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Rotation effects on inhomogeneous mixing in axisymmetric sudden-expansion flows

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Abstract—Rotation effects on variable-density co-axial jet mixing in an axisymmetric sudden-expansion geometry are investigated experimentally. A central air jet surrounded by an annular helium/air jet is injected into a circular tube with an enlarged cross-sectional area. Two cases are examined in detail; one stationary and another with a constant speed of rotation of 840 r.p.m. about the tube axis. Results show that mixing between helium and air is greatly enhanced by rotation. Consequently, the recirculation region downstream of the sudden expansion is reduced and the reattachment length is decreased by about a factor of three. However, the flow at 30 step heights downstream of the sudden expansion is essentially identical for both the stationary and rotation cases.

1. INTRODUCTION

SUDDEN-expansion flows are a common occurrence in airbreathing propulsion systems. A typical example is the integral rocket-ramjet where a sudden-expansion dump combustor is used as the basic ramjet combustor. The reacting flow in such combustors is extremely complicated. As a result, not many details are known of the ramjet dump-combustor flows. This lack of knowledge renders the systematic design of dump combustors for ramjets very difficult and the assessment of such factors as missile rotation, fuel density, fuel injection velocity, etc. on combustor performance very inaccurate. A trial-and-error approach is often used to design ramjet combustors. However, even such an approach would require some basic understanding of the turbulent fluid mechanics in sudden-expansion flows.

Isothermal, incompressible sudden-expansion flows have been examined by numerous investigators. A good review of two-dimensional sudden-expansion flows is given by Eaton and Johnston [1]. As for axisymmetric sudden-expansion flows, a brief review of some recent work is provided by So and Ahmed [2] who also find that rotation of the flow field about the tube axis has tremendous effect on the reattachment length downstream of the sudden expansion. In particular, the reattachment length is found to decrease linearly with increasing rotational speed (Fig. 1). Further examination of published data on stationary axisymmetric sudden-expansion flows by So [3] reveals that, among the important parameters that affect reattachment length, inlet centerline turbulence stands out as the most important; namely, increased inlet centerline turbulence causes the reattachment length to decrease. Since the recirculation region in a ramjet dump combustor is used to anchor the flame, the size of this region is crucial to the performance of the combustor. The studies of So and Ahmed [2] and So [3] have shown that the size of the recirculation region is adversely affected by rotation and inlet turbulence. In actual combustors, other factors such as variable-density mixing, heat release, chemical reactions, etc. could combine to enhance the adverse effects of rotation and inlet turbulence. Therefore, there is a need to study the combined effects of some of these factors on the recirculation behavior in dump-combustor flows.

Numerous attempts have been made by various researchers to study the non-isothermal flow field in model and actual dump combustors. These include the experimental work of Yamada *et al.* [4] and Dunlap *et al.* [5] who investigate the flow field in solid propellant combustors. Because of fuel sublimation, the flow field in the combustor is also affected by the sublimation velocity, which is absent in a liquid-fuel dump combustor. On the other hand, a model dump-combustor flow field is investigated by Chang *et al.* [6] and Drewry [7]. The former examines the distributions of gas species in dump combustors using an on-line gas-sampling system, while the latter studies fuel–air mixing in a non-reacting environment. In addition, Drewry [7] also varies the inlet Mach number from 0.42 to 1 and determines its combined effect with variable-density mixing on the recirculation flow behavior. Even though detailed species concentration measurements are made, velocity measurements are not available in the studies of Chang *et al.* [6] and Drewry [7]. Consequently, a complete interpretation of the combined effects of the various parameters on the recirculation flow behavior is not possible.

