Int. J. Heat Mass Transfer. Vol. 23, pp. 1673–1680
Pergamon Press Ltd. 1980. Printed in Great Britain

VECTOR AND SCALAR CHARACTERISTICS OF OPPOSING JETS DISCHARGING NORMALLY INTO A CROSS-STREAM

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(*Received* 22 *March* 1980)

Abstract—Measurements of mean velocity and a passive scalar (helium tracer) have been obtained for two rows of opposing jets discharging normally into a crossflowing stream and simulate an important aspect of gas-turbine combustor practice. Results are presented for a downstream distance of 6 jet diameters from the jet centre-lines and for a jet-to-mainstream velocity ratio of 2.25. The influence of the non-uniform pitch and pitch-to-diameter ratio is quantified with the opposing jets separated by 4*D*.

For a pitch to diameter ratio of 2, a slight geometrical asymmetry of the central jet for one row of holes results in a severe asymmetry of the velocity field. This effect is not, however, propagated to the opposing side. The scalar flux measurements show the nearest adjacent jet aiding the displaced jet to regain symmetry and the counteraction to this of the opposing jet. With a pitch to diameter ratio of 4, the scalar measurements indicate 'slipping' between the opposed jets. Furthermore, symmetrical arrangement of the jets with this higher pitch-to-diameter ratio leads to impingement of the opposing jets with the jets bifurcating asymmetrically and geometrical asymmetry no longer results in severe asymmetry of the velocity field.

INTRODUCTION

IT IS well known that the temperature distributions in the exit planes of the combustors of gas turbines are non uniform and can have maxima which limit the life of nozzle guide vanes and turbine blades. There are many possible reasons for these non-uniformities and this paper examines the influence of geometric tolerances in an idealised geometry with isothermal flow. The arrangement is shown in Fig. 1 and consists of two rows of jets which impinge upon each other and are subject to a crossflow; the present measurements were obtained with a jet-to-mainstream velocity ratio of 2.25 and with a separation of four diameters between the exit planes of the two rows of jets.

The measurements represent a major extension of the work of Crabb [1] and Crabb and Whitelaw [2] which investigated the flow properties downstream of a single row of jets in cross-flow with a pitch to diameter ratio of 2 and of Khan and Whitelaw [3] where the same arrangement was used to determine the influence of velocity ratio. In all cases, the influence of displacement of one hole, with respect to the others, was determined and shown to be large in that the two jets with smaller separation gave rise to a disproportionately large downstream region of separation. This result suggested that geometric asymmetries associated with manufacturing tolerances can give rise to substantial flow asymmetries and this possibility is tested here for opposed jets with pitch to diameter ratios of 2 and 4 and a separation similar to that in gas turbine practice.

Additional results with a single row of jets in crossflow have been reported, for example, by Kamotani and Greber [4], Holdeman and Walker [5] and Cox [6] and encompass a range of pitch to diameter ratios of 2–12 and ratios of jet to cross-flow velocities from 2.5 to 8.5. Temperature measurements were reported in all cases and were complemented, in the case of [4], by trajectories. It is clear from these results that the double vortex characteristic of the single jet in crossflow, see for example [7–9], is not allowed to develop with pitch to diameter ratios less than 4. In addition and at velocity ratios greater than that examined here, the influence of the position of the wall opposite to the jet exit was shown to influence the flow significantly.

The present work was motivated by the need to understand the flow patterns which stem from opposed jets in crossflow and particularly to determine the magnitude of the flow asymmetries which stem from geometric asymmetries. It is questionable if rows of jets manufactured to realizable engineering tolerances can give rise to a flow which is symmetric within the uncertainties associated with fluid-flow measurements but the main emphasis is on the results of displacing one hole centre-line, by a measured amount, with respect to the neighbouring and opposite centre-lines. The use of idealised geometries and isothermal flows implies that any extrapolation to combustors must be made with great circumspection. The results do, however, provide some guidance and also indicate possible limitations of the use of calculation methods based on the numerical solution of conservation equations in finite-difference form.

FLOW CONFIGURATIONS AND INSTRUMENTATION

The flow configuration comprised a channel of 300 mm width and 100 mm height with five 25.4 mm

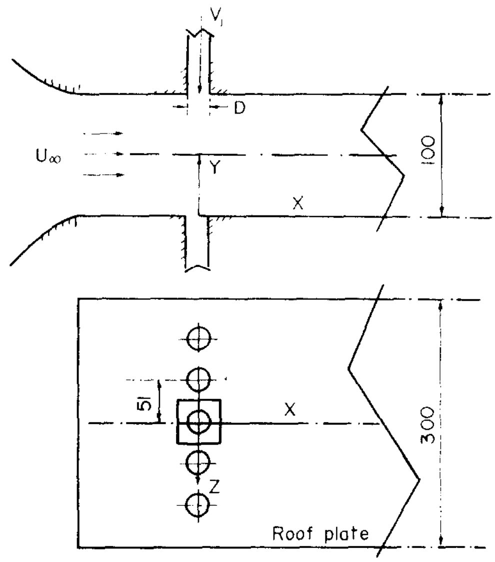

FIG. 1. Schematic of experimental set-up and the co-ordinate system used (dimensions in mm: not to scale).

