Flow Characteristics of Multiple Round Jets Issuing from In-line Nozzle Arrangement

Hiroshi Teramoto and Takahiro Kiwata

Abstract This research reports on an experimental investigation of the flow characteristics of multiple round jets issuing from 6 × 6 in-line nozzle arrangement at low-Reynolds number, $Re \approx 4 \times 10^3$, with five spacing ratios of $l/d = 1.5, 2, 3, 4$ and 5 (where d is a diameter of nozzle, and l is a spacing between the center of nozzles). The mean and fluctuating velocities of the jet flow were measured by constant-temperature type hot-wire anemometer. We found that the bending of the outside jet decreases with increasing the spacing ratio l/d. In the further downstream, the multiple jets merge into a single jet flow and the merging of multiple jets occur more downstream with increasing the spacing ratio l/d. In the case of the small spacing ratio, the maximum velocity of merged jet increases and the merged jet spreads from the near field of jet exit.

Keywords Multiple jets · Confluent jet · Flow interaction · Hot-wire anemometry

1 Introduction

The multiple jets are used in various applications, such as air ventilation system, multiple-jet gas burner, fuel injection nozzle and exhaust stacks and so on. The multiple jets were investigated by a number of researchers to improve the performance of devices. Okamoto et al. [1] researched on the interaction of the parallel twin circular turbulent jet. They showed that the twin-jet interacts and joins in the form of an ellipse at the downstream distance, and it becomes close to a circular jet at far downstream distance. Nasr and Lai [2] investigated the influence of acoustic

H. Teramoto (✉)
Graduate School of Natural Science and Technology,
Kanazawa University, Kanazawa, Japan
e-mail: teramoto@ryuko.ms.t.kanazawa-u.ac.jp

T. Kiwata
School of Mechanical Engineering, Kanazawa University, Kanazawa, Japan

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excitation to the two parallel plane jets. Ghahremanian et al. [3] and Svensson et al. [4] showed that the multiple round jets issuing from an array also merge and develop into a single round jet similar to the confluent twin-jet. Although the multiple jets exist in various applications, the relation between the arrangement of multiple round jets and the flow structures is not clear. The objective of this research is to clarify an influence of spacing ratio l/d (where d is a diameter of nozzle, and l is a spacing between the center of nozzles) on the flow characteristics of multiple round jets issuing from 6 × 6 in-line nozzle arrangement.

2 Experimental Apparatus and Method

Figure 1 shows a schematic diagram of multiple round nozzles and locations of measurements. Specification of multiple round nozzles and experimental conditions are shown in Table 1. The nozzle diameter was $d = 6.0$ mm, and the nozzles were arranged 6 × 6 square matrix in-line arrangement. The spacing ratio of the multiple round nozzles was varied in the range of $1.5 \leq l/d \leq 5$. Also, the coordinate system and the shape of nozzles are shown in Fig. 1. Measurements of mean and fluctuating velocities were made with cross- and single-wire probes, and hot-wire anemometers of the constant-temperature type with linearized output. The output signals of the hot-wire anemometer were converted by a 12-bit A/D converter with sampling frequency of 10 kHz, and 10×10^4 items of data were stored. The hot-wire anemometer was calibrated by a Pitot static pressure tube and an inclined

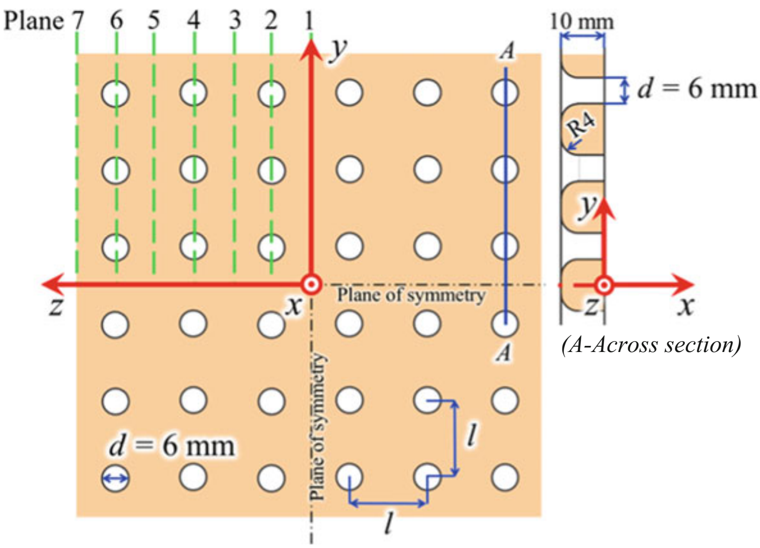


Fig. 1 Schematic diagram of 6 × 6 in-line arrangement of multiple round nozzles

Table 1 Specification of multiple round nozzles and experimental conditions

Nozzle diameter, d [mm]	6				
Nozzle spacing, l [mm]	9.5	12	18	24	30
Spacing ratio, l/d	1.5	2	3	4	5
Reynolds number, Re	4×10^3				
Bulk velocity, U_b [m/s]	9.4				