Detailed measurements of isothermal dump-combustor flows and sudden-expansion flows using hot wires and laser Doppler techniques have been attempted by Habib and Whitelaw [8], Yang and Yu

NOMENCLATURE

- $\tilde{c}$ instantaneous helium volume concentration
- c fluctuating part of $\tilde{c}$
- c' r.m.s. of c
- C mean value of $\tilde{c}$
- d_1 diameter of inlet nozzle (see Fig. 2)
- d_2 diameter of downstream tube (see Fig. 2)
- H step height, $(d_2 - d_1)/2$
- r radial coordinate measured from tube center
- R radius of downstream tube, $d_2/2$
- $\tilde{u}$ instantaneous axial velocity
- u fluctuating part of $\tilde{u}$
- u' r.m.s. of u
- U mean of $\tilde{u}$
- $\tilde{v}$ instantaneous radial velocity
- $\tilde{w}$ instantaneous circumferential velocity
- w fluctuating part of $\tilde{w}$
- w' r.m.s. of w
- W mean of $\tilde{w}$
- x axial coordinate measured from entrance to sudden expansion
- x_L reattachment length.

Greek symbols
- ρ fluid or mean mixture density
- ψ stream function
- Ω tube rotational speed in r.p.m.

Subscripts
- a air
- cl centerline values
- h helium
- j central air jet condition
- 0 annular helium/air jet condition.

[9], Stevenson *et al.* [10] and Durrett *et al.* [11]. Among these studies, only the work of Habib and Whitelaw [8] deals with co-axial jets into a sudden expansion. The others are concerned with a single jet only. Furthermore, Habib and Whitelaw [8] provide detailed measurements of the reattachment lengths and investigate the effects of jet velocity ratio and swirl on the formation of the recirculation region. Therefore, their results provide some insight into the question of fluid rotation on flow reattachment. However, all these studies are concerned with homogeneous flow only and no attempt has been made to study both the scalar and velocity fields together.

The present study intends to fill some of this void and makes an effort to investigate the combined effects of rotation and binary mixing in an axisymmetric sudden-expansion flow. Results from this investigation can then be compared with those obtained by Habib and Whitelaw [8] and So and Ahmed [2] so that the effects of rotation and variable-density mixing on the development of the recirculation region can be identified.

2. EXPERIMENTAL SET-UP

The experiments are carried out in the rotating sudden-expansion flow facility of So and Ahmed [2]. A schematic showing the details of the present test section is given in Fig. 2. Essentially, the test rig is made up of a Plexiglas tube 76.2 cm long and fitted with two well-contoured nozzles made of aluminum. One nozzle is placed at the tube exit end, while the other is located eight tube diameters upstream of the first nozzle. The Plexiglas tube is supported by two pillow block bearings, one at each end of the tube. A hollow aluminum cylinder with the same dimensions as the Plexiglas tube and a closed end is installed against the nozzle at the tube inlet. The closed end of the

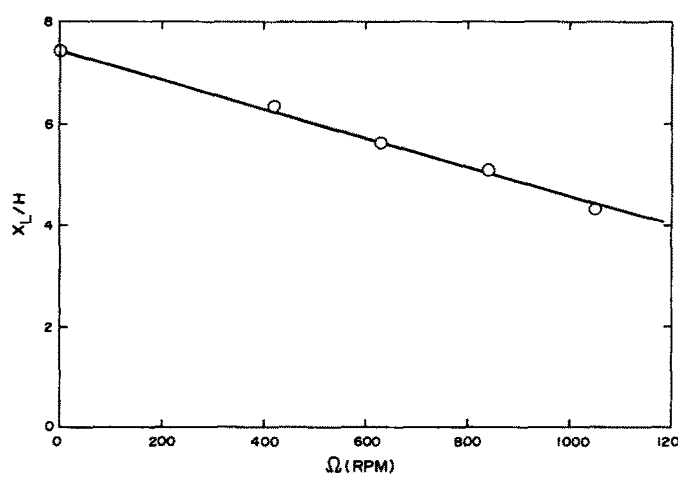

FIG. 1. Effect of tube rotation on flow reattachment (results from ref. [2]).

