532.525

The Interference of Two-Dimensional Parallel Jets
(3rd Report, The Region near the Nozzles in Triple Jets)*

By Eiichi TANAKA**, Shuichi NAKATA***

Flow patterns of three two-dimensional parallel jets were investigated experimentally.

In order to examine the effect of varying the ratio of the velocities in the central and outside jets on flow pattern, detailed measurements of the flow by a hot-wire anemometer and flow visualization by oil film were carried out.

The results obtained are as follows.

(1) The flow fields near the nozzles can be classified in three patterns of the flow according to the velocity ratio.

(2) There is a specific velocity ratio at which the flow is unstable.

(3) The flow patterns by means of visualization agree well with those of the streamlines, qualitatively.

1. Introduction

It is known that the multiple jets, issued parallel from a number of two-dimensional nozzles, interfere with each other.

Detailed experiments on two-dimensional dual jet were carried out recently by D.R. Miller⁽³⁾ and the author⁽¹⁾⁽²⁾, and on the multiple jets by S. Corrsin⁽⁴⁾. But these results give little information on the present investigation of the triple jets.

On the other hand, there are studies concerning the interference of the double concentric jet⁽⁵⁾. This jet flow resembles a two-dimensional triple jet flow. Then, these results give useful information on the present investigation, but they are not applicable to the two-dimensional triple jet flow owing to the discrepancy between plane parallel flow and axially symmetric flow.

In the triple jet, the two outside jets set up a dual jet flow with an associated reverse flow, as reported in the previous papers. When the central jet is introduced in this region, it has to overcome the reversed flow. Therefore, the flow field of triple jet is largely affected by the ratios of the central jet velocity to the outside one and it is expected that the flow becomes unstable under certain condition of the specific velocity ratio.

In this report, the effect of the varying ratio of the velocities in the central and the outside jet on the interference region has been examined by detailed measurements of velocity, turbulence and static pressure. And also included is the classification of flow patterns by the oil film visualization method.

Nomenclature

- a : width of slot nozzle
- b : half width of a jet (half distance between the points at which $u/U=0.5$ in lateral distribution of velocity)
- D_0 : distance between two nozzles
- x : coordinate along the axis of central nozzle
- y : coordinate perpendicular to x
- x_s : coordinate x at the free stagnation point
- u : mean velocity component in x -direction
- u' : turbulence velocity component in x -direction
- U : maximum velocity of u in lateral velocity distribution of a jet

Fig.1 Nomenclature

* Received 3rd August, 1973.

** Assistant Professor, Faculty of Engineering, Gifu University, Kagamigahara.

*** Hitachi Shipbuilding & Engineering Co, LTD.

- U_0 : discharge velocity at nozzle
 U_{0c} : discharge velocity at central nozzle
 U_{0s} : discharge velocity at outside nozzle
 $R_{0c} = U_{0c}a/\nu$
 $R_{0s} = U_{0s}a/\nu$
 h_c : total pressure in central approach duct
 h_s : total pressure in outside approach duct
 J : efflux momentum at outside jet ($= \rho U_{0s}^2 a$)
 J_1 : momentum to downstream at the junction of dual jet
 J_2 : reversed momentum at the junction of dual jet
 p : static pressure referred to atmospheric pressure
 λ : nozzle discharge velocity ratio ($= U_{0s}/U_{0c}$)
 ν : kinematic viscosity of air
 ρ : density of air
 $\phi = \int_0^y u dy / \frac{a}{2} U_{0c}$

2. Experimental equipment and procedure

2.1 Wind tunnel, nozzle, and test section

The experimental apparatus used in this experiment is schematically shown in Fig.2. In this experiment, it is necessary to control the jet velocities in the central and the outside nozzles separately. Then, the approach duct of the nozzle (10) is divided into three parallel rectangular pipes and each section of the duct is 200×110 mm.

Air is supplied from the separate fans (1),(2) to the ducts (3),(4) for the

(1) blower for side jet	(2) blower for central jet
(3) duct for central jet	(4) settling chamber for side jet
(5) pre-contraction for side jet	(6) branch for side jet
(7) duct for side jet	(8) junction for central jet
(9) plenum chamber	(10) nozzle
(11) end plate	(12) traversing equipment

Fig.2 Wind-tunnel and apparatus

central and outside nozzles and the velocity ratio of the jets is changed by the control of each fan's speed.

Nozzles installed at the exit of three separated ducts are shown in Fig.3. Ceiling and floor boundary plates (11) are placed to prevent the secondary flow of the jet as mentioned in the previous paper. In the experimental studies on the interference of three parallel jet flows, it is necessary to arrange such that each jet shows the same properties. Fig.4 shows the measured results of the half width growth b/a , the maximum velocity decay $(U_0/U)^2$, the distributions of velocity u/U and turbulence u'/U of each jet. As seen from these figures, the properties of each jet are the same and in good agreement with the previous works on the single jet.

