseous jet flow with side jets, specifically, the vicinity of a jet nozzle issuing helium gas vertically into ambient air. The helium gas jet with the side-jet is visualized by a planar laser Mie scattering (PLMS) and recorded by a high-speed video camera, in order to investigate the process of side-jet formation.

1 Introduction

A complex phenomenon is generated in the near field of a jet if the mass density of the issuing gas is sufficiently lower than that of the ambient gas. This phenomenon is some radial ejections from the main jet stream, which are referred to as *side jets*. The side jets are formed by self-excited oscillations of the jet column [1, 2]. However, until now, it has not been possible to examine the structure of the side jets in great detail. We developed a three-dimensional imaging method using a planar laser Mie scattering (PLMS) and an oscillating mirror to observe a three-dimensional structure of the initial region of the jet with the side-jet formation, as shown in Fig. 1. [3]. The optical system swept a laser sheet at high speed by oscillating a mirror attached to a galvano-scanner. A large number of

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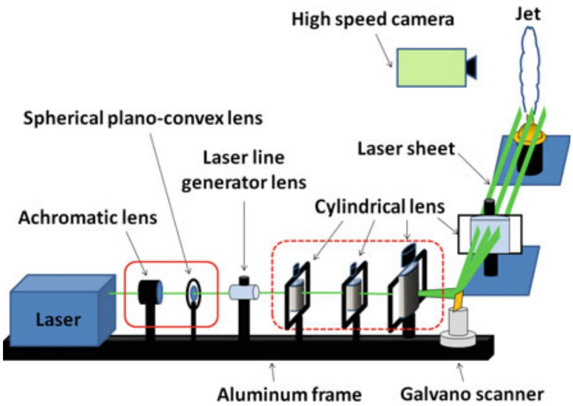

Fig. 1 Experimental apparatus for 3D imaging

cross-sectional images were captured almost simultaneously using a high-speed video camera. The 3D image of the flow field was constructed by image processing with an open software *ImageJ*. The constructed image was interpolated using bicubic interpolation. A helium gas jet with side-jet formation was visualized by three-dimensional imaging, as shown in Fig. 2. A non-dimensional coordinate system is illustrated in Fig. 2. The x and r are respectively streamwise and radial coordinates, and the origin is on the centerline at the nozzle exit. The D_0 is a nozzle diameter. From the 3D visualization, several side jets are generated simultaneously, and a vortex ring is distorted by the side-jet formation at the same time, as painted

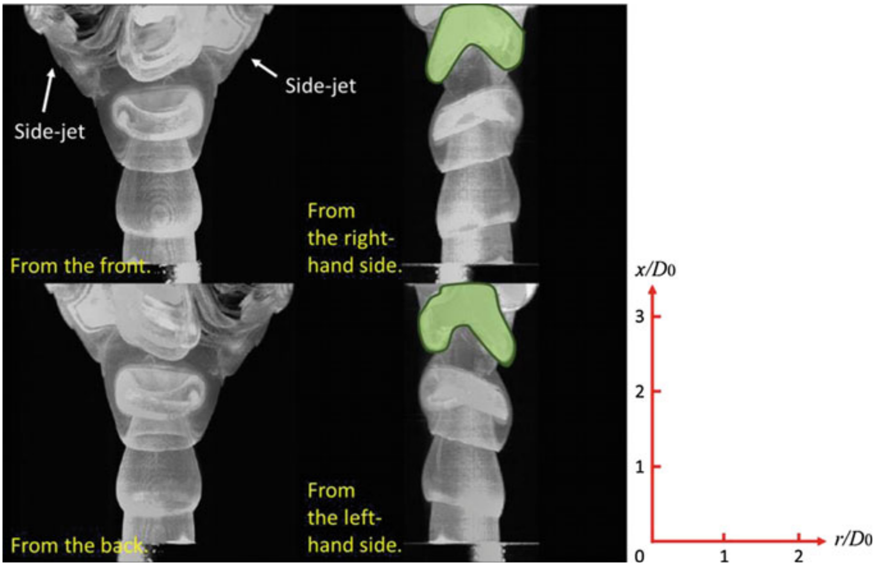

Fig. 2 3D images like the X-ray for a He gas jet at Re = 800

with light green in Fig. 2. A process of side-jet formation has not understood even now. In the present work, streamwise cross-sectional images of a helium gas jet are visualized at a few radial points, such as on the jet center line and in the shear layer, by a PLMS and the visualized images are recorded using a high-speed video camera, in order to investigate the process of side-jet formation.