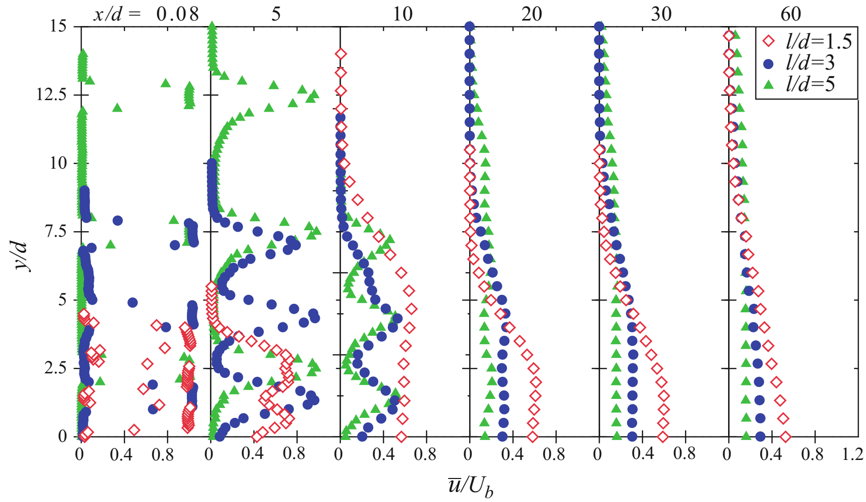
tube manometer. A computer-controlled 3-dimensional traversing mechanism was used for probe positioning. Experiments were performed under a computer control for the automated data acquisition. The mean and fluctuating velocities and spectrum of fluctuating velocity were obtained by using a personal computer and an FFT analyzer, respectively. The bulk velocity, U_b, was defined as the spatial averaged velocity at nozzle exit. Reynolds number, Re, based on the diameter of the nozzle d and the bulk velocity U_b is about 4×10^3. The uncertainties of the mean velocity component and fluctuating velocity component were about 1.1% and 4.3% respectively.

3 Results and Discussion

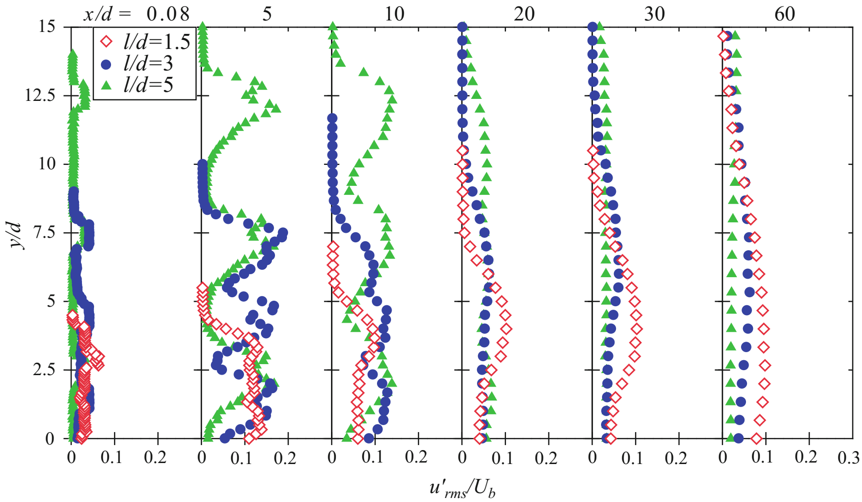
3.1 Mean and Fluctuating Velocity Distributions

Figure 2 shows the downstream development of the streamwise mean velocity $\bar{u}/U_b$ and the streamwise velocity fluctuation u'_{rms}/U_b profiles for $l/d = 1.5$, 3 and 5 at the cross section of Plane 2. Each jets have been formed by multiple round nozzles and the potential core exists in the near field of each nozzle exit. The potential core is maintained until $x/d \approx 5$ in the case of $l/d \geq 3$. For $l/d = 1.5$, the potential core of each jets disappear early, because each jets strongly interact with adjoining jets. In downstream of $x/d > 20$, the multiple jets merge and form a single jet flow whose mean streamwise velocity profile has a flat region. The velocity fluctuation increases at the position which have large velocity gradient such as shear layers between the ambient fluid and the perimeter of multiple jets, and the adjoining jets. The velocity fluctuation at the side of ambient fluid becomes larger than that at the side of center of multiple jets.