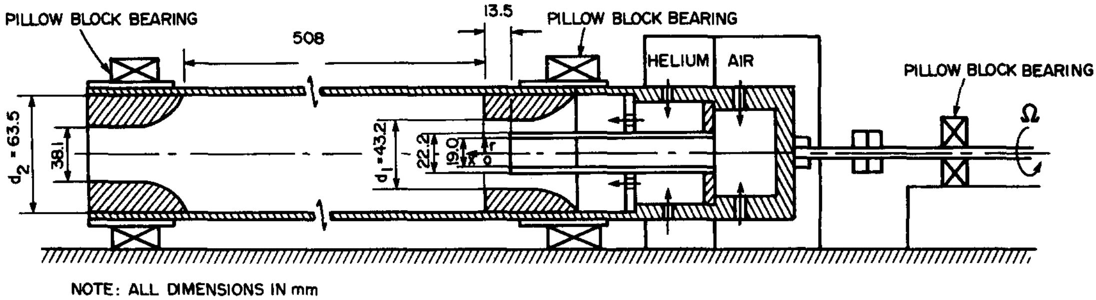

FIG. 2. Detailed geometry of test rig.

aluminum cylinder is fitted with a drive shaft which is connected to the motor drive shaft through a Gerbing coupling. Again, pillow block bearings are used to support the motor drive shaft. A 1.5 hp variable-speed motor connected to a speed controller (not shown in Fig. 2) is used to rotate the Plexiglas tube. The maximum possible speed of rotation is 2500 r.p.m.

For the present study, the hollow aluminum cylinder is equipped with a co-axial cylindrical tube as shown in Fig. 2. This arrangement divides the hollow cylinder into two compartments, thus allowing the admission of two different gases into the Plexiglas tube. Eight holes (6.35 mm in diameter) spaced at $\pi/4$ apart are drilled around the cylinder circumference in the two different compartments to allow gases to flow through the compartments. The dimensions of the test rig are as indicated in Fig. 2, thus giving a step height of $H = 10.15$ mm and a diameter ratio of $d_2/d_1 = 1.47$.

Two settling chambers are used to enclose the aluminum cylinder and an exit chamber (not shown) is used to enclose the open end of the Plexiglas tube. A blower, operating in the suction mode, is connected to the exit chamber. Therefore, gases supplied to the chambers surrounding the aluminum tube will be sucked through the holes and into the Plexiglas tube. Room air and bottled helium, conditioned to room temperature, are used as working fluids in the present experiment. They are supplied through openings in the two settling chambers. Therefore, this ensures that isothermal binary mixing is established inside the test rig.

3. INSTRUMENTATION AND TECHNIQUES

Two different techniques are used to resolve the binary mixing behavior in the rotating sudden-expansion flow. A laser Doppler anemometer (LDA) is used to resolve the velocity field, while a hot-wire type concentration probe, similar to the one used by Ahmed and So [12] and So and Ahmed [13], is used to measure the species concentration field. The probe is designed to be independent of upstream velocity [14] and is calibrated to give helium volume concentrations [12].

According to Brown and Rebollo [14], the hot-wire sensor is sensitive to gas concentration only provided the upstream stagnation condition is constant. In an isothermal rotating flow, the stagnation pressure varies radially. Since the probe is designed like a convergent/divergent nozzle with the hot-wire sensor placed at ~ 100 throat diameters downstream, the same flow condition would prevail at the sensor location provided the same stagnation-to-back pressure ratio exists across the probe. The effect of varying stagnation pressure on probe response at a fixed back pressure has been investigated by Ahmed and So [12] in a swirling flow, where the mean circumferential velocity, W, varies from 0 at the tube center to ~ 20 m s^{-1} near the tube wall. Their investigation shows that over this range of W, the maximum error in the measured mean volume concentration of helium, C, is less than 3%. Consequently, Ahmed and So [12, 13] used a fixed back pressure for the probe to measure C in a swirling flow. For the present application, the maximum W is less than 9 m s^{-1} (for a tube rotational speed of ~ 2500 r.p.m.); therefore, the concentration probe can again be operated with a fixed back pressure. The measurement error is expected to be less than 3% at the maximum.

The shape of the concentration probe is designed like a Z, with a 70 cm long probe support. It is introduced into the test section along the tube axis and through the exit chamber. Therefore, the probe can traverse across the sudden-expansion tube irrespective of whether the tube is rotating or not. The probe is mounted on a manual two-dimensional traverse, so that it can map the flow both along the x- and r-directions. Due to the long length of the probe support, flow-induced vibration causes significant deflection at the probe tip. Strengthening the probe support reduces the probe tip vibration tremendously. However, the probe captured volume is still estimated to have a diameter of ~ 0.5 mm in spite of the fact that the probe opening has a diameter of 0.13 mm. Therefore, the spatial resolution of helium concentration measurement is no better than 0.5 mm.