2 Experimental Apparatus and Method

2.1 Target Flow

The visualized flow is a jet column with side jets in the vicinity of a nozzle issuing a low-density gas jet (a helium gas jet). To produce the side-jet formation, helium gas was issued vertically from a round nozzle into ambient air. A round nozzle for this experiment is shown in Fig. 3. A diameter at the nozzle exit D_0 is 16 mm and an area contraction ratio of the nozzle is 17. Slits attached to the nozzle are used as guidelines for positioning of a laser sheet. The jet Reynolds number is 800 and is defined by $Re = U_{c0} \cdot D_0/\nu_0$. Here, U_{c0} and ν_0 are centerline velocity at the nozzle exit and kinematic viscosity of the jet fluid. The density ratio between the jet fluid (helium gas) and the ambient fluid (air) is 0.14. The jet Reynolds number of 800 is lower limit for the side-jet formation at the used round nozzle. An effect of compressibility is disregarded because the issuing velocity is 5.8 m/s.

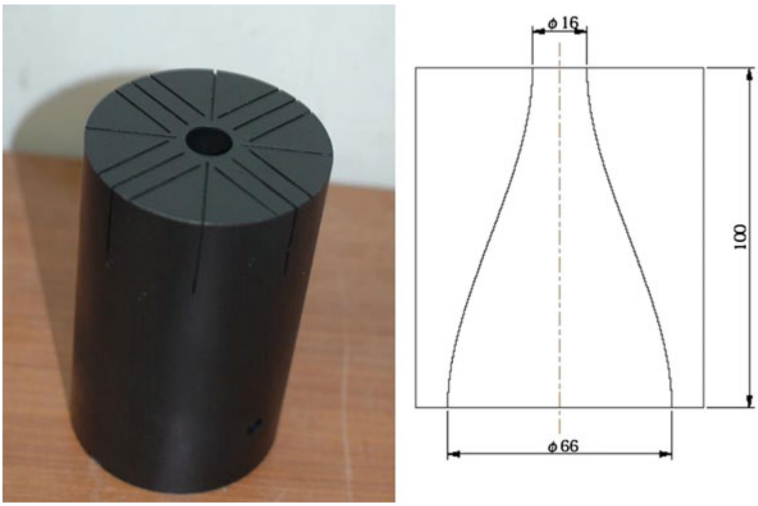

Fig. 3 A round nozzle

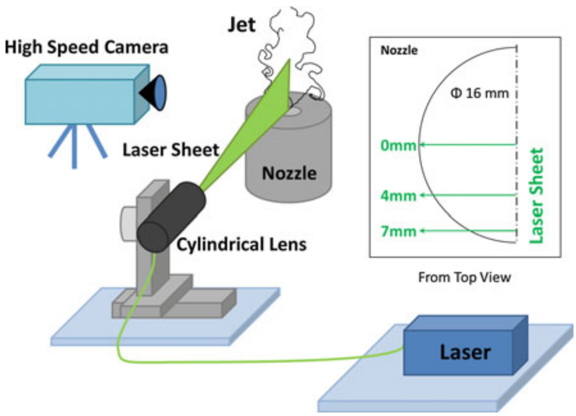

Fig. 4 Experimental apparatus for imaging the streamwise cross-sections in a He gas jet

