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***Abstract*:** Experiments were conducted on the effects of a wall distance and velocity ratio of suction flow to injection flow on the flow and heat transfer characteristics of a circular impinging jet accompanying an annular suction flow. As a result, it is found that in the case of accompanying suction flow, a higher Nusselt number can be obtained compared with in the case without suction flow, under a condition of the wall distance within eight times of injection pipe diameter from the near pipe exit edge. In addition, when the effect of velocity ratio is examined at a fixed arbitrary wall distance, it is found that there exists an optimum velocity ratio where the Nusselt number becomes the maximum. It is shown that these heat transfer characteristics are closely associated with the fluctuating velocity and the mean velocity in the two-dimensional velocity field observed by Particle Image Velocimetry (PIV).

***Keywords*:** flow control, PIV, impinging jet, turbulent flow, heat transfer, heat transfer enhancement.

The necessity of controlling the diffusion and mixing of jet is very high from the viewpoint of engineering (Crow and Champagne, 1971; Hussain and Husain, 1989; Shakouchi et al., 1996; Toyoda et al., 1999; Suzuki et al., 1999). As representative control methods, researches on non-circular jet, excitation of jet, coaxial annular sub-jet and so on have been reported so far. The authors (Nozaki et al., 1996) proposed a novel technique in which an annular suction flow is produced in the circumference of a circular jet by using a coaxial double circular pipe and vortex structure inside the shear layer is manipulated by this suction flow. Multipoint simultaneous measurement of unsteady flow field of a circular free jet accompanying an annular suction flow has been carried out until now by using PIV (Adrian, 1991). Informative results as shown in the following have been obtained in this field (Sonoda et al., 1997; Sonoda et al., 1998; Fukuhara et al., 1999). In the case of constant injection velocity, the accompanying annular suction flow led to the increase of fluctuating velocity in the radial direction in the vicinity of the pipe exit edge. The cause of the increase of the above fluctuating velocity was elucidated from the observation of the phenomenon of an asymmetric vortex in the radial direction.

The impinging jet collides against a heat transfer plane after being blown off through a nozzle. High heat transfer characteristics are obtained in the vicinity of a stagnation point. This is widely used in the industrial field, e.g. for cooling electronic equipment etc. and for drying printed matter etc. (Kataoka, 1998). In this study, the improvement of cooling characteristics of the heated wall surface was tried by applying the impinging jet accompanying an annular suction flow by which the increase of fluctuating velocity was obtained. The temperature of the wall surface is measured with thermocouple and the Nusselt number is calculated from the temperature data. The improved effectiveness of cooling characteristics is examined from this heat transfer.

Multipoint simultaneous measurement of two-dimensional velocity field using PIV is conducted. From the above two measurements, the relation between the heat transfer and the flow characteristics is clarified.

A schematic drawing of the experimental equipment is shown in Fig. 1. Of a horizontally installed coaxial double circular pipe, the inner pipe was used for injection and the outer pipe was used for annular suction. Air was used as a working fluid. From an injection blower, the injection flow was blown off into measuring zone through a discharge-control valve and an injection pipe of 3m. For this injection pipe, sufficiently long entry zone was assured, by which the velocity distribution of fully developed turbulent flow was obtained at the pipe exit edge. The impinging wall was installed perpendicularly to the jet central axis. A square flat plate with 1m × 1m was attached at the pipe exit edge. On the other hand, the suction flow was drawn in by a suction blower through a suction pipe, a chamber, a valve for controlling flow rate and a pipe of 3m for measuring flow rate. The inner diameter of the injection pipe (d_i) and the suction pipe were 47mm and 100mm respectively and the wall thickness of the injection pipe was 1.5mm. By adopting a cylindrical coordinate system, the center of the pipe exit edge was set to the origin point. The z-axis was set in the axial direction of jet center and r-axis was set in the radial direction of it.