The probe is calibrated by placing it in the potential core of a free jet with a known mixture of helium and air. Hot-wire instruments used with the probe consist of DISA Model 56C01 constant temperature anemometer, Model 56C16 general purpose CTA bridge and Model 56N21 linearizer. The hot-wire signal from the linearizer is digitized using a Phoenix Model 6412

A/D converter and then analyzed in a PDP 11-03 mini-computer system. Details of the computer system and the associated data analysis software can be found in So *et al.* [15].

A standard DISA Model 55X LDA system, used by So and Ahmed [2] in their study of rotation effects on sudden-expansion flows, is used to measure the velocity field in the present experiments. An 80 mm focal length front lens is used. This results in a sampling volume with dimensions of 0.26 mm length and 0.04 mm width. Measurements of $\tilde{u}$ and $\tilde{w}$ across the tube are made in the horizontal plane passing through the tube axis and the vertical plane perpendicular to the tube axis. The complete LDA system is mounted on a manual two-dimensional traverse. This traversing mechanism and the one used in conjunction with the concentration probe is accurate to 0.20 mm in the radial direction and to 0.5 mm in the stream direction. The LDA/traversing and probe/traversing systems are mounted on separate support tables, so that motor vibrations from the test rig are completely isolated from these two diagnostic instruments.

The LDA signal quality and frequency resolution are improved by seeding both the air and helium flow. Liquid droplets (50% water and 50% glycerine) generated by two DISA Model 55L18 seeding generators are deposited into the air and helium chambers. Thus, a very high seeding rate is achieved and this provides a nearly continuous LDA signal. Consequently, data can be collected at a fixed rate. This allows the velocity bias to be removed and transit time weighting becomes unnecessary. The droplets are centered around 1 μm and are carried into the chambers by an air stream, the speed of which is used to control the droplet concentration. As a result of seeding and leakage from the air chamber, it is not possible to establish a co-axial stream of pure helium. Therefore, the helium concentration at $x = -13.5$ mm has to be measured to establish the initial condition for the annular helium/air stream. Unfortunately, the axial velocity at this location cannot be measured using LDA. The first location where $\tilde{u}$ is available is at $x = 5.5$ mm. Consequently, the velocities of the co-axial streams at $x = -13.5$ mm are assumed to be uniform in order to determine the total mass flux (air stream plus co-axial helium/air stream) at this location. Subsequent measurements of $\tilde{u}$ and $\tilde{c}$ at $x > 0$ yield mass flux calculations that agree to within 5% of the estimate of the inlet mass flux assuming uniform U at $x = -13.5$ mm for the co-axial jets.

4. TEST CONDITIONS AND DATA ANALYSES

Two sets of experiments are carried out; one with $\Omega = 0$, and another with $\Omega = 840$ r.p.m. (or 88 rad s^{-1}). These experiments are conducted at one inlet condition, i.e. at $x = -13.5$ mm, $C_0 = 0.54$, $U_0 = 8$ m s^{-1} and $U_j = 24$ m s^{-1}. In the course of this investigation, the velocity ratio U_j/U_0 is found to vary between 2.85 and 3.13 with an average value of 2.95, and C_0 varies between 0.54 and 0.55. The density ratio between the annular and air jet, ρ_0/ρ_j, is ~ 0.54. Therefore, the air jet is twice as heavy as the annular helium/air jet.

Concentration measurements are carried out at 13 different x locations ranging from $x/H = -1.33$ to 30.54. The measurements of $\tilde{u}$ are also made at the same locations, except at $x/H = -1.33$ and 30.54. Thus, the mass flux at any x location can be calculated from the $\tilde{u}$ and $\tilde{c}$ measurements and checked for continuity. On the other hand, $\tilde{w}$ is measured at selected locations in the range $1.28 \leqslant x/H \leqslant 24.63$.

