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Experiments on the Flow in and around Jets

Directed Normal to a Cross Flow*

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The present work is done to explain the characteristics of a flow field affected by an interference between a nonuniform cross flow and unheated jets issued from a single circular orifice or a single row of equally spaced circular orifices on a flat floor. Data from measurements of the total pressure and the flow direction and those from flow visualization experiments are presented for a low velocity ratio of 2. In the jet region downstream of a point, at which the minimum jet spread appears in the plane of symmetry of jets, there are large differences between characteristics of a single jet and a component jet of a multiple jet. The floor boundary layer downstream of jet orifices is affected greatly by a circulating flow, which is a vortexlike flow induced within the cross flow. The origin of the circulating flow also is discussed. The mutual interference between component jets of the multiple jet has a great influence on their spreads.

1. Introduction

Mechanical designers encounter often a flow field, which includes a single or a multiple jet injected into a cross flow at an angle to it, as in a flow field accompanied with a film cooling applied to blades and flame tubes for gas-turbine engines and in one appearing during a transition flight of VTOL aircraft. As is well known, the nature of these flow fields is very complicated⁽¹⁾. This situation makes an analytical investigation of a deflected jet in a cross flow difficult. Many experimental investigations, therefore, have been made hitherto⁽²⁾⁻⁽¹⁶⁾, many of which have dealt with a single jet in a uniform cross flow. These investigations present experimental results to determine such characteristics as the trajectory⁽²⁾⁻⁽⁴⁾,⁽⁷⁾⁻⁽⁹⁾ and the spread⁽⁷⁾ of jets, the velocity magnitude⁽³⁾,⁽⁷⁾,⁽⁸⁾ and direction⁽²⁾,⁽⁷⁾ or the total-pressure distribution⁽²⁾ in and around jets, the penetration of jets into a cross flow⁽¹⁰⁾ as a function of the velocity ratio or initial jet angle. Chassaing et al.⁽⁷⁾ also give experimental results to determine the jet axis and the velocity profile in the plane of symmetry of deflected coaxial jets. Margason⁽⁹⁾ determines a jet centre line by photographing a single air jet plume visualized by steam mixed and compares his data with others. The foregoing investigations are made without interference of a boundary

layer on the channel floor with a jet orifice arranged. However, Stoy and Ben-Haim⁽¹²⁾ investigate experimentally and analytically the effects of cross flow velocity profiles on the deflection and impingement of jets in a confined cross-flow. They do not discuss the effects of varying the approach velocity profile on the flow field downstream of a jet orifice.

Kamotani and Greber⁽⁵⁾, Fearn and Weston⁽⁶⁾ and Moussa et al.⁽¹³⁾ investigate a vortexlike flow associated with a single jet in a cross flow. They do not describe the effects of a floor boundary layer on the vortexlike flow. Kamotani and Greber⁽¹⁴⁾ report on interaction patterns of two or three round jets in a semi-infinite cross flow. At present, however, there is only a small amount of information on differences of characteristics between a single jet and each component jet of a multiple jet.

In the film cooling, for example, of gas-turbine blades it is very important to understand the nature of the flow along a blade surface downstream of jet orifices as well as a mutual interference of adjacent jets. However, the heat transfer to the blade surface has been discussed without a good understanding of aerodynamic phenomena in the flow field downstream of the jet orifices, because of complicated aspects in the flow field.

The present investigation, which is concerned with a single and multiple unheated jets at a low velocity ratio, can be regarded basically as extension of the works by Jordinson⁽²⁾, Kamotani and Greber⁽⁵⁾ and Fearn and Weston⁽⁶⁾ in the experiment, but it focuses attention on the interferences among such factors as the floor boundary layer flow, the jet flow and the circulating flow induced by the jets and on the mutual interference of ad-

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jacent jets. The interferences are discussed on the basis of detailed measurements of the total pressure and flow direction in the flow field near the jet orifices.

