JET FLOW INTERACTIONS

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ABSTRACT

In the design of powered lift devices for STOL aircraft, frequent use is made of jet flows which interact with solid surfaces, e.g., in upper surface blowing, blown flaps and especially in lift/thrust augmenting devices. This paper discusses several configurations which involve the interaction of ventilated jets with nearby walls and the effects of nozzle cross-sectional shape on jet mixing. Some of the results from these studies may also be relevant to the problems of disposal of pollutants.

INTRODUCTION

It often proves advantageous to use jet flows involving unusual geometries to improve the effectiveness of aerodynamic devices. This is particularly true in the development of powered high lift devices for use in STOL aircraft design. For example, jet interactions are utilized in upper surface blowing, blown flaps, and in some boundary layer control techniques. Of particular interest in recent years is the jet mixing behaviour in ejector type devices as they are used in thrust and lift augmenting arrangements. Some early work by Whittley(1) indicated that the nozzle exit geometry exercises considerable influence over the jet mixing process. Moreover, jets blowing over nearby, but detached walls, produce significant entrainment of secondary fluid, even in cases where the jet is not fully confined. Some predictions and applications may be found in a paper by Morel and Lissaman(2), while Marsters(3) has presented the results of an experimental study of the interaction of ventilated plane parallel jets. Moreover, experimental data for ventilated plane jets attaching to walls are available(4,5). While some of the cases cited have been subject to experimentation, several important factors have not been examined. It is still of interest to examine the effects of three dimensionality, as exemplified by jets issuing from rectangular slots(6,7,8,9), from cruciform shaped nozzles(9,10), and from rows of slot nozzles.

In this paper we review the work on rectangular jet flows and ventilated plane jets, and present some new experimental data for the following cases: (i) a plane jet reattaching to a curved wall; (ii) mixing characteristics of free jets issuing from cruciform nozzles and (iii) flows from a row of slot nozzles. Where appropriate, the results will be compared with earlier studies. The overall objective of the paper is to provide information which will increase the understanding of very complex jet flows which are either highly three dimensional or are strongly influenced by nearby solid walls.

REVIEW OF INTERACTING JET FLOWS

Over a decade ago, Sforza and his colleagues(6,7) presented their results of studies on rectangular jet flows. One of the principle characteristics reported for these flows is the rate of decay of the centreline velocity. Three regions were discerned: the near region, where a "potential core" exists; the characteristic decay region, where the nature of the decay is dominated by the nozzle geometry; and the axisymmetric decay region, when the jet assumes, for all practical purposes, an axisymmetric behaviour. The early work also showed a "necking down" of the jet width in the spanwise (lateral) direction, before it began to spread laterally. Some evidence of a "saddle back" shaped transverse velocity profile was also observed. In 1976, Sfier(8), reported studies on rectangular jet flows which corroborated much of the earlier work. The saddle back profile was again observed with the peak velocities roughly 15%-20% higher than the mid-plane velocities. Both temperature and velocity exhibited saddle back behaviour. Sfier used two nozzle types, a sharp edged slot and a rectangular channel, 50 slot heights long. The saddle back shape was not in evidence in this latter case. Thus Sfier concludes that the upstream geometry may dominate the flow. This contention is supported by recent work by the present author(9) where it was found that jets issuing from rectangular slots (aspect ratio about 12) with smoothly rounded contraction sections showed no saddle back behaviour, while jet issuing from sharp edged slots (of the same size) cut in thin plates exhibited spanwise mean velocity profiles with pronounced peaks near the

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"ends" of the jets. There is clear evidence that the flow field upstream of the nozzle is of major importance.

Observation of the jet spreading rate and the centreline velocity decay of plane, rectangular jets issuing into still surroundings allows us to shed some light on the mixing characteristics (momentum transfer) of these flows. While free jet studies are important, one often finds jets interacting with solid walls. Three studies by the present author(3,4,5) have examined situations where plane jets (2-dimensional) interact with each other or with plane walls. When two plane parallel jets interact(3), and the space between them is "open", secondary flow is entrained as the jets merge. Downstream of the merge region, the combined jets behave like a single plane jet with a new virtual origin. Upstream of the "merge region" the individual jets behave as plane two-dimensional jets except that their trajectories are curved.

When a plane jet issues from a nozzle offset from a nearby plane wall and a gap exists between the nozzle and the wall, we again find that secondary flow is entrained, and that the jet will "attach" to the wall provided that the gap and/or deflection angle is not too large(4,5). This case has been examined for a plane parallel wall and a plane inclined wall. The latter case models the flow over a deflected flap surface. The plane jet is found to behave as a free jet upstream of "attachment", while beyond the attachment the jet plus its entrained flow resembles a wall jet. Estimates of thrust amplification, wall shear stress, and in the case of the inclined wall, normal forces, have been made. The effect of the entrained flow is manifested in thrust and lift augmentation.

A VENTILATED JET ATTACHING TO A CURVED WALL

Statement of the Problem

Although the literature on wall jets flowing over curved walls is extensive(11-16) it appears that relatively few researchers(17,18) have studied the case where a gap may be present between the nozzle and the curved wall. In the latter two studies the shape of the "attachment surface" consisted of convex circular surface, with a plane, bluff surface upstream. In aerodynamic applications, such as jet augmented flaps for STOL aircraft, the attachment surface would be expected to have a well rounded leading edge. A possible arrangement is shown in Fig. 1. In this sort of application, there will be entrainment of secondary flow through the gap between the nozzle exit plane and the attachment surface. The entrained flow is beneficial in several ways, including boundary layer control and thrust/lift augmentation(4,5). The studies reported in Refs. 17 and 18 do not model the type of flow envisaged in Fig. 1.

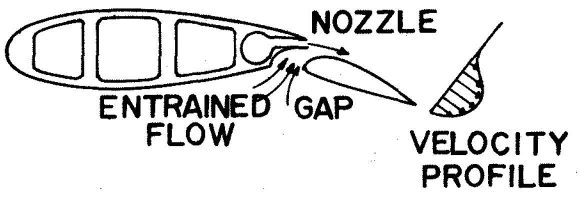

FIGURE 1: A Ventilated Plane Jet Interacting with a Plane Wall.

The work reported in this section extends earlier work, which examined ventilated flows attaching to nearby surfaces, to include the case of a wall of constant (convex) curvature in the streamline direction. A possible application would use a rotating element in place of a flap which would take advantage of both Magnus effect and Coanda effect. However, the primary motivation for the work was to increase the understanding of the nature of ventilated wall jet flows.