Statistical analyses are performed on the data $\tilde{u}$, $\tilde{w}$ and $\tilde{c}$. Their mean and r.m.s. values are calculated from data records obtained at the rate of 2000 samples per second. A total record length of 4 s is analyzed at each sampling location. From the mean values of $\tilde{u}$ and $\tilde{c}$, the stream function

$$\psi = \int_0^r \rho U r \, \mathrm{d}r \tag{1}$$

can be calculated. Here, the mean mixture density, ρ, is given by

$$\rho = \rho_h C + (1-C)\rho_a. \tag{2}$$

Therefore, a normalized stream function plot, ψ/ψ_{cl}, can be constructed and the effects of rotation and variable-density mixing on the recirculation region can be assessed.

5. DISCUSSION OF RESULTS

Before embarking on the experiments, a symmetry check is carried out on the sudden-expansion flow with and without rotation. The axial velocity $\tilde{u}$ is measured across the tube diameter d_2 instead of across the radius R at several x/H locations. Some sample results for U/U_{cl} and u'/U_{cl}, are plotted vs r/R in Fig. 3. It can be seen that the flow is quite symmetric about the tube axis for both the $\Omega = 0$ and 840 r.p.m. cases. Henceforth, all measurements are carried out across the tube radius only. The results of these measurements are presented in the following sections; namely (1) velocity field, (2) scalar field and (3) recirculating flow and reattachment.

5.1. *Velocity field*

The velocity field measurements are shown in Figs. 4–9. Decay of the centerline velocities is given in Fig. 4, while mean velocity distributions along the stream direction are plotted in Figs. 5–7. Finally, the distributions of the turbulent intensities, u'/U_{cl} and w'/U_{cl}, are shown in Figs. 8 and 9. Turbulent shear stresses are not measured and are not presented. However, their absence would not impair the present effort to examine the combined effect of rotation and variable-density mixing on sudden-expansion flows.

Of all the parameters that influence axisymmetric sudden-expansion flow and its reattachment, tube

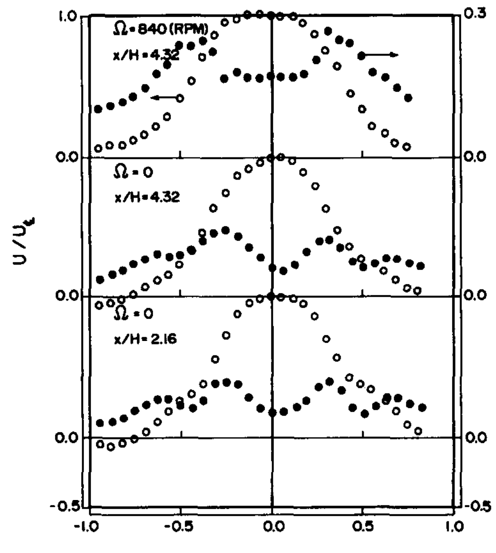

FIG. 3. Mean axial flow and r.m.s. $\tilde{u}$ symmetry for two different Ω.

rotation and inlet centerline turbulence intensity is found to be the most important [2, 3]. However, for co-axial jets into a sudden expansion, the jet velocity ratio (U_j/U_0) is bound to be an important parameter also. Habib and Whitelaw [8] investigate homogeneous mixing of co-axial jets in a sudden expansion for two different U_j/U_0 of 1 and 1/3. Their results show that U_j/U_0 has a significant effect on the centerline behavior of $\tilde{u}$ and some influence on reattachment. When U_j/U_0 is large, the shear layer generated by the annular and central jets dominates over that generated by the sudden expansion, and the centerline behavior of U is similar to that of a sudden-expansion flow with a single jet. As U_j/U_0 decreases to 1/3, the two shear layers remain distinct shear layers for a long distance and interact to produce a different behavior. In this case, U_{cl} undergoes a minimum and a maximum before decreasing slowly as the flow moves downstream. Their results also seem to reveal that, as U_j/U_0 is increased, the reattachment length decreases. Furthermore, the maximum intensity (u'/U_{cl}) decreases as U_j/U_0 is increased. The present experiments are carried out with $U_j/U_0 = 3$. Therefore, if the results of Habib and Whitelaw [8] are any indication, one would expect the shear layer generated by the annular and central jets to dominate and the resultant flow to resemble that of a single jet issuing into a sudden expansion.