holes located across the span of the roof and floor with their centres separated by 51 mm. The holes were connected to 0.76 m long tubes which ensured fully developed flow and were located with their centre-lines 0.30 m downstream of sandpaper trips. The arrangement is shown on Fig. 1 and was operated with mean cross-flow velocity of 10.7 m/s and the average velocity in each pipe was 24.0 m/s corresponding to a Reynolds number of 4.29×10^4. The centre hole on the roof of the channel could be adjusted by means of slip gauges to allow investigation of hole eccentricity and the top row of holes could be moved axially in relation to the floor holes. The jets could also be staggered laterally by moving the floor jets relative to the top row. In addition, and for measurements with a pitch to diameter ratio of four, two holes on the roof and two on the floor could readily be blanked off. In view of the purpose to investigate flow asymmetries, it is important to quantify the tolerances with which the geometric and flow boundary conditions could be prescribed.

The 10 holes were measured in their exit planes and found to be round and of equal diameter within 0.05 mm. The upstream pipes were cut from the same batch of thick-wall, drawn steel and were honed over the four centimeters close to the exit plane to a similar tolerance to that of the exit plane. The pitch of the hole centre-lines was identified within 0.02 mm and the distance between the floor and roof of the channel was uniform within 0.1 mm. The alignment of the centre-lines of the roof holes, with respect to the centre-lines of the floor holes could be achieved within 0.1 mm. These tolerances are considerably better than those found in the construction of gas-turbine combustors and negligible compared to the eccentricities investigated by adjustment of the centre floor hole, i.e. 2.54 mm, 6.35 and 12.70 mm.

The flow to the holes was generated by a fan which passed the air to separate plenum and identical chambers for each of the top and bottom rows of holes. In the absence of the cross-stream flow, measurements of mean velocity were obtained across two orthogonal diameters in the exit planes of each of the ten holes and revealed maximum discrepancies in the flow rates obtained by integration of each of the twenty profiles of less than 1%. Comparison of the profiles indicated local discrepancies of not more than 6% of the maximum velocity value. This result was obtained after some adjustments to the length of tubing between the plenum chambers and the pipes connected to the exit holes. In all cases, the exit profile conformed to fully developed pipe flow.

The flow from the main fan passed through an expansion chamber to a parallel region with screens and honeycomb. It then passed through a contraction of area ratio 12 to its exit plane where the present channel began. Examination of the flow in the channel, with the holes covered by tape, indicated a free stream turbulence intensity of 0.7% in the exit plane and boundary layers which were very thin. Sandpaper trips were located on the floor and roof of the tunnel and close to the beginning of the channel and resulted in boundary layers of momentum thickness 2.65×10^2 at the location of the leading edge of the holes. The shape of these boundary layers conformed to a turbulent flow with identifiable logarithmic regions. Profiles across the tunnel were measured at various cross-stream locations in the entrance plane and confirmed two-dimensionality within 1% of the free-stream value over the centre 93% of the channel.

Measurements of mean velocity were obtained with an impact probe of external and internal diameters 1.1 and 0.61 mm respectively. A transducer and time-averaging voltmeter allowed reproducibility of pressure measurement of better than $\pm 1\%$ for all measurements and considerably better at the higher velocities. Two traverse mechanisms were employed and operated from the roof of the channel. The first allowed the measurements in the exit planes of the holes and the second the downstream results.

The local concentration of a trace of helium gas, which was injected into one or more of the jet flows upstream of the pipe exit was determined by sampling through the impact probe used for the measurements of total pressure and passing to a thermal-conductivity cell. The technique has been described in greater detail in, for example, [1, 2, 10]. Away from regions of flow recirculation, the non-dimensional concentrations are precise to better than $\pm 2\%$ of unity.

RESULTS AND DISCUSSION

Measured values of velocity and temperature have been obtained for the flow conditions shown on Table 1 and are presented here in a sequence which conforms to that of the table. Only those results which indicate significant differences and are potentially useful are presented. Individual measured values are presented to indicate the detail and scatter of results and smooth

Table 1. Flow conditions for the present measurements and legend for the figures (* indicates measurement taken)