Description of Experiments

The experimental facility has been described elsewhere(4). The jet flow issued from a nozzle, shown schematically in Fig. 2. The nozzle thickness, t_p, was 2.54 mm and the nozzle aspect ratio was 45:1. The contraction ratio upstream of the nozzle exit plane was 17.5:1. Wire mesh screens were used to reduce turbulence levels and to provide uniform velocity distribution across the nozzle span. Air was supplied to the nozzle at constant pressure from a compressor/receiver system.

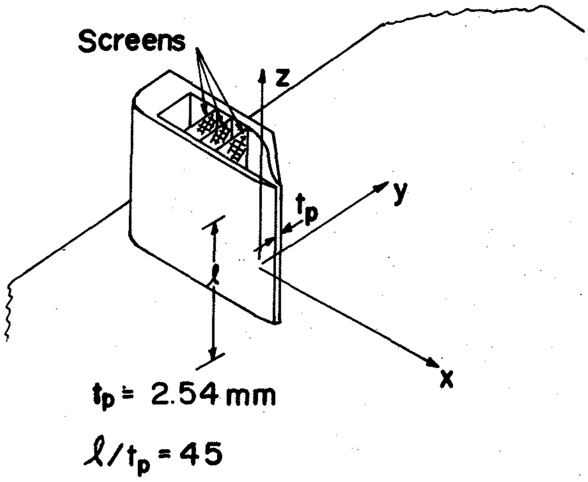

FIGURE 2: Sketch of Nozzle Block Used in this Study.

Two curved surfaces (constant radius and curvature) were used, with R/t_p values of 60 and 35. The spacing between the nozzle centreline and the cylindrical surface, h, (See Fig. 3) was variable with a minimum value of 1.75 t_p. However, because of the thickness of the inner wall of the nozzle block (= 1.25 t_p), observed results for small values of h are considered to be unreliable. The curved surfaces were equipped with static pressure taps along the mid-span, as shown schematically in Fig. 3. The static pressures were observed using a tilting, multi-tube manometer bank. The location of the static pressure taps is listed in Table 1.

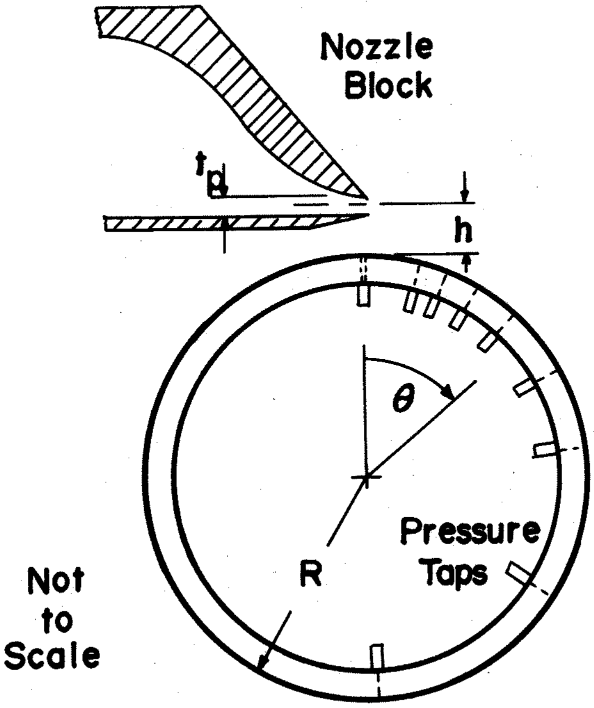

FIGURE 3: Sketch of Nozzle Block and Cylindrical Curved Surface.

TABLE 1

Pressure Tap Locations: Circular Wall

Tap No.	Angular Location Θ, deg.	Tap No.	Angular Location Θ, deg.
1	0	10	55
2	15	11	65
3	20	12	75
4	25	13	85
5	30	14	100
6	35	15	115
7	40	16	135
8	45	17	160
9	50	18	185

A total head tube, located in the mid-span plane, was arranged so that the tip of the probe traversed along radial lines, at any desired angle, Θ, measured as shown in Fig. 3. In this study, mean velocities were measured for only a small range of configurations, and no turbulence measurements were attempted.

The experiments were conducted at a nominal Reynolds number ($Re = V_{jet} t_p / \nu$) of about 12,500. Here V_{jet} is the mean velocity at the nozzle exit plane. The nozzle exit plane velocity was monitored at regular intervals during all experiments. Compressibility effects were ignored since the velocities were generally less than 80 $m\text{-}s^{-1}$. The primary air issued from the nozzle blocks at ambient temperature.

Presentation of Results

The principal observations are the wall static pressure distributions, Δp, observed with various gaps h (the dimensionless gap is H, where $H = h/t_p$). These are shown in Fig. 4 and 5 where the local static pressure defect, normalized with

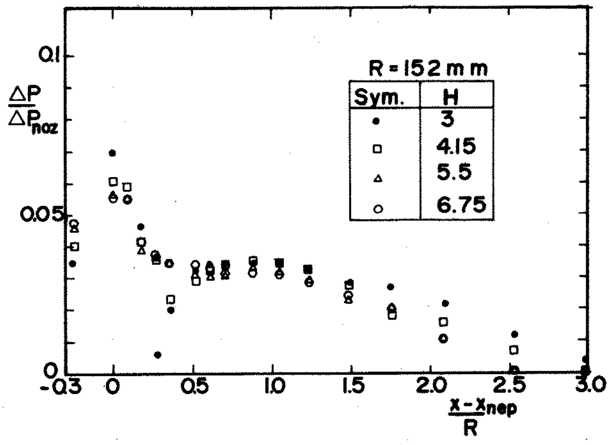

FIGURE 4: Wall Static Pressure Distribution: Large Radius Wall.