Since So and Ahmed's [2] experiments for the $\Omega = 0$ case also have the same (u'/U_{cl}) at the inlet as the present $\Omega = 0$ case, the respective results could be compared to evaluate the effects of variable-density mixing. There are substantial similarities between these two sets of results (compare Figs. 5 and 6), even though So and Ahmed's experiments are on sudden-expansion flow of a single jet and the present experiments are on co-axial jets of different gases into a sudden expansion. The centerline U_{cl} decreases to about $U_j/2$ at about $x/H \simeq 25$ (Fig. 4), similar to the results of So and Ahmed [2]. Furthermore, u'_{cl} and w'_{cl} increase slowly to a maximum at $x/H \simeq 20$ and then decrease downstream (Fig. 4), a trend that is also similar to that shown by So and Ahmed [2]. Reversed flow is still measured at $x/H = 6.03$ (Fig. 5), thus suggesting that the reattachment length for this case is longer than 6.03 and in general agreement with the single jet result (Fig. 6). However, downstream of the reattachment point, the recovery to uniform flow is slower for the case with density variation (Fig. 5). It takes 16 step heights for the near-wall flow to increase slightly for the variable-density mixing case (Fig. 5) while it only takes 8 step heights for the near-wall flow to grow substantially for the constant-density flow case (Fig. 6). The mean circumferential velocity, W, is essentially zero across the tube (Fig. 7). Excess W at the tube centerline is due to the fact that at this location, the LDA measures both $\tilde{w}$ and $\tilde{v}$. Consistent with co-axial-jet flow behavior, two peaks are observed in the U, u' and w' profiles (Figs. 5, 8 and 9). However, due to rapid merging of the two shear layers, the second peak (due to the shear layer generated by the sudden expansion) quickly disappears. For the mean velocity, the second peak vanishes at

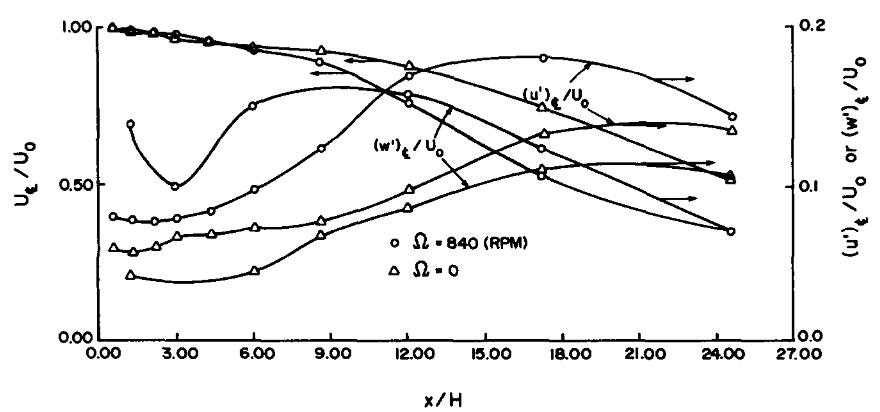

FIG. 4. Centerline velocity distributions for two different Ω.