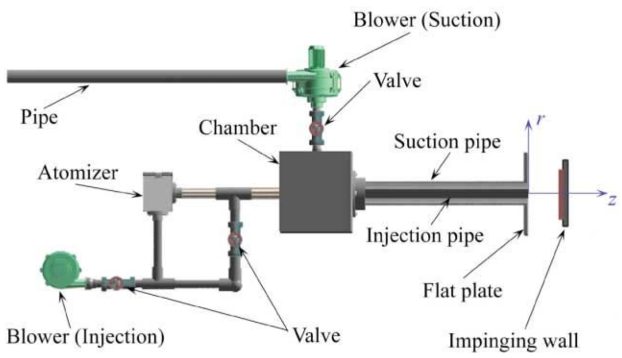


Fig. 1. A schematic of experimental apparatus.

As the impinging wall, a heat transfer plane was prepared by sticking a stainless foil with the size of 300mm × 300mm and the thickness of 0.03mm with short stripe pattern on a Bakelite board with the size of 500mm × 500mm. Experiments were carried out under the condition of uniform heat flux by heating this plane directly with AC current. K type thermocouple was bonded to a back plane of the stainless foil for measuring the wall surface temperature. In addition, jet temperature, heater current and heater voltage were measured. The Nusselt number Nu (= hd_i/λ , where h; heat transfer coefficient, λ ; thermal conductivity of surrounding fluid) was calculated. In this experiment, a suction blower was independently used. Since in actual application an injection blower can be jointly used as a suction blower, additional energy used for suction was not taken into account in the evaluation of improved quantity of cooling characteristics using this Nusselt number.

A schematic drawing of the experimental equipment for visualizing flow and the equipment for image processing is shown in Fig. 2. Talc powders (average particle diameter: 10μm) were used as tracer particles. Concentration pattern of particles was formed by incorporating them into injection flow. As a light source, double pulse Nd: YAG laser (output: 15mJ/pulse, repetition rate: 30Hz) was used. Laser light sheet (LLS), a sheet-like light source obtained by using cylindrical lens, was illuminated intermittently on measuring cross-section (r-z cross-section). As an image input apparatus, NTSC type CCD camera (frame rate: 1/30s) was used. In this frame rate, when the particle moving velocity is high, it is difficult to specify the correlation between concentration patterns at two time instants. Because of this, in the same way as in the previous reports (Sonoda et al., 1997; Sonoda et al., 1998; Fukuhara et al., 1999), the technique of obtaining images at two time instants with the short interval which is independent of frame rate, was adopted. The illumination interval of LLS was changed to one tenth of the previous value due to ten times higher velocity of injection flow than one in the previous condition. The present interval was set to 64μsec. This LLS was continuously illuminated in each frame and output images of CCD camera were transferred to CRV (optical disk) and recorded. Velocity vector was calculated by applying the concentration correlation method to two images obtained at two time instants. In order to obtain time averaging quantity, sampling number was set to 1,000 frames. For a series of analysis by PIV in this experiment, measurement system of velocity by image processing "Current PIV Ver. 1.80 by KANOMAX Japan Inc." was used. On the measurement accuracy of PIV, sufficiently high accuracy is obtained in the present study, as the discussion is given in the previous reports (Sonoda et al., 1997; Sonoda et al., 1998).

