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Variable Control of Jet Decay

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The influence of blowing radially inward with a pair of control jets toward the centerline of and close to the exit from a circular main nozzle is investigated. Two regimes of control-jet influence exist, corresponding to conditions where the control jets are swept away in the turbulent mixing layer of the main jet or where they penetrate the central smooth-core flow. In the first regime, local velocity reductions in the main jet of up to 30% can be achieved with control-jet mass flows of 0.5% of that in the main-jet nozzle without severely distorting the main jet from its circular cross section. The action of the control jets is to promote more rapid mixing of the main-jet shear layer, and the response increases with the square of control-jet relative velocity and with the cube of its relative diameter. In the second regime, the main jet is strongly distorted from a circular cross section and local velocities in the main jet are less sensitive to control-jet velocity. The main-nozzle mass flow is influenced significantly in the second regime only when the control jets are very close to the main-nozzle lip.

Introduction

THE performance characteristics of a fluid-dynamic control system whereby the decay of a jet could be continuously controlled were investigated. A particular objective was the initial design of a control system whereby large-scale, low-frequency fluctuations in a jet could be dynamically controlled, thereby effecting control of the low-frequency sound produced by large distortions of the jet as described by Ffowcs Williams.[1] Although the scope of the present investigation has been limited to control under steady conditions, a fluid-dynamic control system has been selected in preference to any mechanical device because it would offer adequate dynamic response and would be physically more durable.

The decay of the flow from a circular nozzle has been extensively investigated and has been reviewed by Rajaratnam.[2] The influence of mechanical distortion of the nozzle, either by means of notches or by streamlined and bluff tabs, has been examined by Pannu and Johannesen[3] and by Bradbury and Khadem.[4] In the latter case it was found that relatively small bluff tabs protruding radially inward from the nozzle lip could substantially increase the rate of mixing and decay of the turbulent jet. In particular, it was found that when square tabs of side $D/16$ (where D is the main-nozzle diameter) were used, a maximum effect was obtained with only two diametrically opposed tabs. A smaller effect resulted when the number of tabs was increased. On the basis of these results it appeared that the simplest fluid-dynamic controller would be obtained by blowing two small control jets radially into the main jet to simulate the effect of the pair of tabs used by Bradbury and Khadem.[4] Variable control could thus be obtained by adjusting the control-jet stagnation pressure and varying the penetration of the control jets into the main-jet shear layer and smooth-core flow.

Influence of Control Jets on Main Jet Decay

The geometry of the control system is shown in Fig. 1. For most of the observations, a clearance of $D/16$ was allowed between the lip of the main jet and that of the control jet, in both radial and streamwise directions to the main jet, to avoid any interference between the spreading turbulent shear layers of either of the jets and the lip of the other nozzle. Both main- and control-jet nozzles had smooth contractions, and the velocity in both cases was calculated on the basis of the observed stagnation pressure upstream of the nozzles.

From schlieren photographs (Fig. 2) the extent of penetration of the main jet by the control jets can be seen. At low values of control-jet velocity relative to the main jet, the control-jet flow is mixed with and swept away in the turbulent shear layer of the main jet. At high values of control-jet velocity, the control jets penetrate right through the turbulent main-jet shear layer into the central smooth-core flow. The photographs show that when the control jets are active the main jet spreads more rapidly. This demonstrates that the control jets enhance the mixing of the main jet and thus reduce local mean velocities in the main jet. In order to characterize control-jet velocity under compressible flow conditions, a momentum equivalent velocity for the control jets (U_c) is introduced, defined as follows:

$$\rho_0 U_c^2 = \rho_{cn} U_{cn}^2 + (p_{cn} - p_0)\delta_c \tag{1}$$

where suffix *cn* denotes a condition at the control-nozzle exit plane, ρ denotes the density, and p is the local pressure. Suffix *0* refers to ambient conditions, and $\delta_c = 1$ if the control jet is choked or zero if the control jet is not choked. If C_0 is the ambient speed of sound, and the ratio of specific heats of the flow is 1.4, this equation leads to:

$$\frac{U_c}{C_0} = \left\{5\left[\left(\frac{p_{cs}}{p_0}\right)^{0.286} - 1\right]\right\}^{1/2} \tag{2}$$

for values of control-jet stagnation pressure (p_{cs}) less than that required to choke the control jets, and to

$$\frac{U_c}{C_0} = \left\{0.528\frac{p_{cs}}{p_0}\left[1 + \frac{0.528(p_{cs}/p_0) - 1}{0.740\,(p_{cs}/p_0)}\right]\right\}^{1/2} \tag{3}$$