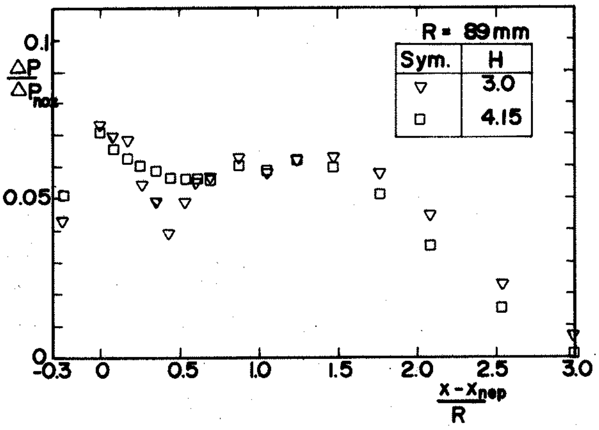

FIGURE 5: Wall Static Pressure Distribution: Small Radius Wall.

respect to the jet total pressure at the nozzle, is plotted against downstream distance measured from the nozzle exit plane. These plots indicate that the "attached" flows follow the curved surface for more than three radians. The general shape of these distributions agrees with the results of Newman's work(11). None of the data presented here are strictly comparable with Newman's work, since even for the cases where the secondary stream was blocked (Fig. 6) the inner surface of the nozzle was not coincident with the curved surface: a small step was present. Neither are these results strictly comparable with those of Paranjpe and Sridhar(18) or the work of Korbacher(17), since in these cases, the attachment surface constituted a bluff body protruding into the spreading jet. Nonetheless, the static pressure distributions show comparable behaviour in all cases. Because the "separation angle" is not sharply defined and hence difficult to locate precisely, no measurements of this quantity were undertaken.

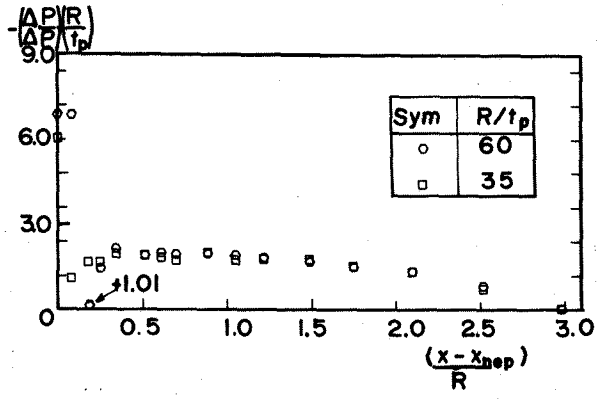

FIGURE 6: Wall Pressure: No Ventilation.

The pressure plots exhibit a region where the pressure is approximately constant, corresponding to a jet centreline which follows an approximately constant curvature path. Considering a radial force balance on an element of fluid along the jet centreline, close to the nozzle exit plane, we have $dp/dr=\rho V^2_{jet}/R^*$ where $R^* = R + h$. Approximating dp/dr by the pressure difference across the jet at the nozzle exit plane, $\Delta p \approx \frac{1}{2}\rho V_s^{\,2}$, we obtain $\lambda = V_{jet}/V_s$. For comparable plane jet flow (which should hold for small h/R), Marsters(3,4), has shown that $\lambda \approx C_1 A + C_2$ where $A = (2h - t_p)/t_p = 2H-1$. Assuming a linear relationship between λ and area, $\lambda \approx B_1 H + B_2$, leads to $R/t_p = 2(B_1 H + B_2)^2 - H$. Values of C_1 and C_2 taken from Ref. 4, yield $B_1 \approx 0.28$ and $B_2 \approx 2.5$. This equation for R/t_p in terms of H represents an estimate of the minimum radius of curvature for the jet trajectory near the nozzle. Using the constants above, $R/t_p (=\tilde{R})$ versus H is plotted in Fig. 7. Data from Refs. 17 and 18 are included along with data obtained in the present work. Clearly, all values subject to experimentation lie well within the stable attached flow retion, suggesting that the curve representing a momentum balance is optimistic. The single point due to Paranjpe and Sridhar(8) is taken from their "hysterisis plot" and probably represents a maximum value of H for the particular R they used. In this case the flat face of their reattachment cylinder was aligned with the nozzle exit plane and thus approximates the conditions of the present study. However, it could be reasoned that the bluff face of their wall would impede secondary flow, making the "effective value" of H smaller than the true value.

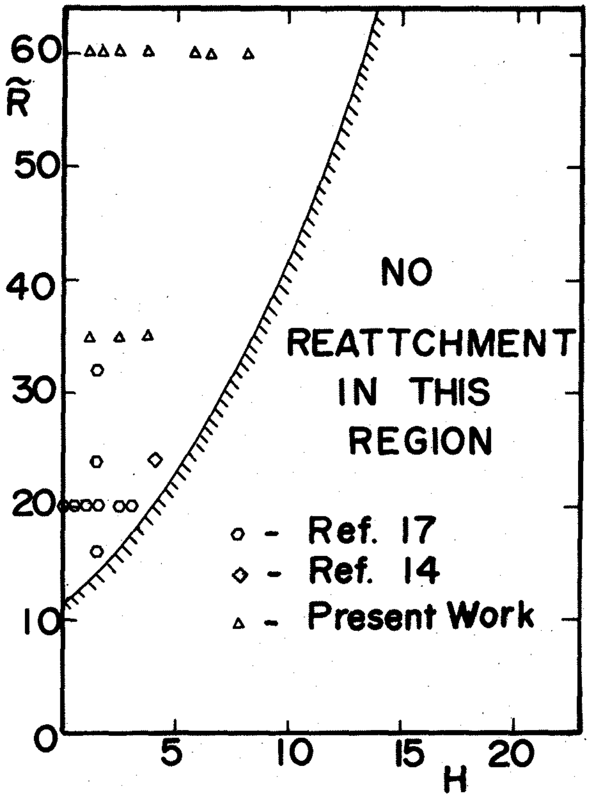

FIGURE 7: Attachment Limits for a Ventilated Plane Jet and a Curved Wall.

Applications

Integrations of the pressure distributions over the cylindrical surfaces yield quantities which can be referred to as "lift" and "drag", per unit span. The "lift" is the component of force, due to pressure on the cylinder, normal to the jet axis. When the flow is turned through almost 180°, the lift component is found to be slightly less than the nozzle exit momentum flux per unit span, $\rho V_{jet}^2 t_p$. If the flow as turned through 180° with no losses (e.g. constant speed) there would be no lifting force. However, as the flow slows down, the pressure on the surface rises, approaching ambient at the point where the flow ceases to follow the wall. The result is a net lifting force on the cylindrical surface. If the surface was terminated at about the 90° point, the lift component would be expected to exceed the nozzle exit momentum flux by a small amount. Similarly, the drag component would be expected to be slightly less than the nozzle exit momentum flux. The net result for the system would be a small net thrust and a lift force greater than the nozzle exit momentum flux. This apparent force amplification is attributable to the momentum imparted to the secondary stream entrained between the jet nozzle and the curved wall. The magnitude of the ratio of secondary to primary mass flow rate can be estimated from Fig. 4 or 5 since $\dot{m}_p = \rho V_s H t_p$ per unit span and $\dot{m}_s = \rho V_{jet} t_p$ so that

$$\frac{\dot{m}_s}{\dot{m}_p} = \frac{\rho V_s}{\rho V_{jet}} H = \left(\frac{\Delta p_s}{\Delta p_{noz}}\right)^{\frac{1}{2}} H$$