2.2 Experimental Apparatus and Visualization Method

The experimental apparatus is shown in Fig. 4. The helium gas jet with the side-jet is visualized by PLMS. The gas jet is seeded with very small particles of smoke that functioned as the Mie scattering particles. The smoke is generated using a smoke generator (Dantec Dynamics, Safex Fog Generator 2010). A continuous-wave (CW) Nd:YAG laser (Japan Laser Corp., DPSS Green Laser, 5 W) is transformed to a light sheet through a cylindrical lens system. The laser sheet, which is less than 1 mm in thickness, is perpendicular to a high-speed video camera (Photron Corp., FASTCAM SA-X2). Cross-sectional images of a helium gas jet are visualized by a PLMS and the time series of the visualized images are recorded using the high-speed video camera. In order to observe the phenomenon of side-jet formation at various locations, the streamwise cross-sections of the jet flow is visualized at the radial positions of 0, 4 and 7 mm, where the central axis of the nozzle is defined as 0 mm as shown in Fig. 4.

3 Experimental Results

The visualized cross-sectional images of the helium gas jet at positions of 0 and 7 mm are shown in Figs. 5 and 6. Each of time-intervals between images in Figs. 5 and 6 is 2 ms.

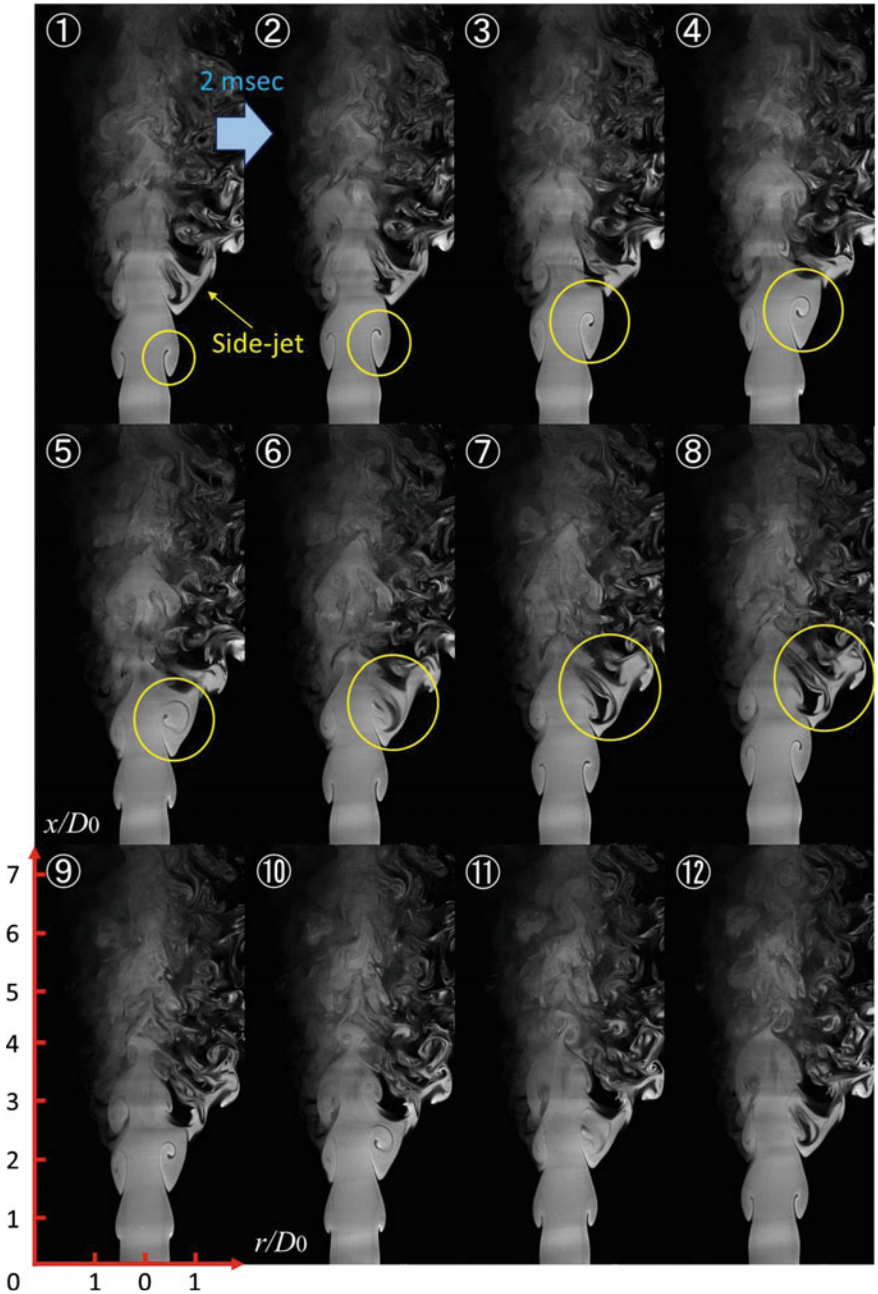

Fig. 5 Streamwise cross-sectional images on the jet centerline (at 0 mm) for He gas jet