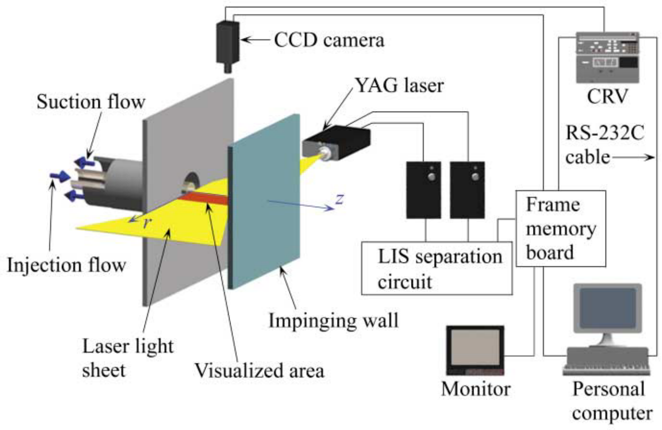


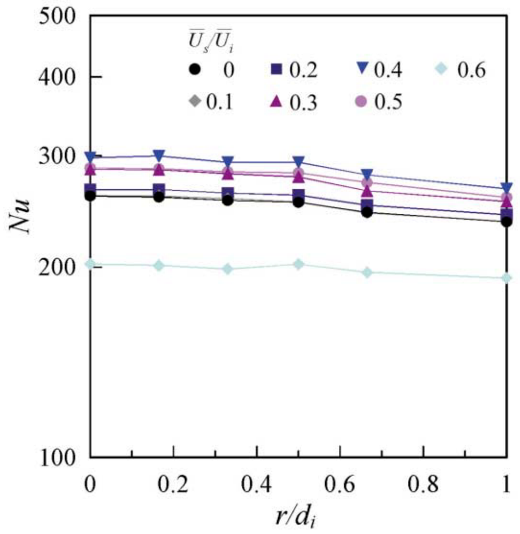
Fig. 2. A schematic of visualization and image processing system.

The distance z_w between the pipe exit edge and the impinging wall (referred to as 'wall distance' hereafter) was changed under 13 conditions in the range of $1 \leqq z_w/d_i \leqq 20$ and the position r in the radial direction was changed under 6 conditions in the range of $0 \leqq r/d_i \leqq 1$. Under the constant injection velocity $\overline{U}_i$ of 20m/s, the ratio $\overline{U}_s/\overline{U}_i$ ($\overline{U}_s$: suction velocity) was changed under 11 conditions from 0 to 1 with small steps of 0.1. These velocities are expressed in terms of average value of the cross-section of pipe path. To raise the accuracy of wall surface temperature measurement, the velocity of injection was increased from 2m/s used in the previous reports (Nozaki et al., 1996; Sonoda et al., 1997; Sonoda et al. 1998; Fukuhara et al., 1999) to 20m/s. In addition, in the experiment using PIV, conditions of the wall distance and velocity ratio are set based on the result of heat transfer characteristics. In order to catch the flow field of the impinging wall side, and to maintain the accuracy of space resolution, the measuring zone in the axial direction is set to a certain section which corresponds to $z/d_i = 2.5$ from the impinging wall surface. It is self-evident that the flow, which runs very near the wall surface in this zone, is important from the viewpoint of clarifying relations between the heat transfer characteristics and the flow characteristics. However, in this experiment, laser light sheet is reflected on the impinging wall surface and this causes many error vectors in analysis. Due to this reason, the results of this zone are not reliable. Therefore, in this report, using flow data in the zone at a little distant from the impinging wall surface, relations between the flow characteristics and the heat transfer characteristics on the heated wall surface are compared and discussed.