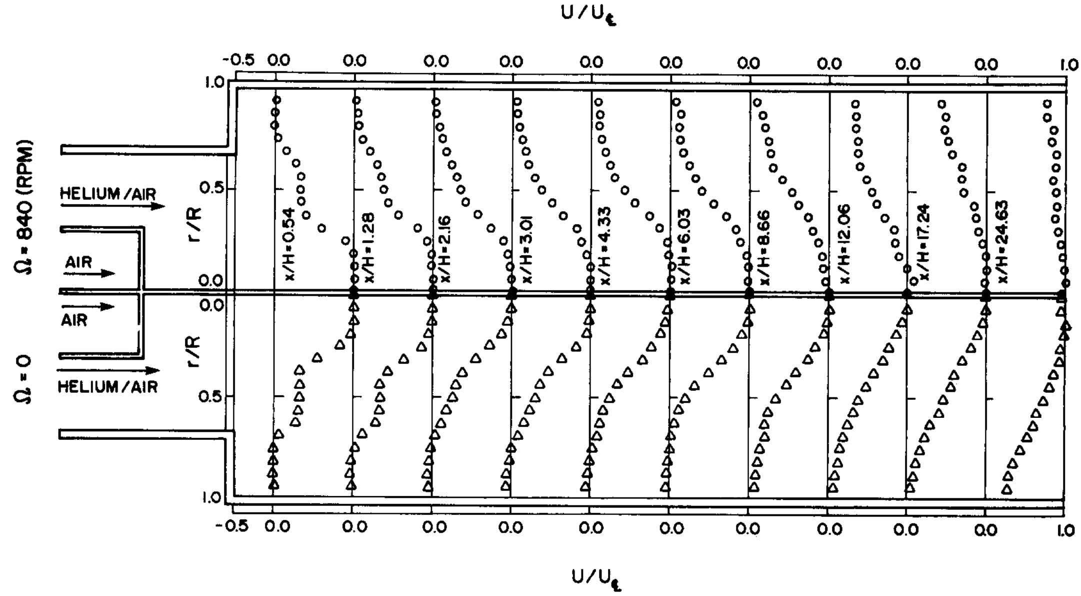

FIG. 5. Distributions of mean axial velocity for two different Ω.

$x/H \simeq 3$, while it takes longer ($x/H \simeq 6$) for the turbulence field to erase the second peaks in u' and w'. Unlike the results of So and Ahmed [2], isotropic behavior is not observed even at $x/H \simeq 24$ (compare Figs. 8 and 9). This implies that the two shear layers are not completely and fully mixed at $x/H \simeq 24$ even though the measured u' and w' are fairly uniform across the tube.

The most dramatic effect of rotation is seen in the measured U profiles. With rotation, forward flow is measured everywhere across the tube at $x/H > 3$. This compares with an x/H value of 8.66 when $\Omega = 0$ (Fig. 5) and an $x/H = 6$ for constant-density flow with $\Omega = 840$ r.p.m. (Fig. 6). Therefore, the results strongly suggest that the recirculation region has been significantly reduced under the combined influence of density difference and rotation. The reduction in size of the recirculation region can be explained as follows. Since the central air jet is about twice as heavy as the annular helium/air jet, the centrifugal force acting on the fluid tends to throw the air element towards the tube wall because the centrifugal force associated with the air element is larger than the inward pressure gradient acting on the fluid at the same radial location. Consequently, the shear layer formed by the air and helium/air streams would curve rapidly toward the wall and serves as a trap for the helium in the recirculation region. This conjecture is essentially substantiated by the measurements of helium volume concentration across the tube (Fig. 10). Another consequence of rotation is the rapid mixing of the two streams. Therefore, uniform flow across the tube is achieved a lot sooner compared to the stationary case (Fig. 5). On the other hand, when the rotation cases with (Fig. 5) and without (Fig. 6) density variation are compared to evaluate the effects of density differ-

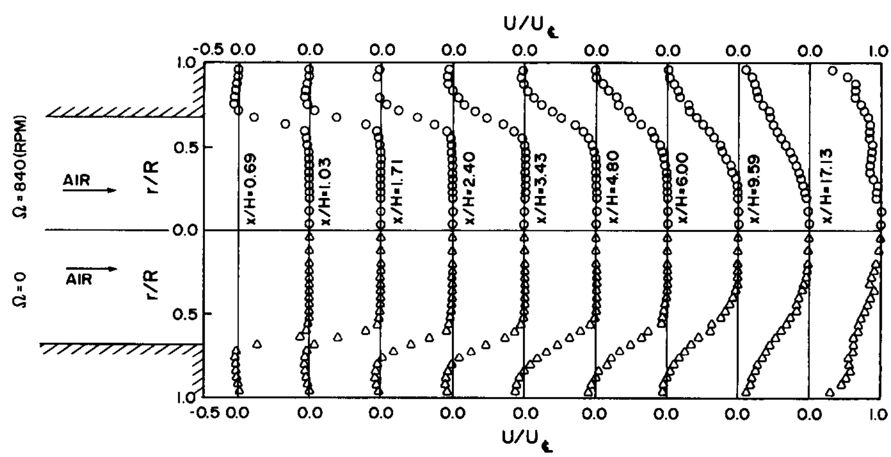

FIG. 6. Distributions of U for two different Ω for constant density flow (results from ref. [2]).