2. Experimental setup and procedure

Figure 1 shows the arrangement of the working section and the air circuit for jets, together with one of probes used. This figure defines for future convenience the coordinate systems based on the jet trajectory and the wind-tunnel coordinate systems. The symbols x, y, z are the longitudinal, lateral and vertical cartesian coordinates with the origin at the centre of the No.5 jet orifice (see Fig.1). The ξ -axis is the maximum total pressure line in the plane of symmetry of the deflected jet. The η -axis is defined by the locus of the maximum total pressure along lines of constant y on a plane perpendicular to the ξ -axis. The ζ -axis is perpendicular to the ξ - and η -axes.

Nine jet orifices (diameter $d=8$ mm ,

Fig.1 Sketch of working section, showing notations

Fig.2 Velocity profiles of boundary layer on channel floor with jet orifices arranged ($P_{t0}=15$ mmAq, $u_j=0$, $x/d=-5$, $y/d=0$)

pitch= $3d$) have each a centre on the y -axis and are arranged symmetrically with respect to the x -axis. A single jet is obtained from the No.5 orifice after blocking the others with adhesive "Cellotape" 0.06 mm thick. A bypass around the upstream end of the working section is available for the floor boundary layer control. The flow rate of a jet is kept constant by adjusting the pressure difference between upstream and downstream of the orifice plate. Both the jet and cross flows are at a room temperature.

Figure 2 shows velocity profiles of the floor boundary layer, whose thickness $\delta=[z]_{u=0.99U_\infty}$ is about 6 mm, where U_∞ is the cross flow velocity and u the velocity within the floor boundary layer. The velocity U_∞ and the total pressure of the cross flow P_{t0} at $x/d=-5$ are 14.8 m/s and 15 mmAq, respectively. They are kept constant throughout the experiment.

Figure 3 shows velocity profiles at jet exits. The mean jet velocity $u_{j\text{ mean}} = (\int_A u_j \cdot dA)/A$ is 29 m/s at the exit, where u_j is the local jet velocity and A the area of the jet exit. The velocity ratio $m=u_{j\text{ mean}}/U_\infty$ is 1.96. The velocities $u_{j\text{ mean}}$ and U_∞ are unchanged throughout the experiment. The velocity profiles from the Nos.1 and 9 orifices deviate from the mean velocity profile shown by a dotted line owing to the effect of side walls of the plenum chamber II (cf. Fig.1) on a flow through it. However, the

Fig.3 Jet velocity profiles at jet exit ($U_\infty=0$, $z/d=0.125$; Letter symbols, No.1, 2, ..., 9, indicate numbers of jet orifices.)

author's preliminary experiment shows that when there are five or more jets, the trajectory of maximum total pressure, i.e. the ξ -axis, belonging to the jet from the No.5 orifice does not depend on the number of jets⁽¹⁶⁾. The foregoing deviation, therefore, offers no problem as far as the No.5 jet is concerned. Measurements of the total pressure and flow direction are made on eleven cross planes perpendicular to the x -axis and carried out mainly by use of a 5-hole probe with the nose of a right pyramid, whose base has sides 2.3 mm long. Near the channel floor ($z < 12$ mm), however, yaw and pitch angles of velocity vectors are measured with a 5-hole pyramid probe and a 3-hole cylindrical probe, 3 mm in diameter, respectively, because the 5-hole pyramid probe, which is operated through a linkwork, cannot be operated structurally near the channel floor. The 3-hole cylindrical probe applies to the measurement in the range of $5 \leq z$ (mm) ≤ 12 in order to avoid an interference between itself and the channel floor. Local total pressures measured are given in the form of total pressure coefficient $C_p = (P_t - P_{t0}) / (P_{tj} - P_{t0})$ as in Ref.(2), where P_t is the local total pressure, and P_{tj} the total pressure at the centre of the jet exit. The jet flow and the cross flow are in the regions of $C_p > 0$ and $C_p \leq 0$, respectively. The jet

boundary is defined as the contour of $C_p = 0$ in the present paper and is determined graphically using data of C_p against z . The jet boundary in the plane of symmetry of the jet is determined clearly and easily below the ξ -axis, but with some difficulty above the ξ -axis, because C_p varies asymptotically from a value of the jet to one of the cross flow. In the present paper, therefore, the upper jet boundary, which is above the ξ -axis, is defined as the contour of $|C_p| = 0.005$, which is referred to as that of $C_p = 0$ hereafter.