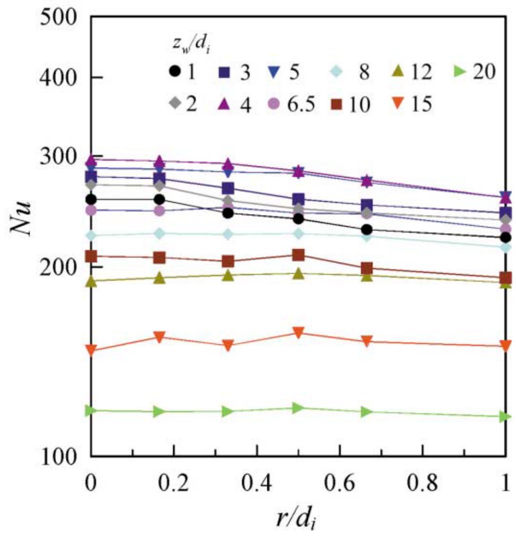
3.1 Heat Transfer Characteristics

The distribution of the Nusselt number in the radial direction on the wall surface with heat transfer is examined. As representative results, for the cases of the wall distance of $z_w/d_i = 5$ and velocity ratio of $\overline{U}_s/\overline{U}_i = 0.5$ (volume ratio: 1.7), respective results are shown in Fig. 3(a) and Fig. 3(b). In the figures, a normalized position r/d_i in the radial direction is expressed on the abscissa and the Nusselt number Nu is expressed on the ordinate. Magnitude correlation of the Nusselt number under each condition is described later. Here, only the change of the Nusselt number in the radial direction is discussed. As can be seen in Fig. 3(a), in the case of any velocity ratio, the Nusselt number gradually decreases when the position in the radial direction is more distant from the pipe center. As shown in Fig. 3(b), in the each condition of $1 \leqq z_w/d_i \leqq 5$, almost similar trend with the above-mentioned result is observed. Therefore, as a representative point in the radial direction, the stagnation point ($r/d_i = 0$) is selected and each condition is compared using the Nusselt number at the stagnation point. In the condition of $z_w/d_i > 5$, the gradient of the Nusselt number in the radial direction becomes a little small, but there is no problem in the scope of later discussions.

The change of the Nusselt number in the axial direction of the impinging wall is examined using the Nusselt



(a) $z_w/d_i = 5$



(b) $(\bar{U}_s/\bar{U}_i = 0.5)$

Fig. 3. Radial distributions of Nusselt Number.

number at the stagnation point. The results are shown in Fig. 4 for each velocity ratio. From this figure, the improved effectiveness of cooling characteristics on the heated wall surface accompanying suction flow is clarified. On the abscissa in the figure, the normalized wall distance z_w/d_i is expressed and on the ordinate, the Nusselt number Nu_0 at the stagnation point is expressed. A dotted line means a line of the reference value (Nakatogawa, 1970) of Nusselt number at the stagnation point which is applied to a circular nozzle. The effect of wall distance is firstly examined for the case without annular suction flow ($\bar{U}_s/\bar{U}_i = 0$). In the range of $1 \leqq z_w/d_i \leqq 4$, the Nusselt number at the stagnation point changes little. When the impinging wall is installed at a downstream position from the vicinity of $z_w/d_i = 4$, it starts to increase and becomes the maximum at the position of nearby $z_w/d_i = 8$. At a downstream position from $z_w/d_i = 8$, it decreases as a reversal trend. Compared with the reference value, these experimental values are shown to be slightly higher at each position in the axial direction. Several factors such as the omission of compensation of heat loss in the Bakelite board and so on can be considered as the cause of this difference. However, since the present study discusses the effects of suction flow, it is considered capable to use the present Nusselt number for the discussion.

Thus, the effect of wall distance is examined for the case of accompanying an annular suction flow. As an example, the case of velocity ratio of $\bar{U}_s/\bar{U}_i = 0.5$ is considered. As can be seen in Fig. 4, the more distantly the impinging wall moves towards downstream from $z_w/d_i = 1$, the more the Nusselt number at the stagnation point increases and at the position of nearby $z_w/d_i = 4$, it becomes the maximum. When the impinging wall is installed at a more distant position toward downstream, it decreases. The qualitative trend where the Nusselt number at the stagnation point increases at first and then decreases, resembles to that in the case without suction flow. In the following, the case of accompanying suction flow is compared with the case without suction flow. From the comparison between the case of $\bar{U}_s/\bar{U}_i = 0.5$ and the case of $\bar{U}_s/\bar{U}_i = 0$, in the range of $1 \leqq z_w/d_i \leqq 5$, the Nusselt number at the stagnation point with suction flow becomes higher than one without suction flow. On the contrary, it becomes lower in the range of $z_w/d_i > 5$. As the result of examining all conditions of velocity ratio in the range of $1 \leqq z_w/d_i < 8$, the Nusselt number at the stagnation point with suction flow becomes higher than one without suction flow. Accordingly, it can be concluded that the improvement of cooling characteristics on the heated wall surface is obtained by accompanying suction flow. In practical meaning, the effectiveness of accompanying suction flow has been confirmed especially in the case of restricted wall distance due to a tight space. Moreover, it is also remarked that on each velocity ratio, the maximum value of the Nusselt number at the stagnation point is the same order value with one in the case without suction flow. As suction velocity increases, the wall distance where the maximum Nusselt number was obtained, becomes nearer to the pipe exit edge. In other words, in the case of fixing the impinging wall at an arbitrary position, the optimum velocity ratio can be obtained where the Nusselt number at the stagnation point becomes the maximum.