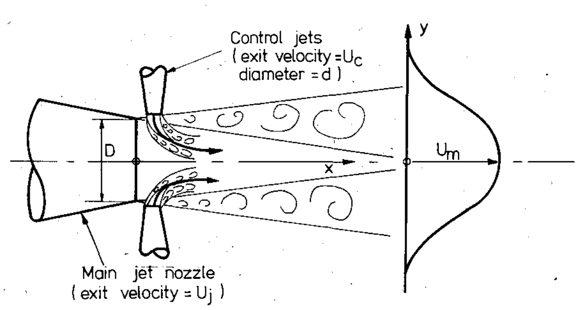

Fig. 1 General arrangement for control-jet layout.

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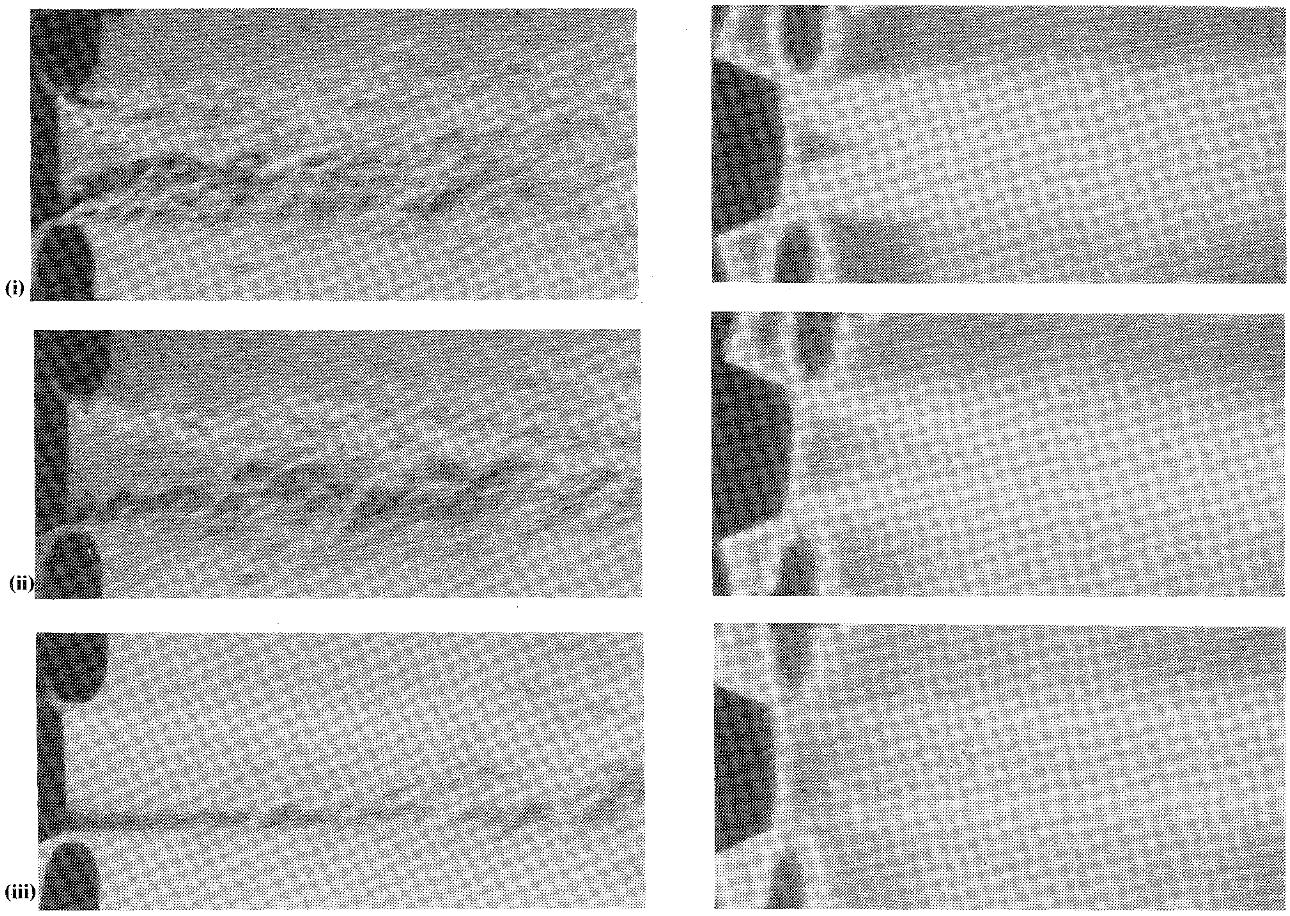

Fig. 2 Schlieren photographs of control-jet pattern ($d/D = 1/8$). a) Spark schlieren; b) time exposure schlieren. i) $U_c/U_j = 1.86$; ii) $U_c/U_j = 0.74$; iii) $U_c/U_j = 0.000$.