2.2 Measurements of velocity, turbulence and flow direction

Because of the interaction between the three parallel jets, the flow field is very complicated and unstable. For these reasons, the measurement of flow direction is very important as well as those of flow velocity and static pressure.

Fig.3 Nozzle

(a) Distributions of velocity and turbulence

(b) Decay of maximum velocity and growth of half width

Fig.4 Properties of each jet

Fig.5 Discharge velocity ratio and total pressure ratio

The improved X-type hot-wire anemometer which was used for the measurement of the Reynolds stress, is applied to measurement of the mean velocity components in x and y directions.

The ordinary hot-wire anemometer, the pressure measuring device and the automatic traversing mechanism used in this investigation are the same as those of 1st report ⁽¹⁾

2.3 Flow visualization

The oil film flow visualizing technique is applied to determination of the detailed flow pattern of the triple jets. An oil suspension of titanium dioxide was spread on a plate which had been painted matt black and the plate was set between the ceiling and the floor plate.

(a) $\lambda = 0.602$

(c-2) $\lambda = 1.12$

(b) $\lambda = 0.865$

(d) $\lambda = 1.28$

(c-1) $\lambda = 1.12$

(e) dual jet

Fig.6 Visualized flow patterns

3. Experimental results and discussion

As mentioned in the previous report by the author, the geometrical scale of flow and pattern in the interference region induced by the two-dimensional parallel jet, altered with the ratio of the distance between two nozzles to the nozzle width. And in the region larger than $D_0/a=16$, the geometrical scale of flow pattern in the interference region was directly proportional to D_0/a .

The present experiment deals with a three parallel jets flow in which the central jet discharges opposite to the reversed flow induced by the outside jets. Then, the effect of the velocity ratio of the outside to the center λ on the flow field was investigated when $D_0/a=22$ (references (1) and (2)).

3.1 Relation between discharge velocity ratio and total pressure ratio in the wind-tunnel

In a free jet issuing from a slot nozzle into still air, the discharge velocity at the nozzle is directly proportional to the square root of the total pressure in the approach duct. However, the discharge velocity ratio of the three jets is not obtained directly from the relation of the total pressure in the approach ducts, because of the interference of three parallel jets. So, the relation between the discharge velocity ratio $\lambda=U_{05}/U_{0c}$ and the square root of the total pressure in the approach duct $\sqrt{h_s/h_c}$ is obtained experimentally, as shown in Fig.5. In this figure, the dotted line $\lambda=\sqrt{h_s/h_c}$ represents the relation when there is no interference, and the experimental points are plotted by a full line curve.

This curve coincides with the dotted line near the point of $\sqrt{h_s/h_c}=0.8$, but is larger than the dotted line at $\sqrt{h_s/h_c}<0.8$ and is smaller than that at $\sqrt{h_s/h_c}>0.8$. The former condition means that the outside jet is entrained by the central jet and under the latter condition the central jet is sucked out by the outside jet.

3.2 Classification of the flow pattern by flow visualization

To classify the flow patterns with a progressive change of λ by use of the streamlines plotting method is very difficult. Therefore, the detailed influences of the velocity ratio and the discharge

Fig.7 Models of flow pattern

Reynolds number $U_0 a/\nu$ on the flow patterns are determined by the oil film method.

In the interference region in which much unevenness of the pressure exists, the correlation between the oil film patterns on the flat plate and the streamlines has to be determined. This relationship will be discussed in the latter section.

The visualized patterns of the flow in the cases of $\lambda=0.602, 0.865, 1.12, 1.28$ and in dual jet are shown in Fig.6. In these photographs, when the central jet is more dominant ($\lambda=0.602$), the outside jet is drawn and absorbed within the confines of the central jet. As the velocity of the outside jet is increased ($\lambda=0.865$), the central jet is absorbed within the boundary of the outside jet. As the velocity of the outside jet is more increased, the central jet overcomes the opposing force of the reverse flow and it is deflected from the axis. Then the central jet joins the one-side jet, and at the downstream point, this combined flow joins the remainder side jet. Thus the interference region when the side jet is more dominant has an asymmetric and larger pattern. At the transition point from symmetric to asymmetric flow patterns i.e., at $\lambda=1.10\sim 1.20$, there develops an unstable condition. So the flow vibrates alternately and generates a large noise. Whence the photograph in Fig.6 (c) lacks clearness. The visualized photograph of the dual jet ($\lambda=\infty$) corresponding to Fig.6 (e) is in good agreement with the previous experiment on the dual jet.