3. Results and discussions

3.1 Contour of constant total pressures in cross planes

Contours of constant C_p in the flow field affected by the single jet and the multiple jet are shown in Fig.4 and in Fig.5, respectively. They depict the contours on the plane perpendicular to the x -axis at positions upstream and downstream of the jet orifice. Though there is still a small jet region of $C_p > 0$ above the contour of $C_p = 0$ in Fig.5(F), this region is not depicted. In Fig.4(a) at a position upstream of the jet orifice, it is found that a part of the contours near the jet orifice shifts in the positive z direction. This indicates a thickening of the floor

Fig.4 Contours of C_p in flow field affected by single jet

boundary layer upstream of the jet orifice due to the blockage effect of the jet. Jordinson⁽²⁾ reports that there are small regions of a negative C_p adjacent to the upstream side of the jet near the floor in cases of $m=4, 6$ and 8 . However, such a region is not found in the present experiment. It seems that the generation of a negative C_p in this region depends on the thickness of the floor boundary layer and the magnitude of m , but the cause is not clear at present. Figure 4(b) to 4(f) show contours downstream of the jet orifice. The jet boundary (i.e. the contour of $C_p=0$) in the cross plane is deformed into a kidney shape after the injection of a jet and then the jet spread is greater in the y direction than in the z direction⁽¹⁾⁽²⁾⁽⁵⁾. Figure 4(d) to 4(f) indicate an effect of the jet on the floor boundary layer as follows. A circulating flow, as shown in detail in Fig.15, causes a surrounding fluid to flow into a wake region of $C_p < 0$ below the jet. This leads to an expansion of the floor boundary layer into the wake region of $C_p < 0$ below the jet and promotes the reproduction of the floor boundary layer below the jet. The other action of the circulating flow is to make the floor boundary layer thin in a small flow region around $y/d=2$, as depicted clearly in Fig.4(b) to 4(e). Now we find differences between the contours in the

flow field affected by the single and multiple jets by comparing Fig.4 with Fig.5. First, the contours at $x/d=-0.625$ in the flow field of the multiple jet shift in the positive z direction not only around the jet orifices, but also in every place between the jet orifices. This means that the multiple jet brings about a greater blockage of the cross flow than that of the single jet. Second, the reproduction of the floor boundary layer below the jet is markedly slower in the multiple jet than in the single one. For example, a floor boundary layer is not found even at $x/d=12.5$ in the multiple jet, as shown in Fig.5(f), while one is found explicitly at $x/d=3.125$ in the single jet, as shown in Fig.4(d). Therefore, it is known easily that the flow field near the floor may be characterized as a highly turbulent region with a large velocity fluctuation in case of the multiple jet. Thus the following is concluded about the flow region near the floor. The flow field affected by the multiple jet cannot be constructed through a superposition of that with the single jet, except in a small region of the reverse flow downstream of the jet orifice as shown in Fig.14.