This exhibits a maximum value of 1.60 and falls to 0.791 for the large radius of curvature at the minimum gap. This estimation is not corrected for curvature effects which may have a sizeable influence. The pressure distribution patterns exhibited in Figs. 4 and 5 suggest that the pressure defect attributable to curvature may be as much as one half the pressure defect at the nozzle exit plane for $R/t_p = 60$ and as much as 3/4 of the defect at $R/t_p = 35$. If these approximate corrections are applied the mass flow ratio ranges from about 1.1 to about 0.56 for the larger radius surface. In any event, these values are somewhat higher than the values found for plane parallel walls and for inclined plane walls(4,5).

MIXING OF CRUCIFORM JET FLOWS

Statement of the Problem

Since jet mixing occurs by transport of momentum across the jet surfaces, it seems reasonable to expect that increasing the surface to cross-sectional area ratio may increase the rate at which momentum is transferred from the jet fluid to the surroundings. The findings of Whittley(1) suggests that this is true for confined flows at least. In a recent study, Marsters(9) has mapped the behaviour of the total pressure for jets issuing from a series of cruciform and rectangular nozzles. Some additional data on the mean flow have been obtained with slightly different cruciform nozzle geometries. These are discussed in terms of the centreline decay and the three-dimensional plots of total pressure.

Description of the Experiments

This work extends the earlier study(9) to include two additional cruciform nozzles. The three dimensional total pressure plots shown in Ref. 9 indicated the importance of the geometry upstream of the nozzle exit. Two different upstream treatments were examined: one, a smooth contour (circular arc) on all surfaces providing a smooth contraction, and two, geometrically similar cross-sections cut in thin plates so that the flow issued a "sharp edged orifice". These two arrangements resulted in significant differences in the down-stream total pressure distributions which were mapped in detail to distances of 36 nozzle slot widths from the nozzle exit plane.

This work reports observations on a smoothly contoured cruciform nozzle of the same family as those presented in Ref. 9, but with $\ell/t_p = 4$, where $t_p = 12.7$ mm, and a second cruciform nozzle, used by Montasser(10), also of $\ell/t_p = 4$, but with $t_p = 7.2$ mm. For this second nozzle, the upstream treatment was a long contoured shape, 20.3 t_p from inlet-to-exit plane, with a contraction ratio of 6.3. The nozzle was fashioned by slush casting a low melting point alloy on a carefully machined brass core. A sketch of this long nozzle is shown in Fig. 8.

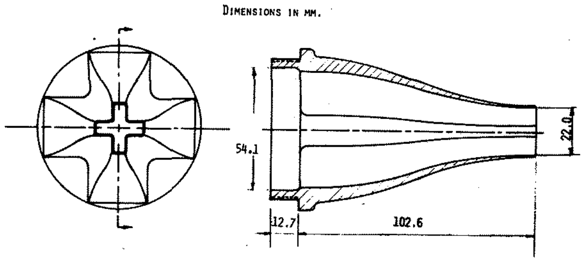

FIGURE 8: Sketch of the Long Cruciform Nozzle used by Montasser(10).

Presentation of Results

The total pressure distributions, taken at several x-stations for both nozzles is shown in Fig. 9. For comparison the total pressure distributions for a cruciform nozzle with $\ell/t_p = 12$ issuing from a contoured nozzle and from an orifice in a thin plate are shown in Fig. 10.

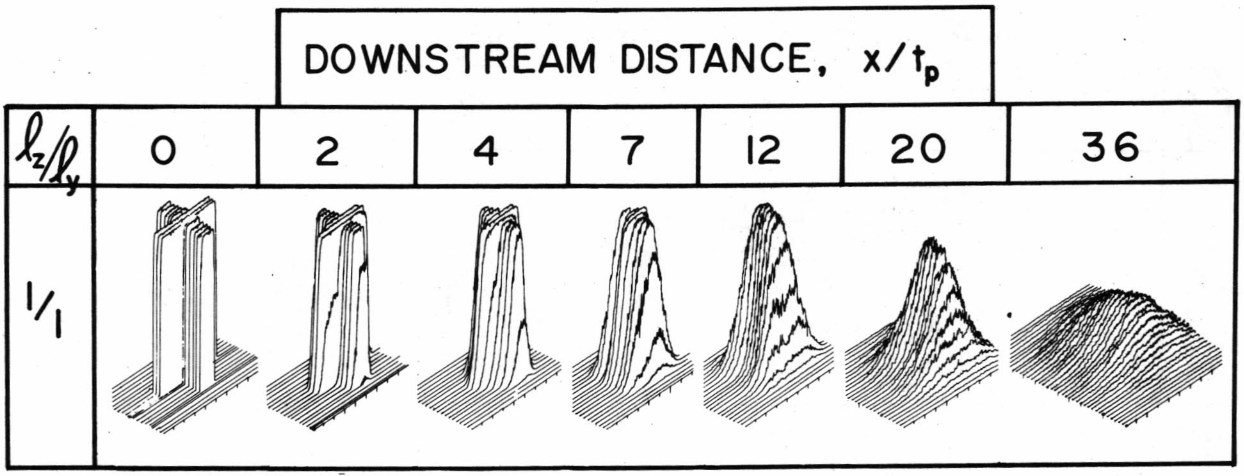

FIGURE 9a: Total Pressure Distribution in Jet Flow from a Cruciform Nozzle at 7 Downstream Stations. In Figures 9 through 11 the Vertical Deflection of the Trace from the Sloping Baseline Represents Total Pressure.