Thus, the flow pattern of the three parallel jets may be classified as models of three types A, B and C as shown in Fig. 7, depending upon the velocity ratio λ . The classified results are shown in Fig.8 which shows a small effect of the Reynolds number at $Re_s < 10^4$, but at the larger Reynolds number than this, the types A and B are divided by the border $\lambda=0.70\sim 0.71$ independently of the Reynolds number. A line $\lambda=0.707$ in this figure shows that the momentum in the central nozzle is equal to the side nozzle, i.e., $2U_{0s}^2 = U_{0c}^2$.

Fig.8 Classification of pattern and effect of Reynolds number

Thus the line $\lambda = 0.707$ divides the flow into the patterns A and B approximately and this means that the flow fields of types A and B are controlled by each nozzle discharge momentum.

In the type C flow pattern, the discharge momentum in the side nozzle becomes more dominant than the central one and therefore the flow field is controlled by the side jets.

In the plane parallel dual jet flow, it is known from the previous paper that a reversed flow occurs in the central region of two jets before combining. Since the central jet in the triple one faces this reversed flow, the flow field of type C is controlled by the ratio between the center jet discharging momentum and the reversed one. Meanwhile, it is possible to obtain the reversed momentum from Fig.19 in the author's previous report⁽²⁾, when $D_0/a = 22$ and we get (downward momentum)/(side jet momentum) = $J_1/J = 1.25$.

We may write $J_1 + J_2 = 2J$ in which J_2 denotes the reversed momentum, and this gives $J_2/J = 0.75$. If such a reversed momentum is equal to the central jet momentum $\rho a U_{0c}^2/J$, $U_{0c}^2/U_{0s}^2 = 0.75$ or the velocity ratio $\lambda = U_{0s}/U_{0c} = 1.15$ is obtained. Consequently, at such a velocity ratio, it is supposed that the transition from type B to C occurs and also the flow is unstable.

Comparing with the experimental results with $\lambda = 1.15$, it is possible to say that such an assumption is appropriate.

3.3 Length of the interference region

The length of the interference region may be considered as the distance x_s of the junction of three jets (free stagnation point) from the nozzle as in the case of the dual jet flow. In the triple jet flow, it is difficult to obtain x_s from the distribution of the velocity, therefore, the visualized pattern is used to obtain x_s . The relation between the position of the stagnation point which is considered the beginning of the reversed flow and λ is shown in Fig.9. As shown in the photographs of Fig.6, the stagnation point is

Fig.9 Positions of free stagnation points

observable at two stations. For the case of $\lambda < 1.5$, x_s of these points are equal because of the symmetry of the flow patterns and they increase with λ .

On the other hand, for $\lambda \geq 1.15$, the flow pattern becomes asymmetric. Therefore, the stagnation points are located at the attaching point of the central jet to the one-side jet and at the junction of the outside jets. These two points of x_s which are shown in Fig.9, indicate that twice the length is necessary for types A and B to combine into C type flow.

In other words, for the dual jet⁽¹⁾, $x_s/D_0 = 1.33$, but in the case of C type flow, $x_s/D_0 = 1.35$ ($\lambda = 1.15$) and larger for $\lambda > 1.15$. Such appearance is due to the reduction of a vacuum pressure in the interference region by the discharge of the central jet. Accordingly, the radius of curvature of the jet increases.

3.4 Distributions of velocity, turbulence and static pressure

Figure 10 (a)~(c) show the distribution of velocity u/U , turbulence $(u'/U)^2$ and static pressure $p/(1/2)\rho U_0^2$ along y-axis for the velocity ratio $\lambda = 0.602$ (type A), $\lambda = 0.865$ (type B) and $\lambda = 1.15$ (type C). The maximum velocity U_{0c} for each value of λ is chosen for the larger value of U_0 and U_{0s} . The velocity ratios shown in this figure correspond to Fig.6 (a), (b) and (d). As seen from each velocity distribution in Fig.10 (a)~(c), there is a reversed flow region between two jets, but their profiles have different properties from each other.

For the case of $\lambda = 0.865$, the central jet is rapidly entrained by both side jets and completely absorbed at $x/a = 12$ where the distribution shows evenness in the middle of the profile.

When $\lambda = 1.28$, the central jet is rapidly entrained by the left side jet at $x/a = 14$. At $x/a = 20$, such a combined jet joins the remainder side jet and the distribution also shows a flatness as in the case of $\lambda = 0.865$.