Figure 3 shows the profiles of the streamwise mean velocity and streamwise fluctuating velocity anew. The vertical axis of each graphs are modified to y/l. At $x/d = 0.08$, the streamwise velocity profiles agree with each other. At $x/d \lesssim 10$, the velocity fluctuations for $l/d = 5$ between adjoining jets are lower than the other spacing ratio. Therefore, the merging of multiple jets with the large spacing ratio occurs more downstream. At $x/d = 60$, the maximum velocity of merged jet for $l/d = 1.5$ is larger than that of the other spacing ratio. In the case of the small spacing ratio l/d, the maximum velocity of merged jet increases.



(a) Streamwise mean velocity $\overline{u}/U_b$ *vs.* y/d

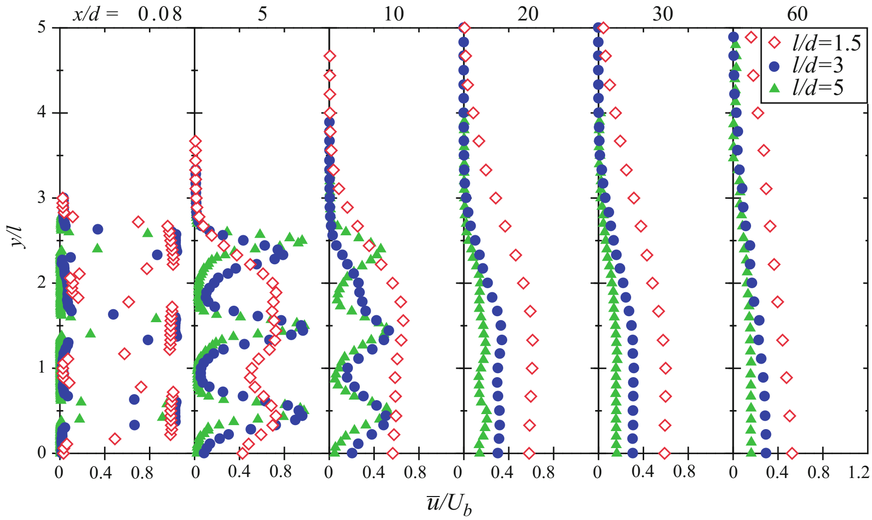


(b) RMS value of streamwise velocity fluctuations u'_{rms}/U_b *vs.* y/d

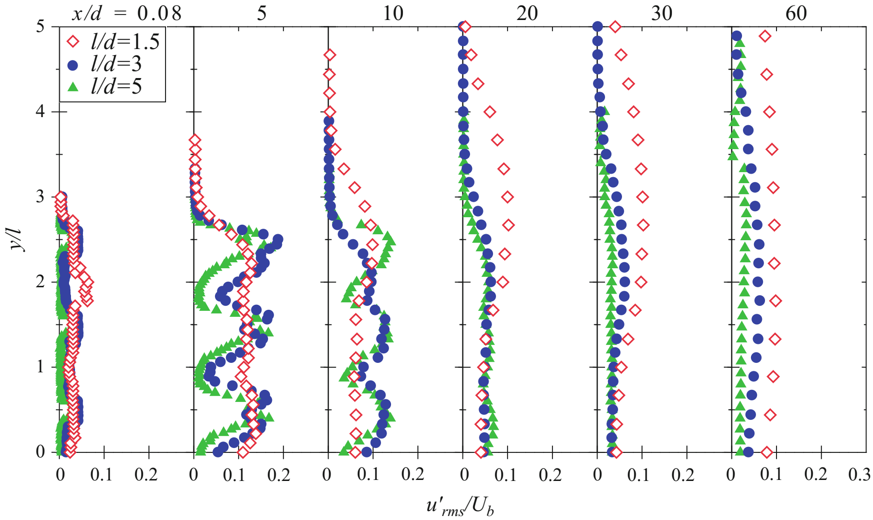
Fig. 2 Profiles of streamwise mean velocity and velocity fluctuation (Plane 2, *y*-axis: *y*/*d*)