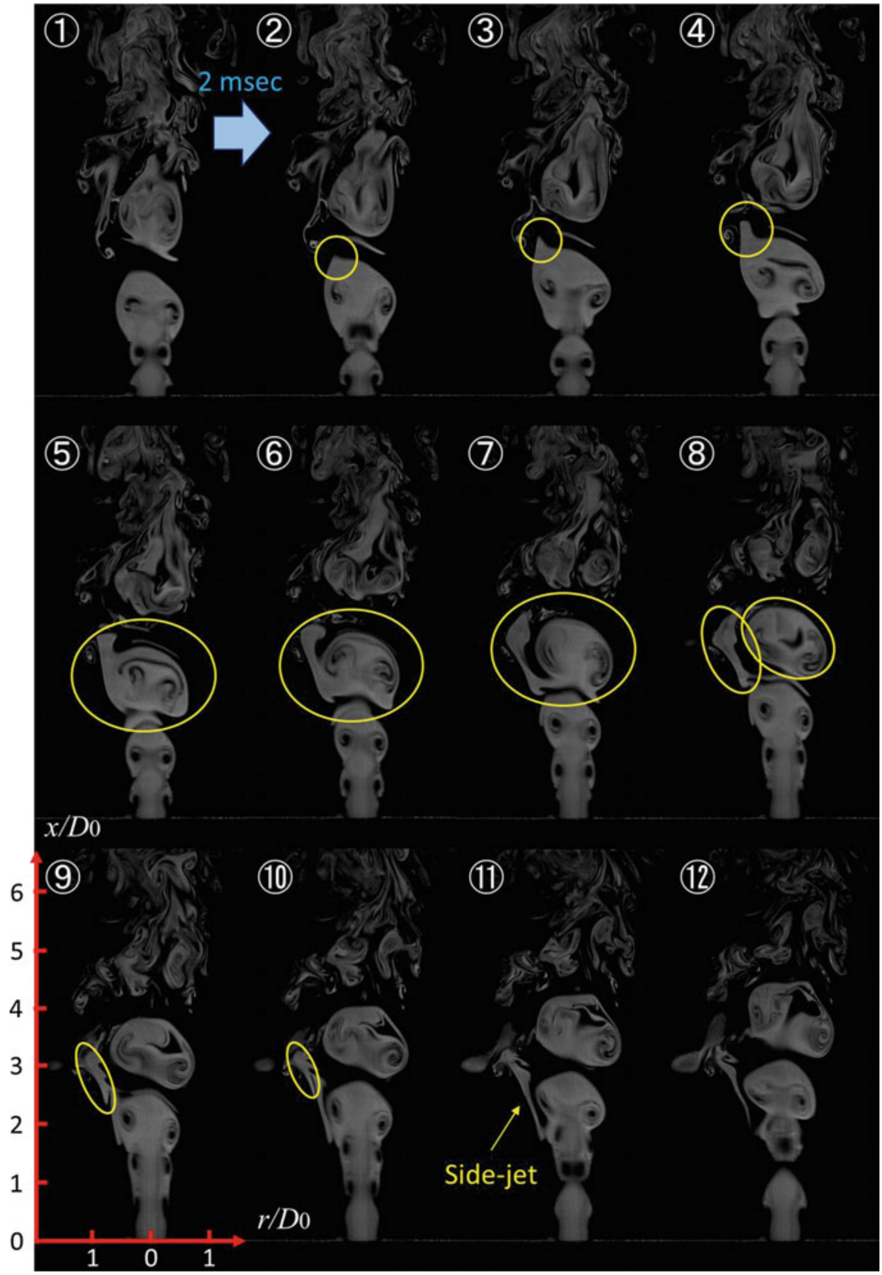

Fig. 6 Streamwise cross-sectional images in the jet shear layer (at 7 mm) for He gas jet

3.1 At 0 mm (on the Jet Center Line)

The jet fluid ejected between the vortex rings radially upward is a side jet, as shown by a yellow arrow in Fig. 5. The vortex ring marked with a yellow circle in the images of No. 1 and 2 in Fig. 5 moves upward. In the image of No. 3, the vortex ring marked with a yellow circle is close to the side jet generated from the preceded vortex ring. In the image of No. 4, the upper right of vortex ring expands toward the side jet. In the images from No. 5 to 8, the part of the expanded vortex ring gradually separates from mainstream of the jet by rotating the vortex ring. This separation looks like a radial ejection from the mainstream flow. The radial ejection, namely a side jet, moves downward on the vortex ring when the vortex ring moves upward, so that the starting point of the side-jet formation is maintained at approximately constant height. In the image of No. 8, the next vortex ring is close to the separated flow like the image of No. 3. After the image of No. 8, a similar process is repeated. Although a side jet seems to eject from a certain height of the jet stream continuously, the side jet is generated intermittently, because the side-jet formation is related to the movement of each vortex. The side jet is seen a continuous phenomenon with the naked eye, because a convection speed of the vortex rings is higher than a moving speed of a side jet. Moreover, in the helium gas jet with this condition, the side jet is generated before merging of the two vortex rings. Consequently, it is thought that the pairing process of vortex rings is not related to the side-jet formation [4]. Visualized images at the 4 mm are similar to the images at 0 mm.

3.2 At 7 mm (in the Jet Shear Layer)