Now we denote with the notation $(C_p)_{max}$ the maximum value of C_p along a line of constant y in a cross plane perpendicular to the x -axis. A comparison be-

Fig.5 Contours of C_p in flow field affected by multiple jet

tween the contours in Figs.4 and 5 indicates that the ordinate z/d giving $(C_p)_{max}$ is slightly greater in the single jet than in the multiple one in the plane of symmetry of the jet, but is almost the same in both types of the jet in the region of $y/d \geq 1.5$. Figures 6(a) and 6(b) show flow patterns around the jet orifice from the oil-film flow visualization experiments, which are made by applying a mixture of lamp-black and diesel oil. There is a close resemblance between the flow patterns due to the single and multiple jets near, especially downstream of, the jet orifice. A flow region resulting in a Λ -shape flow pattern corresponds to a flow passage formed by the air entrained strongly into the jet⁽¹⁵⁾. Thus it can be said that the mutual interference between adjacent jets of the multiple jet will have scarcely an effect on the reverse flow region downstream of the jet orifice, provided a pitch of the jet orifices is not very small, because of the very strong entrainment of the cross flow fluid into the jet in the vicinity of the jet orifice.

3.2 Contour of constant total pressures in and near the plane of symmetry of jets

Contours in the plane of symmetry of the single jet are shown in Fig.7, which is deduced from the data in Fig.4. Figure 8, which is deduced from the data in Fig.7

(a) Single jet

(b) Multiple jet

Fig.6 Oil flow patterns on channel floor ($P_{t0}=15$ mmAq, $P_{tj}=66.9$ mmAq, $U_{\infty}=14.8$ m/s, $u_{j\text{ mean}}=29$ m/s)

shows variations of jet spreads and $(C_p)_{max}$ against ξ and x/d in the plane of symmetry of the jet. Notations in Fig.8 are defined as follows: first suffixes $C_p=0$ and $(C_p)_{max}/2$ added to ζ indicate that ζ is an ordinate of the contours of $C_p=0$ and an ordinate of the contours of the half $(C_p)_{max}$, respectively; second suffixes u and l added to ζ indicate an upper and a lower region with respect to the ξ -axis, respectively. Figure 7 indicates the following. First, it is found that the jet centre line (i.e. the ξ -axis) determined as a locus of $(C_p)_{max}$ is close to that obtained by Keffer and Baines⁽³⁾ as a locus of the maximum velocity measured with a hot-wire anemometer. This will lead to calculation of velocity distributions with a good approximation to those in the whole flow field, when static pressures in the neighbourhood of the floor and a mean static pressure in the cross flow are given. This consideration comes from the fact that there is only a small difference between the static pressures in the regions of the jet and the cross flow, except in the region near the floor, especially near the jet orifice, where there is a large

Fig.7 Contours of C_p , and locus of $(C_p)_{max}$ as jet centre line, in plane of symmetry of single jet

Fig.8 Jet spreads, and decay of $(C_p)_{max}$, in plane of symmetry of single jet

gradient of the static pressure in every direction⁽¹⁷⁾. Second, a distance in the ζ direction between a contour of a given C_p and the ξ -axis is greater in the positive ζ region than in the negative ζ one. This suggests that a mixing between the jet and the cross flow is greater in the positive ζ region than in the negative ζ one. In addition to this a jet width, which is defined as a distance in the ζ direction between the two contours of $C_p=0$ on both sides of the ξ -axis, becomes minimum at ξ corresponding to $x/d \approx 0.6$. Referring to Fig.8, we find that the foregoing location of the minimum jet width is interesting as one which divides characteristics of the jet along the ξ -axis into two distinct parts. This is described from the fact that the maximum total-pressure coefficient $(C_p)_{max}$ is almost unchanged at $0 < x/d < 0.6$, but decreases rapidly at $x/d > 0.6$ as ξ increases. This means that characteristics of the jet are governed by the potential core, whose portion of the jet does not take part in the mixing with the cross flow, in the range of $0 < x/d < 0.6$, and by a gradual increase in the mixing between the jet and the cross flow in the range of $x/d > 0.6$. We can check easily by Fig.5 in Ref.