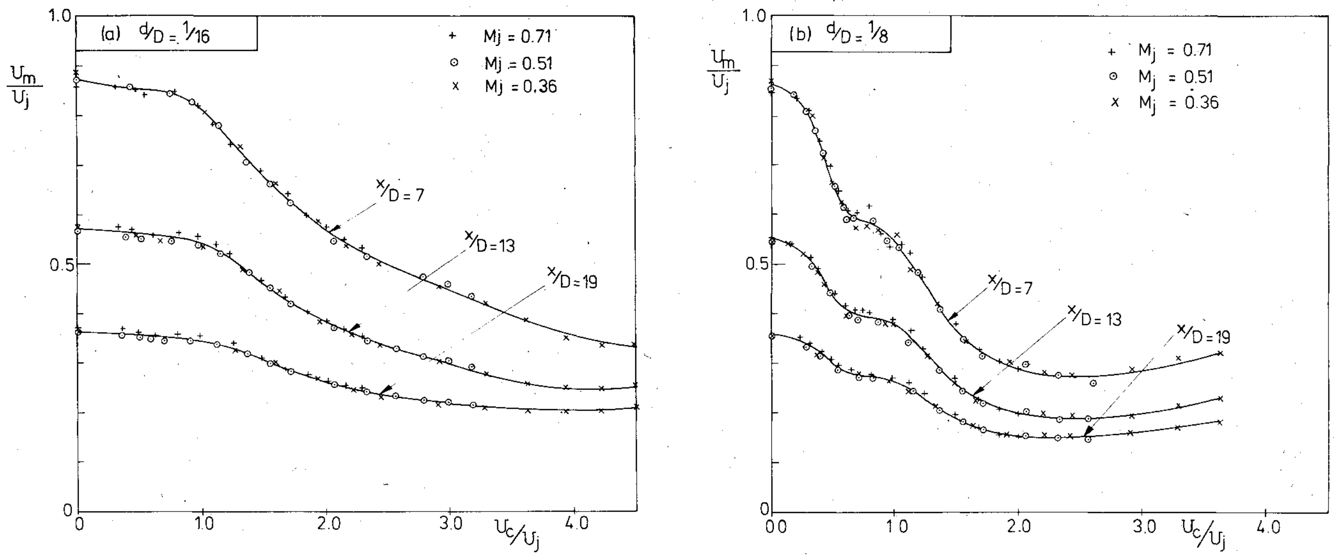

Fig. 3 Variation of local mean velocity (U_m) with control-jet velocity. a) $d/D = 1/16$; b) $d/D = 1/8$. Key: +, $M_j = 0.71$; ⊙, $M_j = 0.51$; ×, $M_j = 0.36$.

Table 1 Maximum sensitivity of local to control-jet velocity

d/D	x/D	$(dU_m/dU_c)_{max}$
1/16	7	0.30
	13	0.19
	19	0.09
1/8	7	0.93
	13	0.43
	19	0.18

Table 2 Parameters relating response of main-jet to control-jet velocity

d/D	Range of $U_c d/U_j D$	A	n	Standard deviation, Max. range nominal value, %
1/16	0-0.15	0.080	2	5.9
1/8	0-0.08	0.738	2	8.1
1/8	0.1-0.23	0.334	1	5.1

when the control jets are choked.