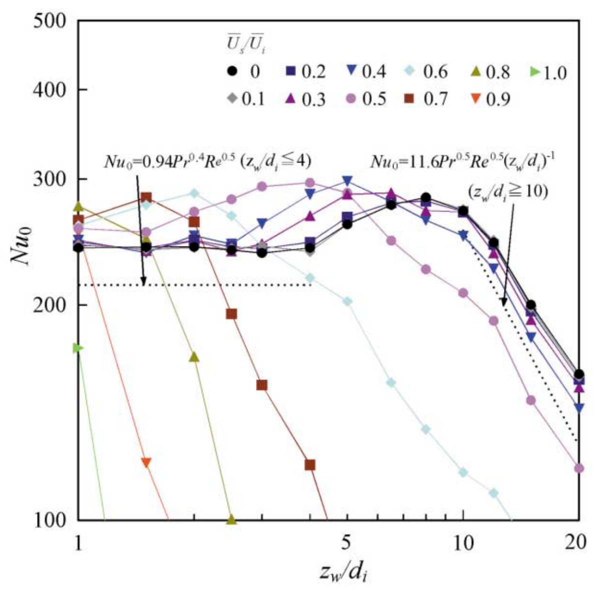


Fig. 4. Axial distributions of Nusselt Number (r/d_i = 0).

3.2 Flow Characteristics

In order to clarify the relation between the flow characteristics and the heat transfer characteristics on such a wall surface with heat transfer, the flow characteristics of impinging jet are examined using PIV. The effect of wall distance is firstly examined in the case without an annular suction flow. Component $\widetilde{U}_z$ in the axial direction of time averaging velocity and synthesized component S' (= $\sqrt{u_z^2 + u_r^2}$) from a component u_z in the axial direction and a component u_r in the radial direction of fluctuating velocity are normalized by $\overline{U}_i$. For the case of z_w/d_i = 2, 5 and 8, contour maps of them are shown in Figs. 5(a)-(c). As shown in the previous chapter, the measuring zone in the axial direction is set respectively in the zone of 0.25 ≦ z/d_i ≦ 1.75, 2.5 ≦ z/d_i ≦ 4.75, and 5.5 ≦ z/d_i ≦ 7.75. Considering the axial symmetry of flow, the measuring zone in the radial direction is set in 0 ≦ r/d_i ≦ 1.5 of only one side zone. The zone in the vicinity of the pipe exit edge (0 < z/d_i < 0.25) is not displayed due to the similar reasons of removing the zone in the vicinity of the impinging wall. As shown in Fig. 5(a) for the case of z_w/d_i = 2, the zone with steep velocity gradient and high fluctuating velocity, which shows a shear layer, exists at a position in the radial direction of near r/d_i = 0.5. Compared with one in the case of free jet without the impinging wall (Sonoda et al., 1998; Fukuhara et al., 1999), no remarkable difference between these distributions is seen except one in the vicinity of the impinging wall. For the case of z_w/d_i = 5 (Fig. 5(b)), the velocity gradient at a position in the radial direction of near r/d_i = 0.5 becomes more gentle and the zone with high value of fluctuating velocity extends wider than in the above-mentioned case. When the impinging wall is installed at a more distant position toward downstream (z_w/d_i = 8), the trend can be seen to become stronger. In this case, the mean velocity decreases more or less, but the zone with high value of fluctuating velocity extends in the radial direction from the position nearby r/d_i = 0.5. Therefore, it is considered that the increase of fluctuating velocity in impinging jet contributes to the increase of the Nusselt number of the wall surface with heat transfer.