Fig.9 Contours of C_p , and locus of $(C_p)_{max}$ as jet centre line, in plane of symmetry of multiple jet

Fig.10 Jet spreads, and decay of $(C_p)_{max}$, in plane of symmetry of multiple jet

(12) whether the range of $0 < x/d < 0.6$ corresponds to the potential core or not. In addition to this there is the following large difference between the jet spread at $0 < x/d < 0.6$ and that at $x/d > 0.6$. The distance along the ζ -axis from the ξ -axis to the upper jet boundary $\zeta_{C_p=0,u}$ has a tendency to vary linearly in the range of $0.6 < x/d < 8$ in the present experiment. The slope of $\zeta_{C_p=0,u}$ is smaller at $x/d < 0.6$ than at

$x/d > 0.6$ and this is clearer in the multiple jet (cf. Fig.10) than in the single jet. On the other hand, the distance in the ζ direction from the ξ -axis to the lower jet boundary $\zeta_{C_p=0,l}$ decreases rapidly toward

the location $x/d \approx 0.6$ and then remains unchanged after a gradual increase at $x/d > 0.6$. However, variations of the jet spreads obtained as a locus of the half $(C_p)_{max}$ point, namely $\zeta_{(C_p)_{max}/2,u}$ and $\zeta_{(C_p)_{max}/2,l}$, against ξ are similar to that of $\zeta_{C_p=0,l}$ against ξ .

Figure 9 shows some contours of C_p in the plane of symmetry of the central component jet of the multiple jet. A comparison between the maximum total-pressure lines (i.e. the ξ -axis) in Figs.7 and 9 indicates a better penetration of the single jet into the cross flow. According to Kamotani and Greber⁽¹⁴⁾, who investigate the effect of an opposite channel wall on jet trajectories as a function of the channel height and the velocity ratio, we can make sure that there is scarcely an aerodynamic effect of the opposite channel wall on trajectories of the jet in the present experiment. In addition we find that the jet spread in the ζ direction is greater in the multiple jet than in the single jet at $x/d > 0.6$, i.e. in the region downstream of the minimum jet width. This will be discussed later in connection with Fig.10.

Figure 10 shows characteristics in the plane of symmetry of the central component jet of the multiple jet. The increase in $\zeta_{C_p=0,u}$ with an increasing ξ is

steeper than that in the single jet (cf. Fig.8). On the other hand, $\zeta_{C_p=0,l}$ decreases rapidly with an increasing ξ in the range of $x/d < 0.6$, as in case of the single jet. However, $\zeta_{C_p=0,l}$ has a tendency to increase gradually in the range of $x/d > 0.6$ as ξ increases. Variations of $\zeta_{(C_p)_{max}/2,u}$ and $\zeta_{(C_p)_{max}/2,l}$ against ξ are similar to that of $\zeta_{C_p=0,l}$. The variation of $(C_p)_{max}$ against ξ is the same as that in the single jet in the range of $x/d < 3.5$. However, the decrease in $(C_p)_{max}$ with an increasing ξ becomes slower in the multiple jet than in the single jet in the

range of $x/d > 3.5$. The difference between the behaviours of $(C_p)_{max}$ in the single and multiple jets is attributed to the fact that the spread or mixing of the single jet progresses into the cross flow in both of the y and z directions, but that of the multiple jet does mainly in the z direction owing to a blockage effect of two jets adjacent to a jet under consideration.

Figure 11 shows a lateral spread of the single jet B , which is defined as an arc distance from the ξ -axis to a contour of a given C_p along a curve of the maximum total-pressure coefficient $(C_p)_{max}$ on the cross plane perpendicular to the x -axis in Figs. 4 and 5. The spread B is close to a lateral jet spread measured along the n -axis. The spread B increases steeply to a large value at $x/d=0.6$ (i.e. at the position of the minimum jet spread in the plane of symmetry of the jet) as ξ increases, and then a rate of the increase in B against ξ diminishes rapidly at $x/d > 0.6$. This suggests that there is a strong mixing, which progresses in the lateral direction between the jet and the cross flow at $x/d > 0.6$, as discussed already about the jet spread in the plane of symmetry of the jet. Referring additionally to $\zeta_{C_p=0,u}$ and

$\zeta_{C_p=0,z}$ in Fig. 8 or 10, we find that when

Fig. 11 Lateral spreads of single jet

Fig. 12 Lateral spreads of multiple jet

ξ increases, the jet spread decreasing in the ζ direction is accompanied by that increasing in the lateral direction. This situation is similar to a large deformation of the cross section of a long circular pipe applied with a bending moment.