Local velocities in the main-jet flow were observed using a pitot-static tube having the NPL-type elliptical nose design. Figure 3 shows how the velocity on the centerline is reduced as the ratio of control-jet to main-jet velocity is increased for two different control-jet diameters. The main-jet velocity U_j was calculated from Eq. (2) on the basis of momentum flux, as for the control-jet velocity U_c. It is seen that the use of velocities given by Eqs. (1-3) has achieved the desired collapse of results in terms of the influence of the control jet upon main-jet decay, the decay being controlled by the ratio U_c/U_j and the diameter ratio d/D. Where the larger size control jet ($d/D=1/8$) is used, a much stronger influence is observed and the response of the main jet appears to be divided into two regions, for $U_c/U_j<0.6$ and $U_c/U_j>1.0$ approximately. The former region corresponds to cases where the control jet disrupts only the turbulent shear layer, but does not penetrate the smooth core significantly, as shown by the schlieren flow visualization (Fig. 2ii). The latter region corresponds to conditions where the control jets penetrate the smooth-core flow (Fig. 2i). The smaller control-jet size ($d/D=1/16$) produces a much less distinct change of behavior (Fig. 3a). The maximum sensitivity of local velocity to control-jet velocity $(\mathrm{d}U_m/\mathrm{d}U_c)_{\max}$, which occurs in the lower range of U_c/U_j, where the control jets disrupt the shear layer but do not penetrate the core, is shown in Table 1. The local velocity U_m denotes the mean velocity on the jet centerline and decreases steadily with increasing x/D. The highest sensitivity is obtained closer to the main-jet nozzle and approaches unit values for the large control jets ($d/D=1/8$) at $x/D=7$.

The characteristic law relating local velocity reduction to control-jet velocity was found to be close to $(-\Delta U_m/U_m)=A(U_c/U_j)^n$, as shown in Fig. 4 and Table 2. In the range where the control jet did not penetrate the core, the value of n was close to 2, whereas under conditions of stronger control-jet action it was near to unity. This finding suggested that in the former range the relative velocity reduction $-\Delta U_m/U_m$ was determined by the momentum flux injected by the control jets, and that the overall influence of the control jets could be represented by their momentum flux relative to that of the main jet. For this reason, Fig. 4 shows the local relative velocity reduction in terms of the parameter $U_c d/U_j D$, the square root of the ratio of jet momenta. The data for the two control-jet sizes do not collapse, however, and significantly different values of the constant A are obtained which are not in proportion to $(d/D)^2$. On the basis of these results it thus appears that a relation

$$-\Delta U_m/U_m=5.9\times10^2(U_c/U_j)^2(d/D)^{3.2}$$

best describes the results in the range where the control jets do not penetrate the main-jet core flow. This implies that the control-jet effect cannot be related simply to the momentum of that jet and that there is a significant size effect introduced by the diameter ratio d/D.

The distribution of local mean velocity over the flow cross section was observed by pitot-static probe traverses at $x/D=13$. For the range of control-jet operation described in the preceding paragraph, the jet remained close to circular in cross section. Thus under these conditions the increased rate of jet decay is caused by more rapid mixing in the turbulent shear layer. Where the control jet does penetrate the smooth-core flow of the main jet, significant distortion of the jet results, as shown in Fig. 5. The main jet is then split into two halves by the control jets, similar to the distortion observed by Bradbury and Khadem[4] using a pair of rigid tabs. The onset of distortion of the jet cross section was found to correspond to the distinct change in characteristics shown in Figs. 3b and 4b, at a velocity ratio of $U_c/U_j=0.6$ for $d/D=1/8$ and at $U_c/U_j=2.4$ for $d/D=1/16$. Thus we see that the physical basis for the changes in jet decay sensitivity to control-jet blowing lies in the change from enhanced shear layer mixing for lower ranges of U_c/U_j to severe distortion of the form of the main jet for the larger values of U_c/U_j.

When the control jets are located close to the main jet, they do interfere with main-jet-nozzle mass flow owing to the effective blocking action that the control jets produce, and thus main-nozzle mass flow can be reduced as control-jet velocity is increased under conditions of constant stagnation pressure and velocity in the main jet. As the clearance between the main-jet-nozzle lip and the control jet was increased, moving the latter further away in a streamwise direction x, the main-nozzle mass flow was influenced to a lesser degree until, with the control jets at $x/D=0.75$, no effect on main-nozzle flow was observed. However, the control action was still effective with this larger separation, as shown in Fig. 6. The control jets produced a somewhat smaller reduction of local velocity in the main jet at this larger separation, although sensitivity $(\mathrm{d}U_m/\mathrm{d}U_c)$ is observed almost comparable to that with very small control-jet/main-nozzle clearance. At the larger separation between nozzles the main-jet local velocity also shows a smoother variation with control-jet velocity, with a much less distinct change in characteristics from nonpenetrating to penetrating control-jet flow as discussed in previous paragraphs. This would be expected, as the main-jet turbulent shear layer would be much thicker at $x/D=0.75$,