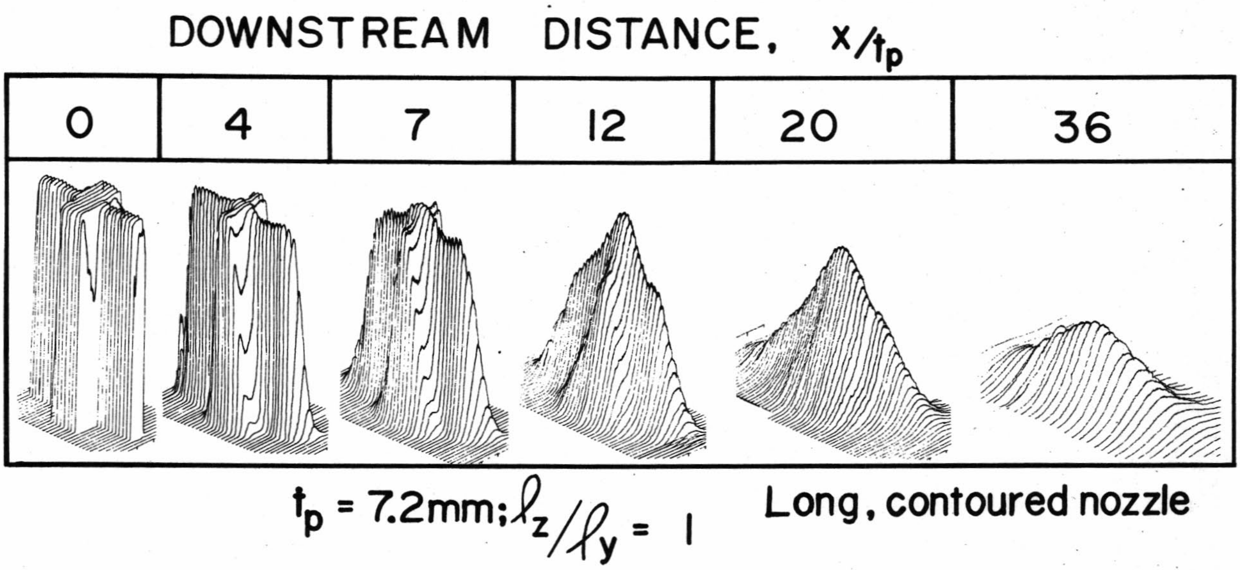

FIGURE 9b: Total Pressure Distribution Jet Flow from the Cruciform Nozzle used by Montasser(10).

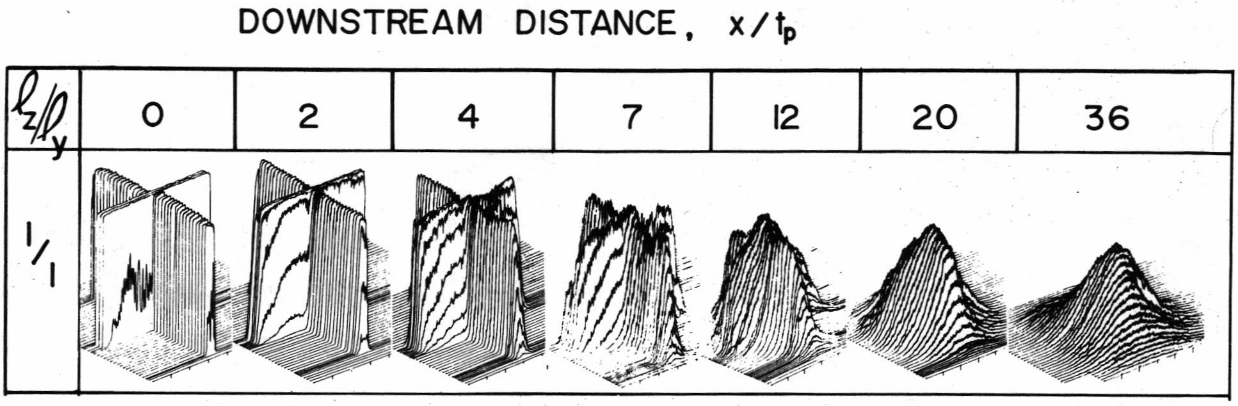

FIGURE 10a: Total Pressure Distribution in a Jet Flow from a Contoured Nozzle of an Aspect Ratio 12 (Ref. 9).

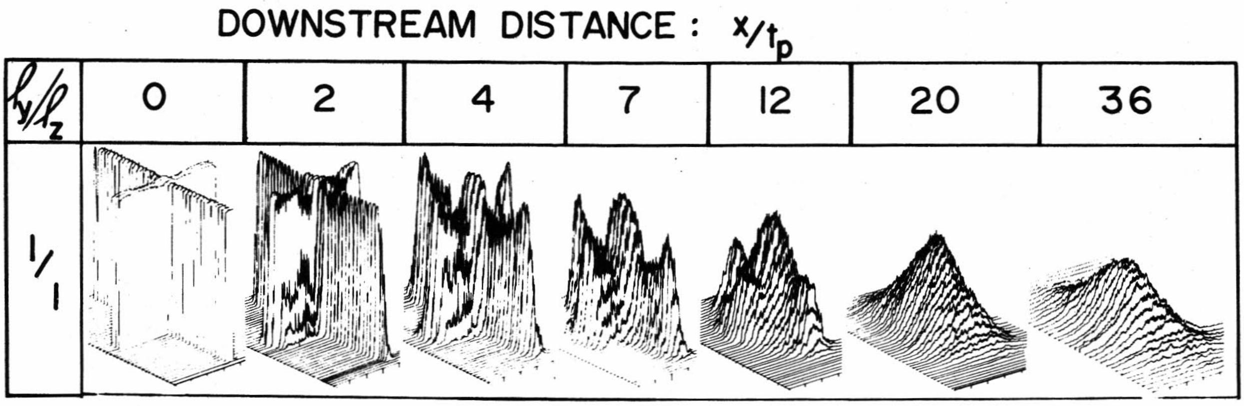

FIGURE 10b: Total Pressure Distribution in a Jet Flow from a Cruciform Nozzle Cut in a Thin Plate. (Ref. 9).

Similar plots for rectangular slot jets issuing from a contoured nozzle and an orifice in a thin plate are shown in Fig. 11. The effects of upstream shaping are clearly evident.

In the case of round and plane (2-dimensional) jet flows, the mean velocity achieves a self preserving form a few nozzle "lengths" from this nozzle exit. The centreline decay may then be taken as a measure of the rate at which the jet momentum is being imparted to the surrounding fluid. The evidence in Figs. 9 to 11 all indicate that in the case of cruciform jets, and rectangular slot jets issuing from sharp edged orifices, the centreline velocity is not representative of the momentum flux in the jet fluid. The profiles do not achieve similarity until far downstream. This point is effectively illuminated by considering the measurements centreline velocity decay, plotted in Fig. 12. The data are shown only for the configurations dealt within Figs. 9, 10 and 11. The full lines indicate the decay rates predicted (an generally observed) for plane and round jets. Reference to centreline decay only would suggest very slow momentum transfer, but examination of the total pressure plots indicates that the fluid in the "arms" is rapidly mixed, but that the centre portion of the jet is effectively isolated from the surrounding fluid while the shear layers grow, consuming the cruciform arms first. This is most dramatically seen by comparing the centreline decay rates for the three contoured nozzles.