Figure 12 shows lateral spreads of the central component jet B in case of the multiple jet. A comparison between Figs. 11 and 12 indicates the following. The spread B reaching the contour of $C_p=0.1$ or 0.2 , which lies in an inner portion of the jet region, is the same in the single and multiple jets. However, B reaching the contour of $C_p=0.025$ or 0.05 , which lies in an outer portion of the jet region, is larger in the multiple jet than in the single jet at $x/d > 0.6$. This behaviour of B is explained by the fact that with the multiple jet a component jet under consideration is prevented by others adjacent to it from mixing with the cross flow at a low total pressure. This leads to a larger value of B reaching the contour of $C_p=0.025$ or 0.05 at $x/d > 0.6$ in case of the multiple jet in comparison with the single jet.

Now in the succeeding Figs. 13, 15 and 16, flow directions only are indicated by arrows of the same length irrespective of the velocity magnitude.

3.3 Flow direction on a plane parallel to the channel floor

It is shown in Fig. 6 that the boundary layer along the floor flows steeply into the predominant negative pressure region downstream of the jet orifice at $0.5 < x/d < 3$. According to Fig. 13, however, there is no longer any steep variation of flow directions in a horizontal plane at $z/d=1$, which is outside of a region of the reverse flow described later in Section 3.4. This indicates that the predominant negative pressure rapidly decays with an increasing z , and that the floor boundary layer is a skewed one around the jet, especially around the single-jet orifice. The flow of jet regions enclosed with a chain line in Fig. 13 is accompanied by the y component of the velocity, which brings about a jet spread. Figure 13 denotes also a particular flow pattern downstream of the region of the reverse flow. Namely, there is a sudden change of the flow direction at $|y/d|=0.4$ in the multiple jet, and at

Fig. 13 Flow directions on plane parallel to channel floor

$|y/d| \approx 0.6$ in the single jet. This change can be explained as a superposition of two kinds of flows :

(1) the wake flow, which is brought about by an obstacle of the jet placed in the cross flow

and

(2) the circulating flow, which is induced secondarily by the jet, as shown in Figs.15 and 16.

The y velocity component of the circulating flow near the floor is opposite in direction to the y velocity component of the wake flow. Thus, these flows meet at $|y/d| \approx 0.4$ or 0.6 and the flow pattern in Fig.13 is brought about.

3.4 Flow direction in the plane of symmetry of jets

There is a region of the reverse flow

Fig.14 Oil flow pattern in plane of symmetry of central component jet of multiple jet ($P_{t0} \approx 15$ mmAq, $P_{tj} = 66.9$ mmAq, $U_\infty = 14.8$ m/s, $u_{j \text{ mean}} = 29$ m/s)

Fig.15 Correlation between flow directions and contours of C_p in flow field affected by single jet (numbers in figure indicate values of $C_p \times 10$.)

at $0.5 < x/d < 3$ below the jet, as illustrated in Fig. 6. It is difficult to measure the flow direction and the total pressure by use of the present types of the probe in the reverse flow. In order to clarify the flow pattern downstream of the jet orifices, therefore, the oil-film flow visualization technique is applied to a plate 0.6 mm thick placed in the plane of symmetry of the central component jet of the multiple jet. A flow pattern is illustrated in Fig. 14. According to this the flow downstream of the jet orifices is separated into reverse and favourable flows at a branching point $x/d=3$. The reverse flow occupies the region of $0.5 < x/d < 3$ and flows toward the downstream end of the jet orifices. The favourable flow moves along the deflected jets into the flow region downstream of the branching point. The branching point is at $x/d=3$ in both the single and multiple jets in the present experiment. There is little effect of adjacent jets on the region of the reverse flow in case of the present multiple jet (cf. Fig. 6). It is found from experimental results also that below the lower jet boundary at $x/d=3$, in which there is the upstream end of the region of the favourable flow, local pitch angles of the arrow measured counterclockwise from the x -axis are greater in the single jet than in the multiple one, though this result is not shown as a figure. This means that the fluid in the favourable flow is drawn up strongly toward the jet in case of the single jet.