The case of installing the impinging wall at a more distant position toward downstream than z_w/d_i = 8 is considered. As an example, the result at z_w/d_i = 15 is shown in Fig. 6. As shown in Fig. 4, this is a condition where the Nusselt number decreases more than one at z_w/d_i = 8. The velocity gradient in the vicinity of r/d_i = 0.5 becomes more gentle than one at upstream positions. The zone with high value of fluctuating velocity occupies the whole measuring zone. Compared with one at the position of z_w/d_i = 8, the maximum value of fluctuating velocity is in the same order, while the mean velocity considerably decreases. Therefore, it is considered that even if the zone with high value of fluctuating velocity exists, the remarkable decrease of mean velocity leads to the decrease of the Nusselt number.

Next, the effect of wall distance in the case of accompanying an annular suction flow is examined. As an example, the result of constant velocity ratio of $\overline{U}_s/\overline{U}_i$ = 0.5 is shown in Figs. 7(a)-(c). The wall distance is the same with one in Figs. 5(a)-(c). Figure 4, Fig. 7(a) and Fig. 7(b) are the cases where the Nusselt number becomes higher than one without suction flow, while in Fig. 7(c), it becomes lower. In Fig. 7(a), the velocity gradient at the

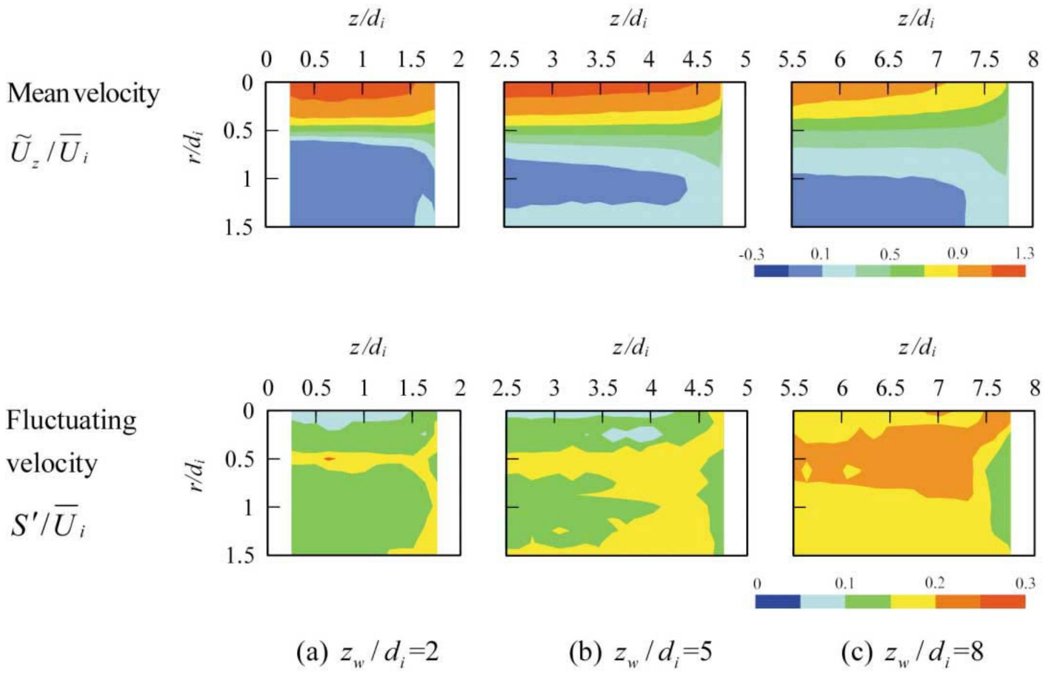


Fig. 5. Contour maps of mean velocity and fluctuating velocity ($\overline{U}_s/\overline{U}_i$ = 0).