These data suggests the following sequence in the "erosion" of the jet flow field. First, shear layers grow on all surfaces, and one may think of a tranverse "potential core" with respect to the cruciform arm thickness, which extends the order of $6t_p$ to $10t_p$ downstream. Simultaneously, a shear layer grows inward from the "ends" of the cruciform arms. The total pressure distribution at $x/t_p = 7$ and 12 illustrate this idea, and the notion that the centreline fluid is not influenced by the shear layers until the "spanwise potential core" is terminated at some point between 12 and 20 slot widths downstream. As a result, turbulent transport of momentum does not affect the centreline seriously until the cruciform arms have been processed by the growing shear layers. The overall efficiency of the momentum transfer process could only

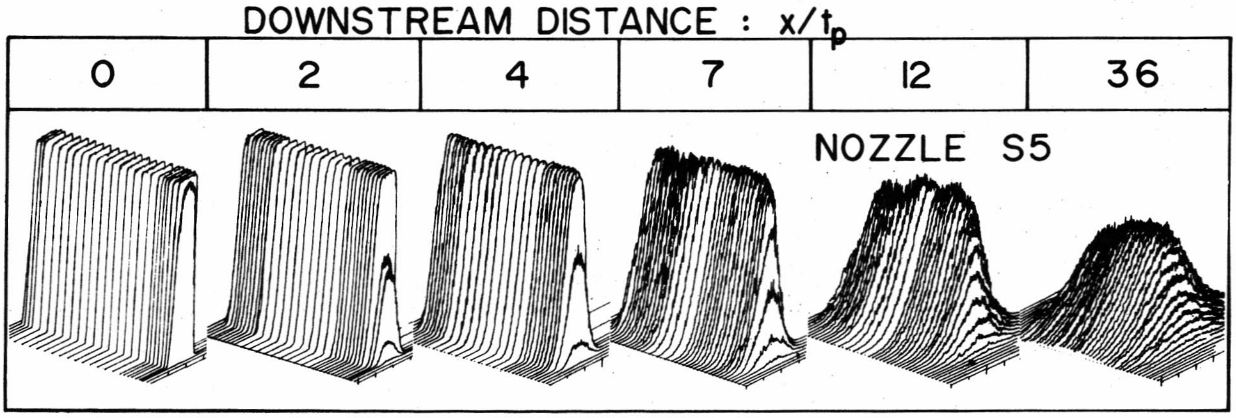

FIGURE 11a: Total Pressure Distribution for a Jet Flow from a Smoothly Contoured Slot Nozzle, Aspect Ratio: 12; t_p = 12.7 mm.

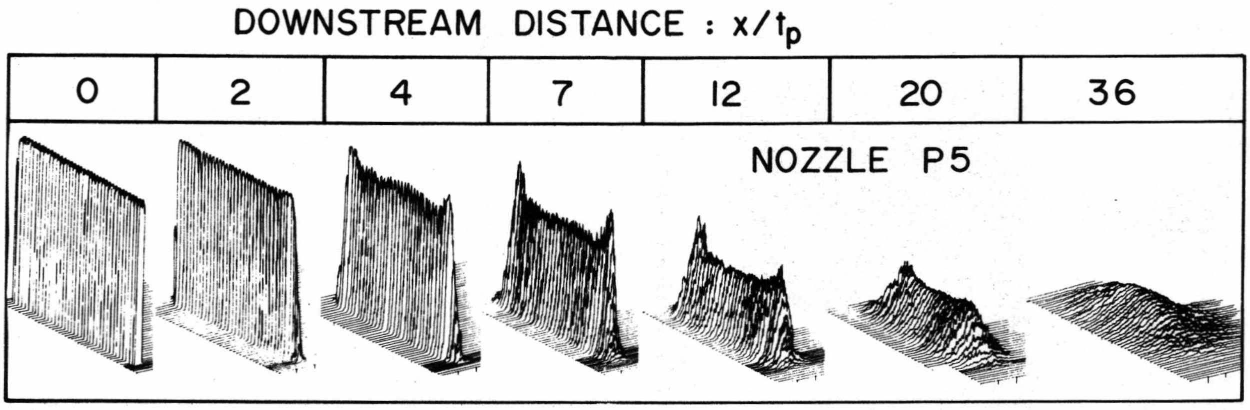

FIGURE 11b: Total Pressure Distributions in a Jet Flow from a Slot (Aspect Ratio 12, t_p = 12.7 mm) Cut in a Thin Plate.

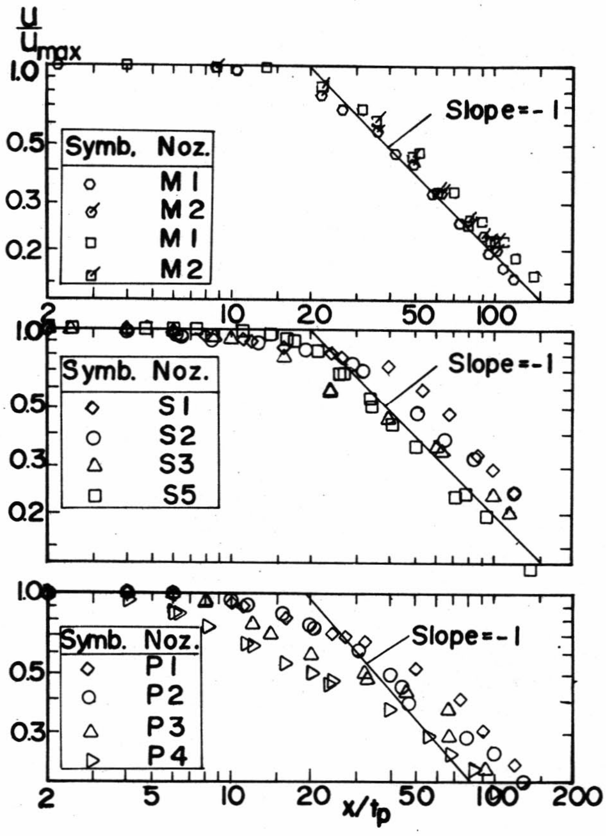

FIGURE 12: Centreline Decay of Velocity from Various Cruciform Geometries. M1 and M2 are geometrically similar nozzles used in Ref. 10. The letters P and S refer to slots cut in plates (P) or smoothly contoured nozzle shapes (S). The pertinent dimensions are given in Table 2.