Pitch-to-diameter ratio	Profiles	Poisitions of the opposing jets	Eccentricity of top central jet	Y/D 3.5	3.0	2.5	2.25	2.0	1.75	1.5	1.0	0.5	Legend for the figures
$(S/D) = 2$	Velocity profiles	Jets opposing	$e = 0$	*	*			*			*	*	○———○
			$e = 0.1D$	*				*		*			◓—×—×—◓
			$e = 0.25D$	*	*			*			*	*	◐—·—·—◐
			$e = 0.5D$	*		*		*			*		●- - - -●
		Floor jets staggered laterally (i.e. $Z = -1.0D$)	$e = 0$	*	*			*			*	*	⬒———⬒
			$e = 0.5D$	*			*	*	*			*	□— — —□
		Ceiling jets staggered axially ($X = 1.0D$)	$e = 0$		*			*			*		◧———◧
			$e = 0.5D$		*			*			*		■·········■
	Concentration profiles	Jets opposing	$e = 0$	*	*			*					○———○
			$e = 0.25D$	*	*			*		*			◐—·—·—◐
			$e = 0.5D$	*	*			*		*			●- - - -●
		Floor jets staggered	$e = 0.5D$	*		*				*			□— — —□
		Ceiling jets staggered	$e = 0.5D$	*				*		*			■·········■
$(S/D) = 4$	Velocity profiles	Jets opposing	$e = 0$	*				*			*		○———○
			$e = 0.5D$	*				*			*		●- - - -●
		Floor jets staggered laterally	$e = 0$	*	*			*			*	*	□— — —□
			$e = 0.5D$	*	*			*			*	*	■—·—·—■
	Concentration profiles	Jets opposing	$e = 0$	*	*			*		*			○———○
			$e = 0.5D$ Top central seeded	*	*			*		*			●·········●
			$e = 0.5D$ Floor central seeded	*	*			*		*			◐—×—×—◐
		Floor jets staggered laterally	$e = 0$	*				*			*		□— — —□
			$e = 0.5D$	*				*			*		■—·—·—■

lines are drawn to represent and interpolate the measured values. In all cases, X is measured downstream from the centre-line of the floor holes, Y is measured from the floor and Z is measured from the vertical symmetry plane of the tunnel.

Velocity values measured at X/D of 6 and at various distances above the floor of the channel are shown on Figs. 2–4. Figure 2 corresponds to opposed jets, Fig. 3 to floor and roof jets staggered in the Z-direction by one diameter and Fig. 4 to floor and roof jets staggered in the X-direction by one diamrter. The influence of the lateral displacement of the central, roof jet, with respect to its neighbours is shown on all these figures.

The general nature, and symmetry, of the flow may be deduced from Fig. 2 which shows for the symmetric case ($e = 0$) that the free stream flow accelerates between the jets and results in maximum velocities greater than 1.5 U_∞ in the plane and at locations mid way between the jet centre lines. At Y/D of 2, the two maxima are within 1% of each other though a slightly greater asymmetry exists at Y/D of 3.0 and 3.5 suggesting that the velocities of the roof jets are slightly less equal than those of the floor. The influence of the eccentricity of the central roof jet is, as was the case with the single row of jets of [1], to increase the velocity maximum in the larger gap between the neighbouring jets and to reduce the velocity maximum behind the two more closely neighbouring jets. For the largest eccentricity (e = 0.5D) the maximum is increased from around 1.25 U_∞ to 1.45 U_∞ at Z/D of -1.0 and reduced from 1.25 U_∞ to 0.92 U_∞ at Z/D of $+1.0$ and at the vertical plane corresponding to Y/D of 3.0. The effect is less at an eccentricity of 0.1 which might be regarded as corresponding to an upper limit of manufacturing tolerances for combustors but is still significant at Y/D of 3.5 and at Y/D of 3.0 (not

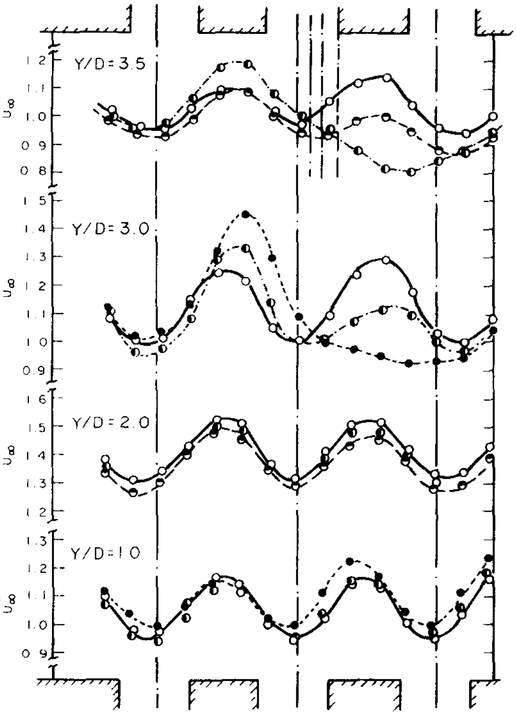

FIG. 2. Velocity profiles for opposed jets with a pitch-to-diameter (S/D) ratio of 2 (chain lines show centrelines of the jets).

shown). The penetration of the effects of the asymmetry to the lower half of the flow is not important except for the case of 0.5 D eccentricity where the velocity maximum at $Z/D = 1$ has been increased by around 10% due again to the two closely neighbouring roof jets presenting a barrier to the free stream which is accelerated between the wider gap between roof jets, as previously discussed, and between the midplane and the floor.