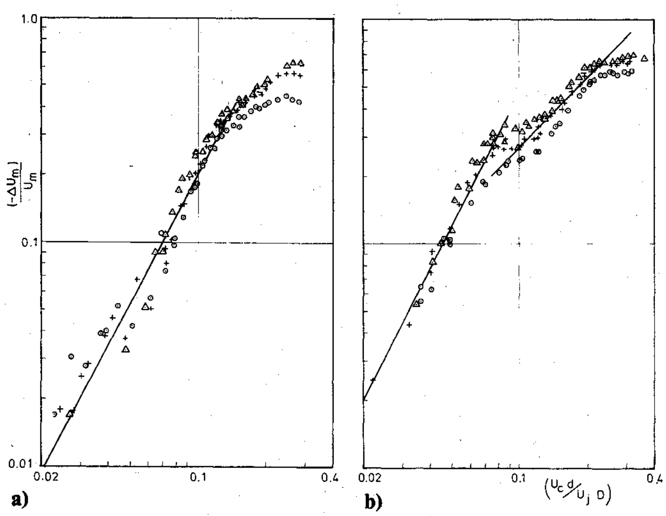

Fig. 4 Incremental reduction of local velocity ($\Delta U_m/U_m$) with $U_c d/U_j D$. a) $d/D=1/16$; b) $d/D=1/8$. Key: Δ, $x/D=7$; +, $x/D=13$; ⊙, $x/D=19$.

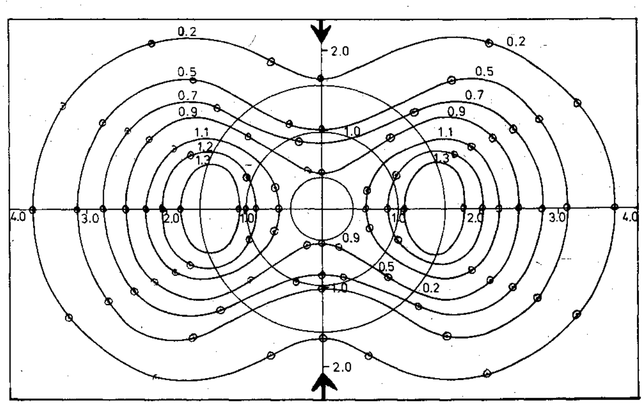

Fig. 5 Contours of equal velocity on jet cross section. ($x/D=13$, $d/D=1/8$, $M_j=0.71$, $U_c/U_j=1.68$, coordinates are in units of y/D, values against curves are for U/U_m, where U_m is the velocity at the jet center. Circles indicate cross section of undisturbed main jet. Contours are smoothly fitted to data points shown.)

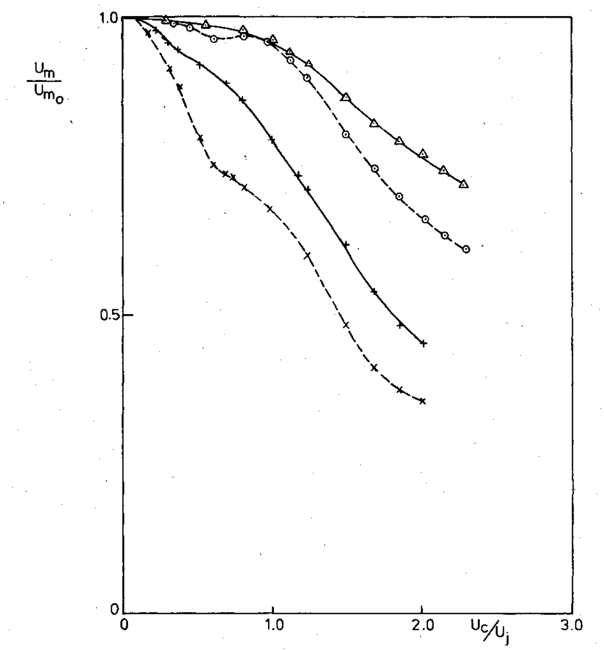

Fig. 6 Variation of local mean velocity (U_m) for different control-jet locations:—control jets at $x/D = 0.75$; ---control jets at $x/D = 0.063$; ▲, ⊙, $d/D = 1/16$; +, ×, $d/D = 1/8$ ($M_j = 0.71$).