It is seen from the distribution of turbulence Fig.10 (middle) for the case of $\lambda = 0.602$ and 0.865 that the profiles of the central jet are symmetrical as in a single jet, but asymmetrical in the side jet owing to the curvature of the jet axis. While for $\lambda = 1.28$, the central jet curves and therefore shows asymmetrical profiles. The largest value of turbulence $(u'/U_{0c})^2 = 0.08$ exists in the central jet for $\lambda = 0.865$, where the central jet diverges sideways due to the strong entrainment of both side jets. Likewise, the largest intensities of the side jet for each $\lambda = 0.602, 0.865, 1.28$ are $(u'/U_{0s})^2 = 0.05, 0.053$ and 0.045 , respectively and these intensities are equal to those of the dual jet flow.

As for the distribution of static pressure Fig.10 (below), the pressure is negative in the region surrounded by the jets, whereas the pressure at the junction is super-atmospheric. In the case of $\lambda = 1.28$, the pressure distribution is also a-

(c) $\lambda = 1.28$ (b) $\lambda = 0.865$ (a) $\lambda = 0.602$

Fig.10 Distributions of velocity, turbulence and static pressure

(a)

(a)

(b)

(b)

(c)

(c)

Fig.11 Stream lines

Fig.12 Static pressure contour lines

symmetric just as the velocity profile and the super-atmospheric pressure occurs at the two points of $x/a = 1.2$ and $x/a = 20$.

3.5 Checking of the visualized flow pattern by the streamlines and the static pressure contour lines

The oil film visualizing method is a very useful technique to know the complex flow field, but not a quantitative measurement. Therefore, the flow patterns of the three parallel jets must be compared with the streamlines which have been obtained by the integration of the velocity distributions. For this purpose, the streamlines and flow direction obtained by the X-type hot-wire probe are shown in Fig.11 (a), (b) and (c) corresponding to the photograph of Fig.6 (a), (b) and (d), respectively. The streamlines shown in this figure are obtained by graphically integrating the lateral distributions of the longitudinal velocity component u , i.e.,

$$\psi = \int_0^y u dy / \frac{a}{2} U_{0c}$$

However, the streamlines near the free stagnation point are not shown because the velocity measurement near the stagnation point is very difficult owing to the smallness of velocity and fluctuation of the direction. And a mark S.P. $\otimes$ shows the stagnation point appearing in the flow visualization.

Comparing Fig.11 (a)~(c) with Fig.6 (a), (b) and (d) respectively, the flow patterns in both figures agree very well. Therefore, the flow patterns with oil film technique are the most useful means to understand the information of the flow.

Furthermore, by examining the photographs in detail, there are revealed differences in Fig.11 such as the streamlines of the jet being sucked in the center of circulation and these points translating upstream by a small distance. It is supposed that these differences are caused by the pressure gradient imposed upon the boundary layer on the oil film plate.

In order to confirm this effect, the static pressure contour is taken from Fig. 10 (below) and shown in Fig.12 (a)~(c). Comparing this contour with the visualized photographs of Fig.6, the center position of swirls is found to agree well with the minimum pressure point. This agreement is caused by the flow from the stagnation point to the minimum pressure point in which the pressure is remarkably negative, i.e., $p/(1/2)\rho U_0^2 = -0.1 \sim -0.2$. Consequently, the visualized flow patterns are slightly different from the streamlines, because of the pressure effect on the oil film plate.

4. Conclusion

(1) The flow patterns in the interference region of three parallel jets vary and are classified with the variation of the nozzle discharge velocity ratio $\lambda = U_{0s}/U_{0c}$ into the following three types.

A-type ($\lambda < 0.707$) - the momentum in the central jet is large and it entrains both side jets.

B-type ($0.707 < \lambda < 1.15$) - the momentum in the central jet is small and it is entrained by both side jets.

C-type ($\lambda > 1.15$) - the momentum in the central jet is much smaller than the outside jets and the central jet is entrained at first by the one-side jet. This combined jet joins the remainder side jet.

(2) At the velocity ratio near $\lambda = 1.15$, the flow is most unstable and generates a large noise. At $\lambda = 1.15$, the reversed momentum associated with the outside jet is equal to the central nozzle discharge momentum and these two flows oppose each other.

(3) The flow pattern obtained by the oil film visualization is slightly affected by the pressure distributions, but agrees well with the streamlines.

Acknowledgements

The authors would like to acknowledge the consistent guidance and encouragement of Professor Y. Furuya and Professor M. Murakami of Nagoya University.

References

- (1) E. Tanaka: Bulletin of JSME, Vol. 13, No. 56 (1970-2), p. 272.
- (2) E. Tanaka: Bulletin of JSME, Vol. 17, No. 109 (1974-7), p. 920.
- (3) D. R. Miller and E. W. Comings: Jour. Fluid Mech., Vol. 7, No. 2 (1960-2), p. 237.
- (4) S. Corrsin: NACA Wartime Rep., (1944-11).
- (5) N. A. Chiger and J. M. Beer: Trans. ASME, Ser. D, Vol. 86, No. 4 (1964-12), p. 797.