Figure 3 corresponds to roof and floor holes staggered in the Z-direction by one diameter and also shows the effect of an eccentricity of $0.5D$ of the central roof hole. The velocity distribution for zero eccentricity are similar but displaced at Y/D of 0.5 and 3.5, i.e. $0.5D$ from floor and roof, and should be uniform at Y/D of 2.0. The lack of uniformity suggests that flow asymmetries considered negligible at Y/D of 0.5 and 3.5 have been magnified to become significant at Y/D of 2.0. Again, the free stream has tended to accelerate between the jets to give a central-plane, average value of around 1.3 U_∞. The non-uniformity of the central-plane velocity distribution may, in part, reflect the preference of the free stream to yield maximum velocities at locations of equal velocities at lower and higher values of Y. The effect of hole eccentricity is even larger than on Fig. 2 at Y/D of 3.5 but is of similar magnitude at Y/D of 0.5. A lower mass flow and velocity excursions from the average exist at Y/D of 0.5, than at 3.5, and are probably associated with the asymmetry of the hole arrangement, with respect to the

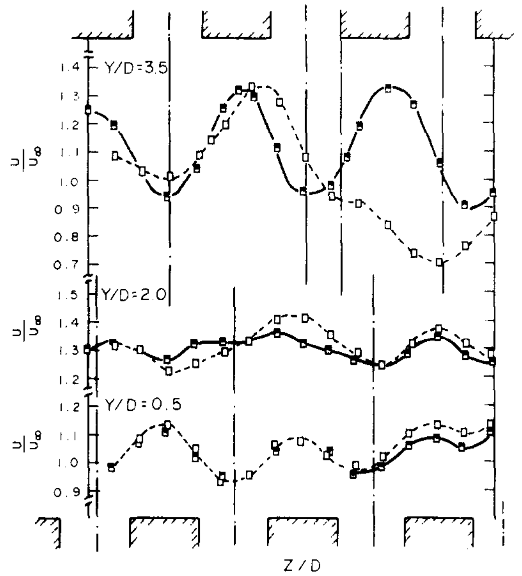

FIG. 3. Velocity profiles with the floor jets staggered laterally ($Z = -1.0D$) and S/D of 2.

tunnel walls, and the related reduction in mass injected.

The velocity results for the axially staggered case, Fig. 4, reflect the different effective X-values of the measurements above and below the mid plane. Thus, the velocities of the lower half, corresponding to $X/D = 6$, are lower than those of the upper half which correspond to X/D of 5. This accounts for the slightly higher velocities of the figure when compared to those of Fig. 2. The effect of the 0.5 D eccentricity is much larger than that of Fig. 2 and is probably greater than can be explained by the X-value alone. Thus, the free stream has been divided by the lower jets and accelerated between them and towards the roof when it encounters a second row of jets, this time emerging from the roof and with eccentricity. The result is a larger wake region and pronounced asymmetry at the mid plane.

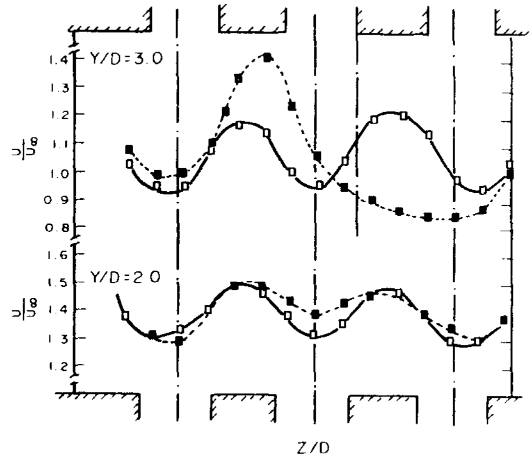

FIG. 4. Velocity profiles with the ceiling jets staggered axially ($X = D$) and S/D of 2.