be assessed by integrating the total pressure profiles at successive downstream stations and comparing the results with velocity decay rates for round nozzles. This has not been done. However, Montasser(10) has obtained force data for confined mixing using both round and cruciform jets and has found small but measurable increases in the overall thrust obtained using cruciform nozzles. This indicates increased momentum transfer rates and supports the conclusion of Whittley(1)

TABLE 2

Dimensions (mm) of Cruciform Nozzles

No.	Arm Length, ℓ_y	Slot Width t_p	Ratio of Arm Lengths ℓ_y/ℓ_z
M1	22	5.5	1
M2	28.8	7.2	1
P, S1	152.	12.7	1
P, S2	152.	12.7	2/3
P, S3	152.	12.7	1/3
P4	50.4	12.7	1
P5	152.	12.7	0

MULTIPLE NOZZLE FLOWS

Statement of the Problem

There is some evidence(1) that replacing a long slot nozzle with a segmented slot nozzle improves the thrusting capabilities of a thrust augmentor. Unfortunately, except for a few isolated studies, for example, Knystautus(19), there is little information on the nature of the mixing of multiple jets. While the final application in thrust augmenting devices requires a knowledge of the confined mixing processes, it was felt that useful insights could be gained from studying the behaviour of a row of slot jets issuing into still surroundings. Of particular interest is the nature of the merging of multiple jets into a single jet which ultimately, in the case examined here, takes on the characteristics of an axisymmetric jet.

The nozzle configuration used is shown in Fig. 13 which includes a sketch showing the coordinates and nozzle dimensions.

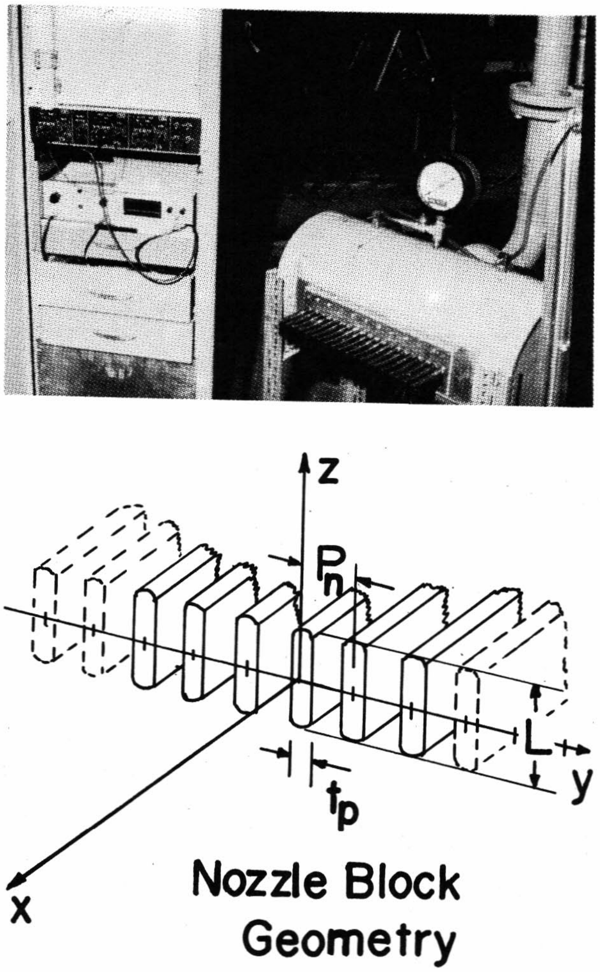

FIGURE 13: Photograph of Nottle Array and Sketch of Geometry.

Description of the Experiments

The experimental program consisted of carrying out velocity traverses across the flow for various nozzle combinations. By blocking the flow through alternate nozzles, the nozzle pitch could be changed from 2.22 t_p to 4.45 t_p. Some three dimensional total pressure plots have been obtained. An example of these is shown in Fig. 14. Fig. 15 consists of a sequence of transverse (y-direction) traverses carried out at several downstream stations, up to a distance of 102 t_p from the nozzle exit plane. These observations were made at a Reynolds number (Re = $V_{jet}t_p/\nu$) of about 47,000. This set of data shows clearly the coalescence process for 5 nozzles.

Presentation of Results

The averages of the peak velocities are plotted against downstream distance in Fig. 16 for several cases of nozzle spacing, number and pressure ratio. This gives a composite picture of the velocity decay and indicates clearly the near region, a characteristic decay region and finally a decay region characteristic of axisymmetric jet flows. The centreline decay shows a "cross over" behaviour of the same sort as appears in the case of two mixing plane jets(3). Detailed examination of the mean flow field has not yet been done, so that the spreading rates for the individual jets before coalescence are not available.

It seems clear that this class of flows will require considerable detailed study before the influence of the important parameters is fully understood. Studies of this flow field are continuing to obtain data to assist designers in

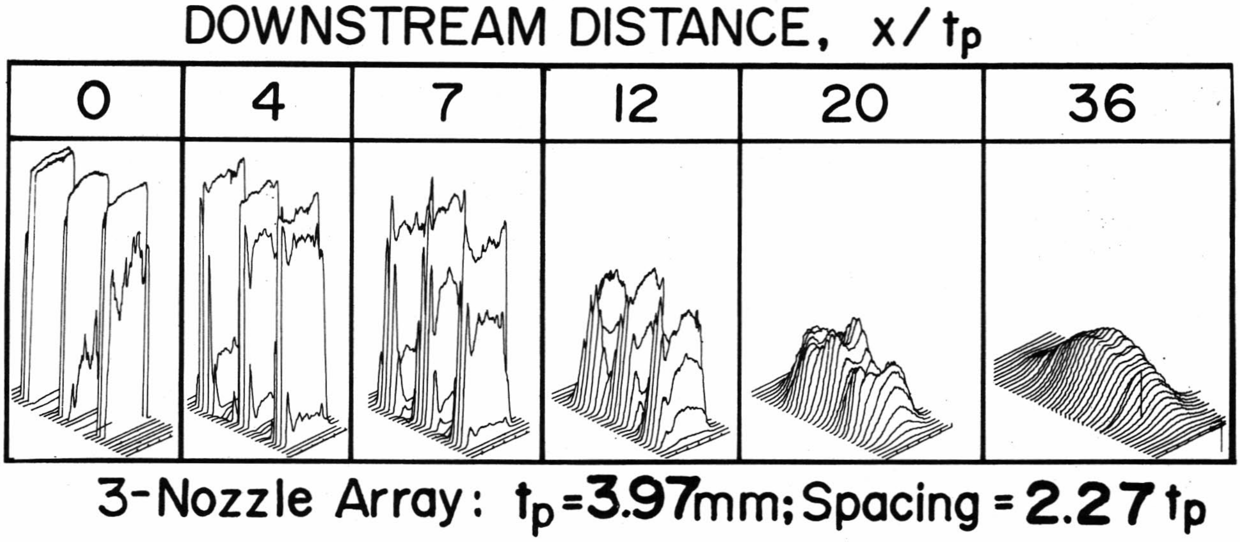

FIGURE 14: Total Pressure Distributions for 3-Nozzle Array.