3.5 Flow direction in cross planes

Figures 15 and 16 show flow direc-

tions in the flow field affected by the single and multiple jets, respectively, together with some contours of C_p from Figs. 4 and 5. Arrows in the figures show only flow directions projected on cross planes perpendicular to the x -axis. Thin arrows near the y -axis (i.e. near the channel floor) indicate that yawing angles only are measured with the 5-hole probe in order to avoid an interference effect of the floor on the 3-hole cylindrical probe. References (5) and (6) investigating a single jet report also on the generation of a circulating flow, which is similar to one in Fig. 15. However, these investigations give no information as to the effect of the circulating flow on the floor boundary layer. From Fig. 15(a) at a small distance upstream of the jet orifice, we find a fluid going away from the jet in the cross flow, because the cross flow follows an obstacle of the jet. Figure 15(b) to 15(f) illustrate flow directions in the cross planes downstream of the jet orifice. From Fig. 15(b) obtained in the cross plane near downstream of the jet orifice, we find easily that the floor boundary layer flow and the cross flow begin to go into the region of the predominant negative pressure adjacent to the downstream end of the jet orifice through the floor boundary layer. There is a more marked inflow into the wake of the jet from a wider area of the cross flow, as x/d increases. At the same time a circulating flow is gradually formed in the cross flow downstream of the jet orifice. The circulating flow covers a wide area including the jet and the cross flow and becomes clear with an increasing x/d . The centre of the circulating flow shifts in the positive z direction with an increasing x/d , and goes away from the plane of symmetry of the jet. From the foregoing considerations we can say that the circulating flow is brought about by a combined action of two factors, i.e. the floor boundary layer and the predominant negative pressure adjacent to the downstream end of the jet orifice. In addition to this we can say that the circulating flow influences greatly the contours of C_p near the floor, in other words, the floor boundary layer on the basis of the correlation between flow directions and contours of C_p .

Figure 16 shows flow directions in the flow field affected by the multiple jet. The flow directions are indicated

Fig. 16 Correlation between flow directions and contours of C_p in flow field affected by multiple jet (numbers in figure indicate values of $C_p \times 10$.)

with arrows in the flow region covering a half pitch of the jet orifices. We find a little circulating flow in Fig.16. Though there is a correlation between flow directions and contours of C_p reproduced from Fig.5, the flow field is very complicated in comparison with that of the single jet owing to an interference effect of the component jets. With the multiple jet the flow direction is very irregular even at $x/d=12.5$, where there is a clear circulating flow in case of the single jet.

4. Conclusions

(1) A flow field of a multiple jet arranged at a small interval of component jets cannot be constructed through a superposition of one from the single jet. However, it seems that the reverse flow region, which lies downstream of the jet orifices, with a predominant negative pressure is scarcely affected by the adjacent jets.

(2) With the single jet the floor boundary layer below the jet is greatly affected by the circulating flow and is reproduced by the circulating flow faster in the single jet than in the multiple one.

(3) The decrease in $(C_p)_{max}$ along the ξ -axis is greater in the single jet than in the multiple one, except in the region of the potential core near the jet orifice. The blockage effect of the adjacent jets on the lateral spread of a given component jet is noticeable in the multiple jet.

(4) The spreads $\zeta_{C_p=0,u}$ of the single and multiple jets vary linearly with ξ , except in the immediate neighbourhood of the jet exits. The gradient $d\zeta_{C_p=0,u}/d\xi$ is greater in the multiple jet than in the single one.

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