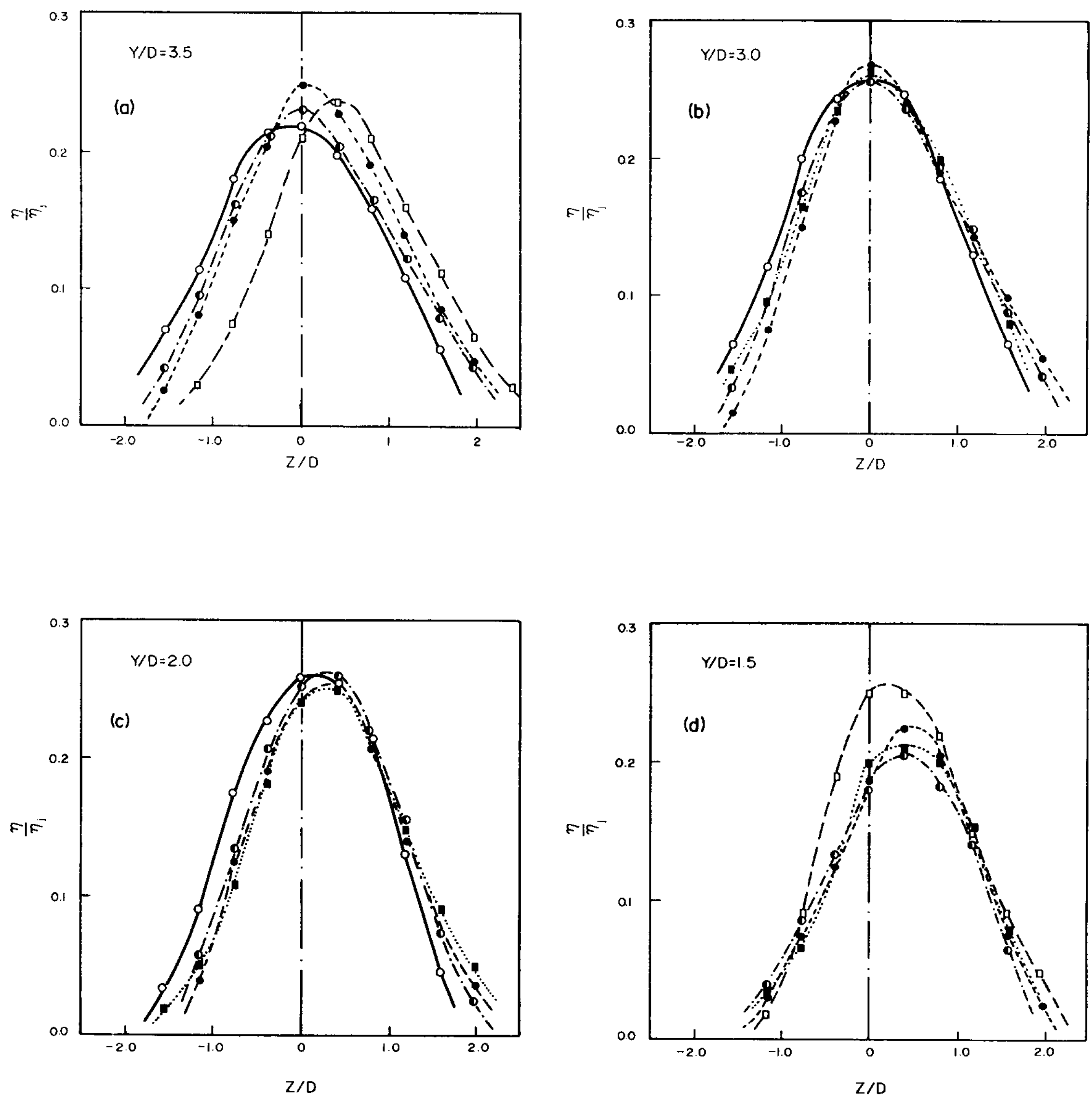

FIG. 5. Concentration profiles at 6 downstream diameters ($X = 6D$) with the jets directly opposing and staggered and $S/D = 2$.

The non-dimensional concentration profiles of Fig. 5 were obtained with a trace of helium in the central roof jet and again correspond to the legend of Table 1. These concentrations may be interpreted as the non-dimensional value of any passive scalar including, for example and in the absence of reaction and radiation, of temperature. For the geometrically symmetric case, the profiles are also symmetric with a maximum value on the jet centre line at Y/D of 2.0 and lower values in the near-wall region: this may be deduced from Figs. 5a, b and c. Figure 5a also shows that lateral staggering of the jets with hole eccentricity causes greater asymmetry of the jet fluid at X/D of 6 than the eccentricity of a single hole alone which results in a tendency for the jet fluid to return to a symmetric distribution about the centre line of a corresponding non-eccentric jet. Figure 5b confirms this last result at Y/D of 3.0 and also shows that axial staggering of the roof and floor jets, with central roof-hole eccentricity, also results in near symmetric jet fluid. Figures 5c and 5d, show that the apparent symmetry about $Z = 0$ is not maintained at Y/D of 2.0 and 1.5 where symmetry remains but with an axis corresponding to that of the eccentric jet. Thus, and in contrast to the velocity characteristics, the influence of the scalar quantity extends beyond mid-plane and to an important extent.