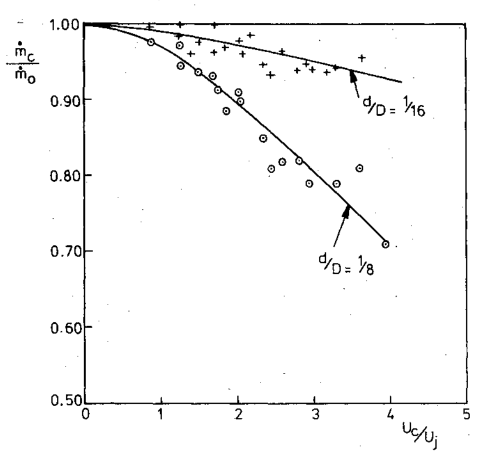

Fig. 7 Reduction of main-jet mass flow (m_c) with control jets at $x/D = 0.063$ (m_0 = mass flow with no control-jet flow): +, $d/D = 1.16$, ⊙, $d/D = 1/8$ ($M_j = 0.71$).

and thus the penetration of the control jet flows would show a more progressive development.

The reduction of main-nozzle mass flow by the control jets at close separation of nozzles is shown in Fig. 7. The main-nozzle mass flow was observed by a flow meter upstream in the supply pipe to the nozzle. At the condition where the control jet begins to substantially penetrate the main jet core ($U_c/U_j = 0.6$ and 2.4 for $d/D = 1/8$ and 1/16, respectively) the reduction of mass flow (1.5% and 4.5%, respectively, from Fig. 7) is much less than the corresponding reduction of local centerline velocity (26% and 31%, from Fig. 4 at the same conditions where the change in characteristics occurs). Thus we see that the influence of the control jets is predominantly to enhance the mixing rate in the main-jet turbulent mixing zone to produce a more rapid decay and that these reductions in local velocities are influenced by the reduction of main-nozzle mass flow to a much smaller extent.

Conclusions

The influence of the control jets is related to their effective velocity, making appropriate corrections for compressible flow effects. Two regimes of control-jet action have been identified. At moderate control-jet velocities, the main jet is not penetrated or severely distorted and the main-nozzle mass flow is not greatly influenced. Within this regime the action of the control jets is to enhance the mixing rate in the main-jet turbulent zones and to bring about reductions of the local velocities up to approximately 30%. The reduction of main-jet velocity was found to vary with the square of control-jet velocity and the cube (approximately) of control-jet size. Thus control-jet action cannot simply be related to relative velocity, relative mass flow, or relative momentum flux, and a significant size effect exists depending upon the diameter ratio of the nozzles d/D. Within this first regime the mixing main jet remained essentially circular in cross section, the more rapid decay being induced therefore by enhanced turbulent mixing.

The second regime of control-jet action occurs at higher control-jet velocities, the transitional velocity ratio U_c/U_j depending upon the ratio of nozzle sizes d/D. In this regime, the control jet penetrates the smooth core of the main-nozzle flow and introduces a significant distortion of the main-jet cross section from circular form. Although the control jets retain their action for a variety of spacings between main and control nozzles, as this spacing (in a main-jet streamwise sense) is increased, so the transition from nonpenetrating to penetrating behavior becomes less distinct although the control action is retained.

The most sensitive control of main-jet decay is achieved at lower control-jet velocities in the first regime of control action, where the control jets do not distort the main flow severely but act to enhance its mixing rate. Thus enhancement of turbulent mixing by moderate-velocity control jets is a more sensitive means of control than strong control-jet or mechanical tab action, which both produce severe distortion of the jet from its circular cross section. Although a larger control-jet size will produce a significantly greater sensitivity (dU_m/dU_c), the variation of control effect with control-nozzle size shows that comparable local velocity changes can be achieved with less control-jet mass flow by using a smaller control-jet size. For example, Fig. 4 shows that a 10% reduction in main-jet local velocity can be brought about using a control-jet mass flow of 0.44% of the main-jet mass flow from the smaller control nozzles ($d/D = 1/16$), whereas the same reduction with larger control nozzles ($d/D = 1/8$) requires a control-jet flow of 0.56%. However, the influence of control-jet size on the mass flow required to produce a given effect is clearly not very great, as could also be inferred from the variation of main-jet velocity reductions with $(U_c/U_j)^2 (d/D)^{3.2}$ shown by the results of Fig. 4.

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