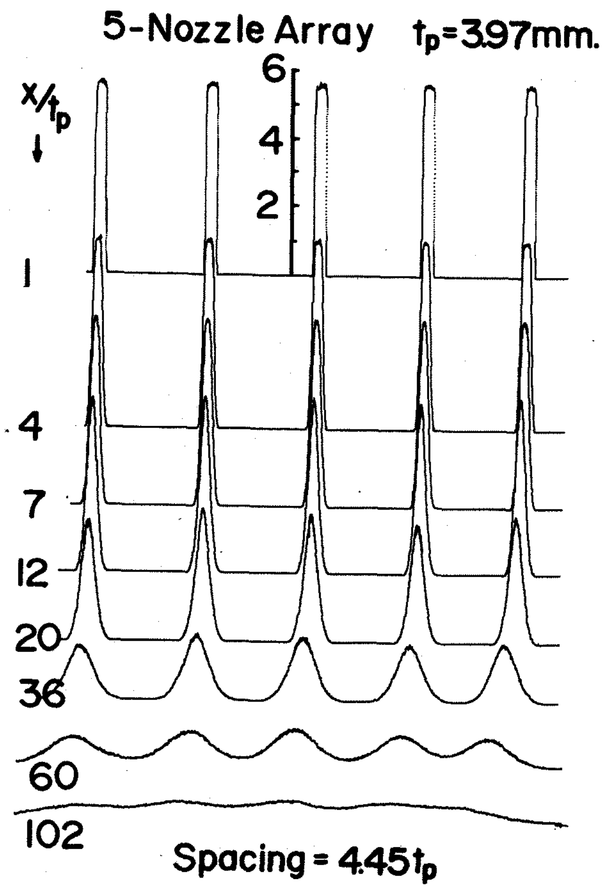

FIGURE 15: Spanwise Traverses (Total Pressure) for 5-Nozzle Array.

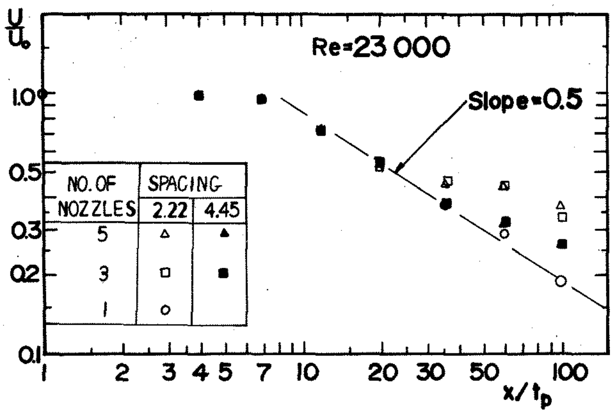

FIGURE 16: Decay of Peak Velocity in Multi Nozzle Jet Flow.

optimizing the geometry of nozzle arrays for purposes such as thrust augmentation.

SUMMARY AND CONCLUSIONS

In this paper we have presented some new results from experiments on three cases of jet flows where interactions, either with nearby solid surfaces or with other parts of the jet flow field, play a major role in the development of the flow field.

In the case of plane jets attaching to curved surfaces we have attempted to establish regions where attachment is possible when the flow is ventilated. Further, we have illustrated the effectiveness of this type of flow in "force vectoring" with measurable augmentation effects.

The cruciform nozzle study has shown that the centreline decay cannot be used as a measure of the extent of momentum transfer. It is argued that the cruciform "arms" shield the central portion of the jet. Although the total pressure diagrams are helpful as a flow visualization tool, the understanding of the mechanics of the flow development awaits more detailed study of the turbulence structure within the flow field.

The discussion concerning the flow field from a row of multiple jet nozzles is based upon some preliminary studies. Although the development of the flow field has been illustrated by means of total pressure diagrams, any conclusions drawn at this stage must be highly tentative.

Work is continuing in all the areas discussed in this paper. It is hoped that these results presented here will be of value to others working in the field of jet flows. The data may also be of value to turbulence researchers and to those who construct numerical models of free shear flows.

ACKNOWLEDGEMENTS

This work was conducted with the aid of a grant (No. A4310) from the National Research Council of Canada. The data were obtained with the assistance of Ms. M. Iwaniw and Messrs. Chris Hay, Tom Bernsten and Wael Montasser.

NOMENCLATURE

A	Secondary flow area
B_1, B_2	Constants
C_1, C_2	Constants
h	Gap between nozzle centreline and attachment surface
H	h/t_p
ℓ	Length of slot nozzle
ℓ_y, ℓ_z	Cruciform arm length
$\dot{m}_p$	Primary mass flow rate
$\dot{m}_s$	Secondary mass flow rate
p	Static pressure
P_n	Nozzle pitch (Fig. 13)
Δp	Pressure difference

Δp_{noz}	Nozzle pressure ratio
Δp_s	Secondary flow pressure drop
r	Radial coordinate
R	Radius of curved attachment surface
R^*	R + h
$\tilde{R}$	R/h
Re	Reynolds number
t_p	Nozzle "thickness"
x, y, z	Cartesian coordinates centred at nozzle exit plane, x along the jet axis
x_{nep}	Location of nozzle exit plane
U	Jet centreline velocity
U_o, U_{max}	Jet centreline velocity at nozzle exit plane
V_{jet}	Mean velocity at nozzle exit plane
V_s	Velocity of secondary flow

Greek Symbols

λ	V_{jet}/V_s
ρ	Flow density
θ	Angle defined in Fig. 3
ν	Kinematic viscosity

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