Results, corresponding to those of Figs. 2, 3 and 5 but for a pitch to diameter ratio of 4, are presented in Figs. 6–8. As shown by Fig. 6, the eccentricity effect is reduced and this stems from the ability of the free stream to better penetrate the gap between the two neighbouring jets where they are separated by 3.5 D rather than the 1.5 D of Fig. 2. The tendency for asymmetry, even with a nominally symmetric arrangement of holes, should be noted on Fig. 6 and will be discussed further in relation to Fig. 8a which confirms

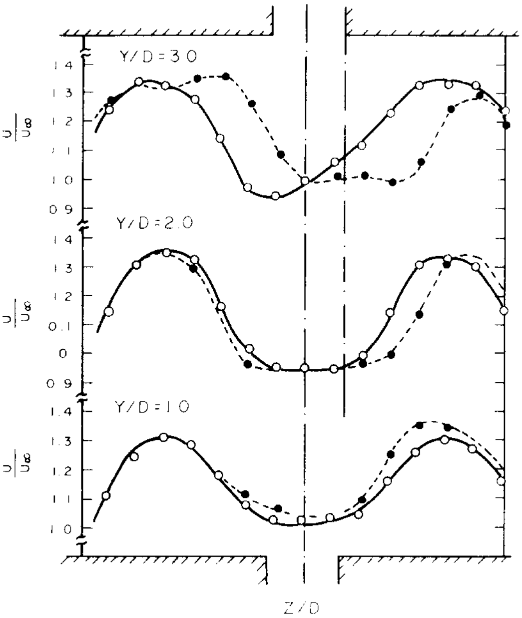

FIG. 6. Velocity profiles for opposed jets with S/D of 4.

that the opposed jets tend to diverge, in opposite directions from the hole centre line.

The results of Fig. 7 suggest that the non-uniformity of the mid-plane velocity value of Fig. 3 do result from the free stream accelerating more in regions of equal velocity above and below the midplane. The eccentric-jet results follow the expected pattern with significant penetration beyond the midplane but little at Y/D of 0.5.

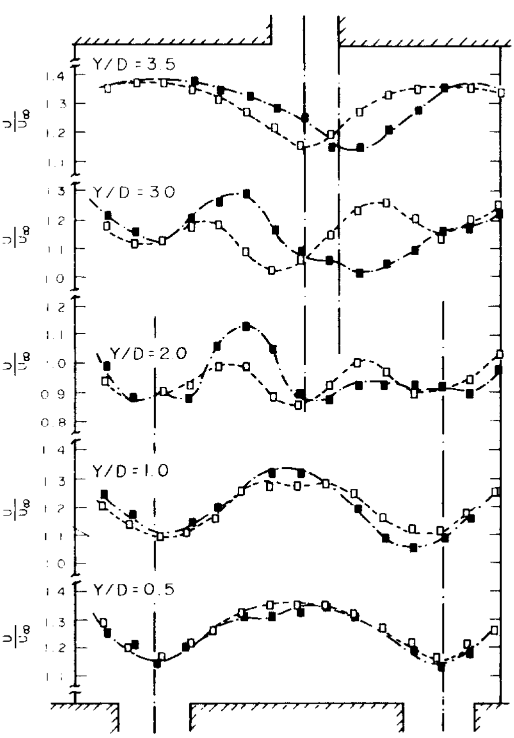

FIG. 7. Velocity profiles with the floor jets staggered laterally ($Z = -1D$) and S/D of 4.

The non-dimensional concentration results of Fig. 8 show, for the symmetric arrangement of jets, that the expected symmetry does not exist and that the fluid from the seeded central-roof jet has tended to bifurcate and in an asymmetric manner. This is consistent with the asymmetry revealed by Fig. 6 and is important in that it implies that, with opposed jets unconstrained by surrounding jets or walls, a symmetric arrangement cannot be achieved with the dimensional tolerances of the present arrangement. With an eccentricity of 0.5 D, the constraints exerted by neighbouring jets are revealed by the extent to which the results obtained with the top and bottom central jets carrying the helium tracer deviate from a mirror image. Here the results with the floor jet carrying the helium were actually obtained at Y/D corresponding to 4 D minus the value shown.

CONCLUDING REMARKS

The previous section quantifies the influence of various hole arrangements on downstream values of mean velocity and helium concentration. The results have been discussed in terms of asymmetries but can also usefully be appraised in terms of the degree of mixing and resulting excursions, in the case of the scalar quantity from uniform values. In this context, the laterally staggered arrangements give the best performance although eccentricity of one hole, with respect to its neighbours, can cause a significant region of lower velocity and higher scalar flow. The results with the two pitch-to-diameter ratios should be compared in this way in the realisation that S/D of 2 corresponds to twice as much jet fluid.

The results show that geometric asymmetries can give rise to important flow asymmetries and that, particularly for the lower value of pitch to diameter ratio, these are relevant to the manufacturing tolerances of gas-turbine combustors and to the resulting flow uniformity. With the larger pitch to diameter ratio, opposed jets are shown to bifurcate asymmetrically and engineering tolerances to be of lesser importance.