On the other hand, in Fig. 6, the side jet is formed in left-hand side, as shown in a yellow arrow. In the image of No. 2 in Fig. 6, the left side of a vortex ring indicated by a yellow circle is preceded from an opposite side of the vortex ring. This fact shows that the vortex ring is tilting. The portion indicated by this yellow circle is going to become a side jet. The jet fluid ejects from the vortex ring in the direction of upper left in the image of No. 2–4, and the flow is separated simultaneously with rotation of the vortex ring from the upper left of the vortex ring in the image of No. 5–7. In the image of No. 8, the separated flow and the vortex ring are divided. In the image of No. 9 and 10, the separated flow in the image of No. 8 drifts, and it connects with the next vortex ring. Although the ejection from the braid region is not recognized from the Figs. 5 and 6, it is found that the ejected flow not only consists of a separation from the vortex ring, but also of the fluid of the braid region, because the flow in the braid region changes the flow direction by rotation of the vortex ring, when a side jet is formed by rotation of the vortex ring, by watching the original image.

4 Conclusions

The results of flow visualization at the initial region of a helium gas jet are summarized as follows:

(1) A flow is separated simultaneously with rotation of a vortex ring from the upper side of a vortex ring. An ejection from the braid region is also generated because the flow direction changes in the braid region by rotation of the vortex ring. A side jet is formed from these two processes.
(2) A side jet is generated intermittently.
(3) A side of a vortex ring with a side jet is preceded from a side of the vortex ring without a side jet. The vortex ring is tilting when the side jet is formed.
(4) The side-jet formation does not depend on a pairing process of vortex rings.

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