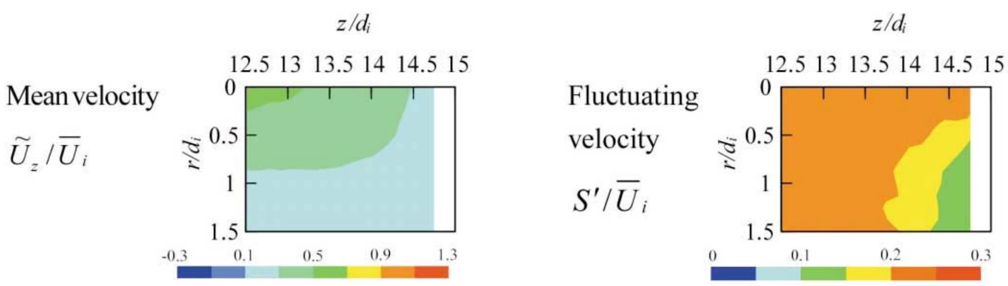


Fig. 6. Contour maps of mean velocity and fluctuating velocity ($\overline{U}_s/\overline{U}_i$ = 0, z_w/d_i = 15).

position nearby r/d_i = 0.5 becomes a little more gentle than the distribution shown in Fig. 5(a) and the zone with high value of fluctuating velocity extends more than one in Fig. 5(a). In Fig. 7(b), this trend can be seen to become stronger. Therefore, for the case of z_w/d_i = 2 and 5, it is considered that the increase of fluctuating velocity contributes to the increase of the Nusselt number, with no remarkable decrease of mean velocity. On the other hand, in Fig. 7(c) for the case of z_w/d_i = 8, the velocity gradient becomes more gentle than the distribution shown in Fig. 5(c) and the mean velocity considerably decreases. It is considered that this causes the decrease of the Nusselt number as observed in the phenomenon shown in Fig. 6.

The case of increasing suction velocity is considered. As an example, for the case of velocity ratio of $\overline{U}_s/\overline{U}_i$ = 0.6 and the wall distance of z_w/d_i = 2, the result is shown in Fig. 8. As shown in Fig. 4, this is a condition where the Nusselt number increases more than in the case of velocity ratio of 0.5. By increasing suction velocity, the velocity gradient becomes a little more gentle than the distribution shown in Fig. 7(a) and the zone with high value of fluctuating velocity extends much more. It is considered that the increase of fluctuating velocity contributes to the increase of the Nusselt number with no remarkable decrease of mean velocity.

From the above results, it is found that these flow characteristics are closely associated with the heat transfer characteristics on the several conditions such as the wall distance and velocity ratio. As a future subject, the realization of PIV measurements with high accuracy is desirable for the survey of the vicinity of the impinging wall. By this realization, it will be much more clearly elucidated that the Nusselt number has a close relation with the increase of fluctuating velocity and the decrease of mean velocity.