In addition to their relevance to engineering practice, the results are important for the development of calculation methods in that they quantify the effect of the common assumption of symmetric flow boundary conditions. Clearly, assumptions of this type can result in erroneous results if a geometric asymmetry exists or, as in the case of S/D of 4, impinging jets bifurcate asymmetrically. It is important to know the likely magnitude of these errors so that calculations can be made with asymmetric geometry if considered necessary and with the additional cost. The asymmetric bifurcation of jets is not likely to be successfully calculated in the immediate future.

Acknowledgement—The authors gratefully acknowledge financial support from the Science Research Council.

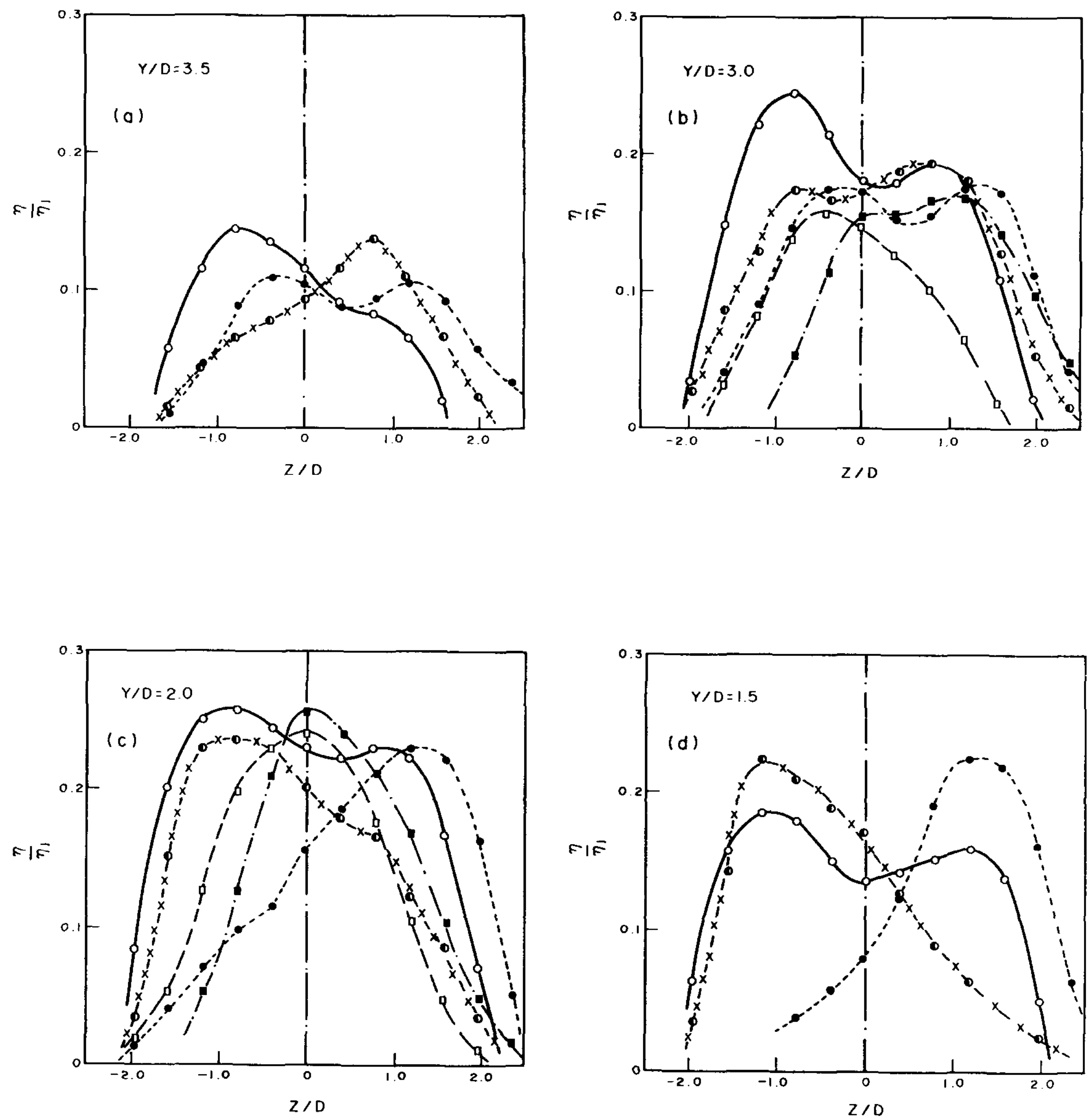

FIG. 8. Concentration profiles for directly opposing and staggered jets with $S/D = 4$.