3.2 Velocity Peak Positions and Spreading of Multiple Jets

As shown in Fig. 4, the round jets at the side of the center of the arrangement and the ambient fluid are defined as “inside jet” and “outer jet”. The jet between inside jet and outside jet is defined as “middle jet”. Figure 5 shows the three peak positions of the mean streamwise velocity profiles at the cross section of Plane 2. Three



(a) Streamwise mean velocity $\overline{u}/U_b$ *vs. y/d*



(b) RMS value of streamwise velocity fluctuations u'_{rms}/U_b *vs. y/d*

Fig. 3 Profiles of streamwise mean velocity and velocity fluctuation (Plane 2, *y*-axis: *y*/*l*)

jet peak positions show agreement with each nozzle spacing ratio. This result represent that the flow field of the multiple jets has similarity. The peak positions of outside jets are bend toward to the center of the flow. It is the influence of the entrainment between outside and middle jet. In addition, the outside jet peak disappears at $x/l \approx 4$. It indicate that the outside jets merge with adjoining jets such as

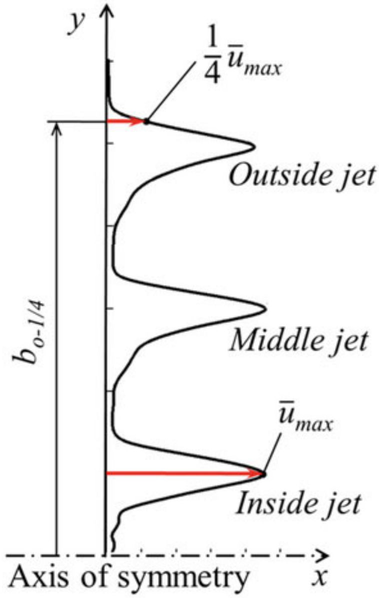


Fig. 4 Definition of jet positions

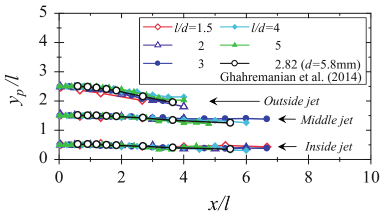


Fig. 5 Peak positions of mean streamwise velocity (Plane 2)

middle jets. The peak positions of middle and inside jets exist until $x/l \approx 6$. From this result, all jets merge fully and develop as a single flow at $x/l \gtrsim 6$.

Figure 6 shows the spread of the multiple jets for all of the spacing ratio, l/d = 1.5, 2, 3, 4 and 5 at the cross section of Plane 2. The width of $b_{o\text{-}1/4}$ is defined as the y-coordinate of $\bar{u} = \bar{u}_{max}/4$ for the outer jet, where $\bar{u}_{max}$ is the maximum velocity at the measured cross sections (as shown in Fig. 4). In the near field of the nozzle exits, $x/l \lesssim 4$, the width of multiple jet flow shrinks. This result shows good agreement with the experimental data by Ghahremanian et al. [3]. In downstream of $x/l \gtrsim 10$, the width of $b_{o\text{-}1/4}$ increases gradually. In the case of $l/d \leq 2$, the multiple jet flow spread becomes large with decreasing spacing ratio l/d. On the other hands, the spacing ratio of $l/d \geq 3$, the change of the width of $b_{o\text{-}1/4}$ with respect to x/l does not depend on spacing ratio l/d.

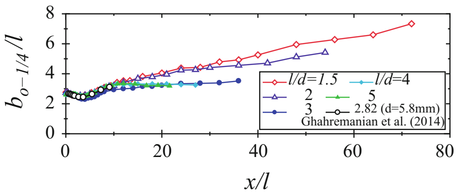


Fig. 6 Spread of multiple jets (Positions of $\bar{u} = \bar{u}_{max}/4$, Plane 2)

4 Conclusions

The influence of the spacing ratio *l*/*d* on the flow characteristics of multiple round jets were investigated experimentally. The following conclusions can be drawn:

(1) The bending of the outside jet decreases with increasing the spacing ratio *l*/*d*, and the merging of multiple jets occur more downstream.
(2) In the case of the small spacing ratio *l*/*d*, the maximum velocity of merged jet increases.
(3) In downstream, the spread of merged jet for $l/d \geq 3$ hardly depend on the spacing ratio *l*/*d*.
(4) The flow characteristics of multiple round jets depend on the spacing between the centers of nozzles *l*.

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