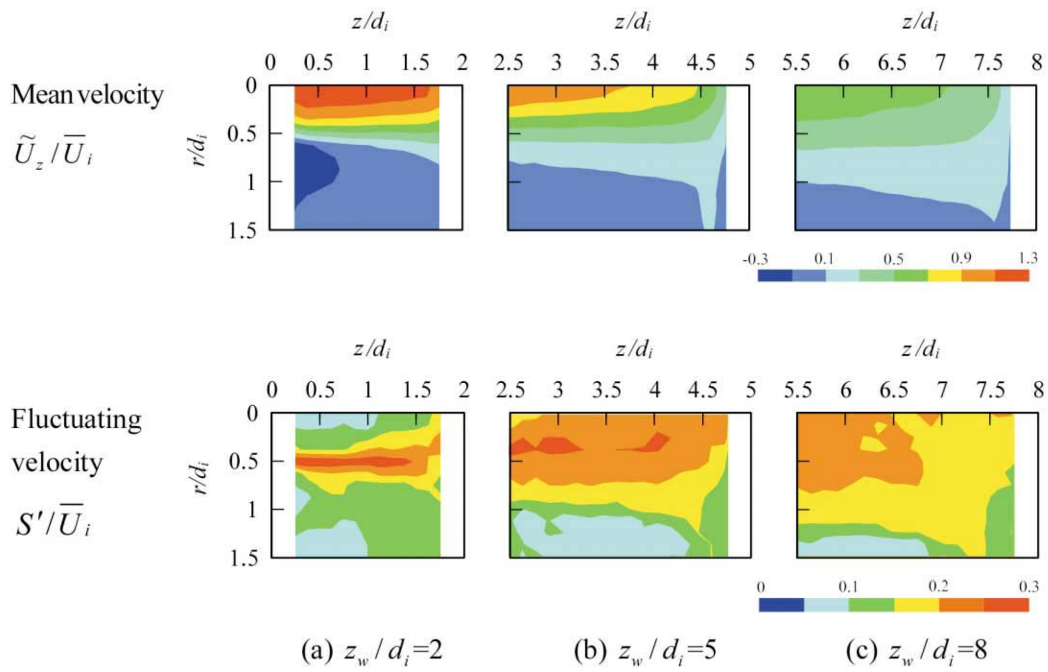


Fig. 7. Contour maps of mean velocity and fluctuating velocity ($\overline{U}_s/\overline{U}_i$ = 0.5).

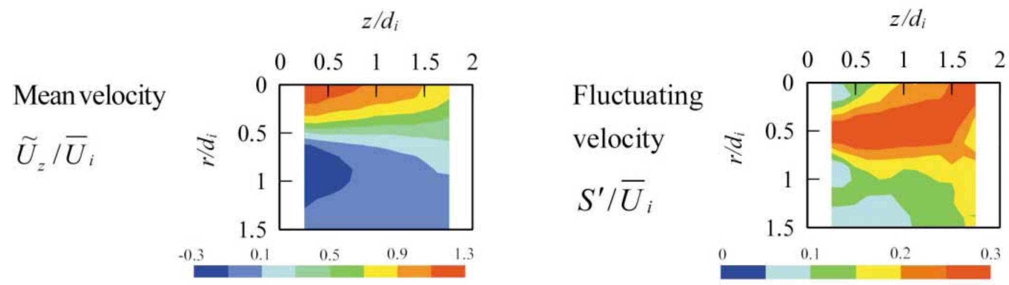


Fig. 8. Contour maps of mean velocity and fluctuating velocity ($\overline{U}_s/\overline{U}_i$ = 0.6, z_w/d_i = 2).

Experiments were conducted on the effects of the wall distance and velocity ratio on the flow and heat transfer characteristics of a circular impinging jet accompanying an annular suction flow. The following results were obtained.

Under the condition of the wall distance within eight times of the injection pipe diameter from the near pipe exit edge, the higher Nusselt number was obtained in the case of accompanying suction flow than that without suction flow. In other words, in the case of restricted wall distance due to a practically tight space, the effectiveness of accompanying suction flow was confirmed.

As suction velocity increased, the wall distance where the maximum Nusselt number was obtained, became nearer to the pipe exit edge. It was found that in the case of examining the effect of velocity ratio while installing the impinging wall at an arbitrary fixed position, there existed the optimum velocity ratio where the Nusselt number became the maximum.

When the Nusselt number increased, the fluctuating velocity of impinging jet increased. On the other hand, when the Nusselt number decreased, the mean velocity considerably decreased. It was found that the heat transfer characteristics on the wall surface were closely associated with the flow characteristics of impinging jet.

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