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CARACTERISTIQUES VECTORIELLES ET SCALAIRES DE JETS OPPOSES ET PERPENDICULAIRES A UN ECOULEMENT PRINCIPAL

Résumé—Les mesures de vitesse moyenne et de scalaire passif (hélium tracer) ont été obtenues pour deux rangées de jets opposés qui se déchargent normalement à un écoulement principal et qui simulent un aspect important pratique des brûleurs de turbines à gaz. Les résultats sont présentés pour une distance en aval de 6 diamètres de jet à partir des lignes médianes des jets et pour un rapport de vitesse du jet au courant principal égal à 2,25. L'influence de la non-uniformité du pas et du rapport pas/diamètre est quantifiée pour des jets opposés séparés par 4 *D*.

Pour un rapport du pas au diamètre égal à 2, une légère asymétrie du jet central pour une rangée de trous a pour résultat une asymétrie importante du champ de vitesse. Les mesures de flux scalaire montrent que le jet immediatement le plus proche aide le jet déplacé à retrouver la symétrie tandis que le jet opposé contrarie cela. Avec un rapport pas/diamètre égal à 4, les mesures de scalaire montrent un glissement entre les jets opposés. De plus, un arrangement symétrique des jets avec une valeur plus importante du rapport entraine le heurt des jets opposés avec les jets bifurquant asymetriquement et l'asymétrie géométrique n'a plus pour résultat une asymétrie importante du champ de vitesse.

VECTOR UND SCALAR CHARAKTERISTIKA VON GEGENLÄUFIGEN STRAHLEN, DIE SENKRECHT IN EINEN QUERSTROM EINDRINGEN

Zusammenfassung—Messungen der mittleren Geschwindigkeit und ein passives Scalar (Helium tracer) wurden erhalten für zwei Reihen gegenläufiger Strahlen, die senkrecht in eine Querströmung eindringen und einen wichtigen Aspekt der Gasturbinenpraxis simulieren. Ergebnisse werden wiedergegeben für einen Abstand von der Strahlmittellinie 6 Strahlungsdurchmesser stromabwärts und für ein Verhältnis von Strahl zu Hauptstromgeschwindigkeit von 2,25. Der Einfluß nicht einheitlicher Teilung und des Teilungsdurchmesserverhältnisses ist wiedergegeben für gegenläufige und im Abstand von 4D angeordnete Strahlen.

Für ein Verhältnis von Abstand zu Durchmesser von 2 verursacht eine leichte geometrische Asymmetrie des Zentralstrahls für eine Lochreihe eine starke Asymmetrie des Geschwindigkeitsfeldes. Dieser Effekt wird aber nicht auf die Gegenseite übertragen. Die scalaren Flußmessungen zeigen, daß der nächstliegende anhaftende Strahl dem verdrängten Strahl zur Wiedergewinnung der Symmetrie verhilft, während für den gegenläufigen Strahl die Gegenwirkung eintritt. Bei einem Verhältnis von Abstand zu Durchmesser von 4 zeigen die scalaren Messungen einen "Schlupf" zwischen den gegenläufigen Strahlen. Bei diesem größeren Abstand-zu Durchmesserverhältnis führt weiterhin eine symmetrische Anordnung der Strahlen zum Zusammenprall der gegenläufigen Strahlen, wobei sie sich asymmetrisch aufgabeln; eine geometrische Asymmetrie führt hier nicht mehr zu einer starken Asymmetrie des Geschwindigkeitsfeldes.

ВЕКТОРНЫЕ И СКАЛЯРНЫЕ ХАРАКТЕРИСТИКИ ВСТРЕЧНЫХ СТРУЙ, ИСТЕКАЮЩИХ ПОД ПРЯМЫМ УГЛОМ К ПОПЕРЕЧНОМУ ПОТОКУ

Аннотация — Проведены измерения среднего значения скорости и пассивного скаляра (меченый гелий) для двух рядов встречных струй, истекающих под прямым углом к поперечному потоку и моделирующих важный аспект процесса, происходящего в газотурбинной камере сгорания. Результаты получены для расстояния вниз по потоку, равного 6 диаметрам струй, отсчитываемого от их геометрических осей, и для отношения скоростей струй и основного потока, равного 2,25. Проведено количественное сравнение влияния неравномерности шага и отношения шага струй к их диаметру со случаем встречных струй, отстоящих одна от другой на расстоянии 4D.

При отношении шага к диаметру, равном 2, небольшая геометрическая асимметрия центральной струи в одном ряду отверстий вызывает сильную асимметрию в распределении скоростей. Однако этот эффект не распространяется на противоположную сторону. Измерения потока скаляра показывают, что смежная струя способствует восстановлению симметрии в смещенной струе, в то время как встречная струя оказывает противоположное действие. При отношении шага к диаметру, равном 4, имеет место эффект проскальзывания между встречными струями. Кроме того, при таком значении отношения симметрично истекающие струи соударяются со смещенными, но геометрическая асимметрия не вызывает сильной асимметрии в распределении скоростей.