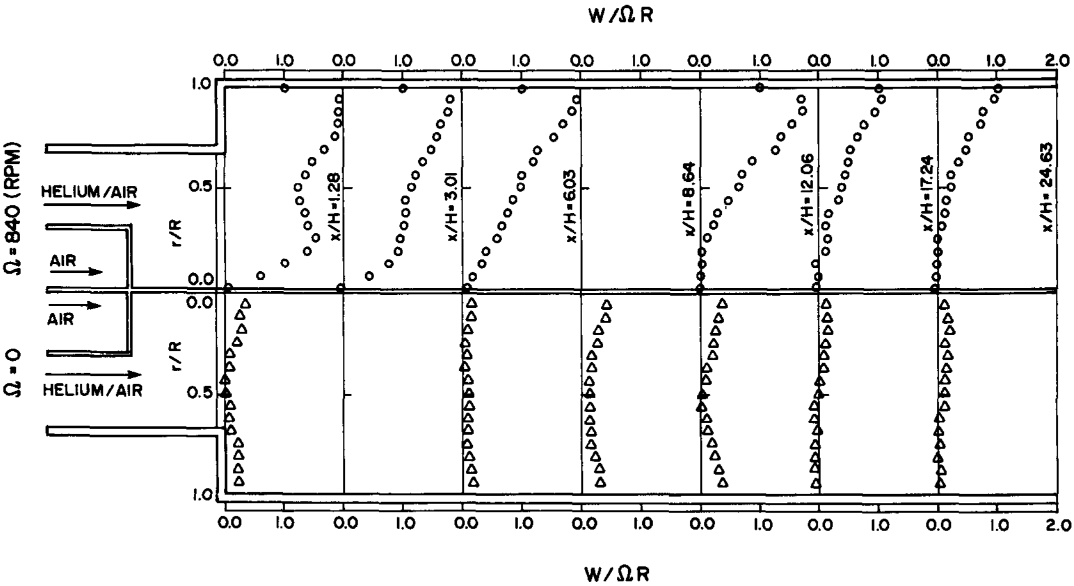

FIG. 7. Distributions of mean circumferential velocity for two different Ω.

ence, one can conclude that the approach to uniform flow is being delayed by density difference but not to the extent observed in the stationary case.

The rapid merging of the two shear layers is also evident from the measurements of u' and w' (Figs. 8 and 9). As a result, the centerline values of u' and w' are substantially higher than the stationary case (Fig. 4). Furthermore, the peak values of u' and w' are also higher than the corresponding $\Omega = 0$ case; thus reflecting the intense mixing that goes on in the merged shear layer in the $\Omega = 840$ r.p.m. case. Based on these results, it can be concluded that density difference and rotation combine to reduce the recirculation region drastically and enhance mixing in the flow tremendously. The enhanced mixing is advantageous to burning inside a dump combustor, but the concomitant reduction in the size of the recirculation region is detrimental to flame holding in the combustor.

Finally, some comments about the W profiles are offered. The circumferential velocity of the fluid is induced by the combined action of tube rotation and fluid viscosity. Therefore, theoretically speaking, W should not be larger than ΩR anywhere inside the tube. So and Ahmed [2] measure a substantial overshoot in W in the recirculation region. However, as the flow moves toward the reattachment point, the overshoot in W quickly vanishes and disappears altogether downstream of the reattachment point. They explain this by attributing it to the transfer of energy from the axial to the circumferential direction due to turbulent shear and pressure and to the effect of the rotating shear layer acting on the recirculating region, which tends to rotate at constant ΩR due to low U

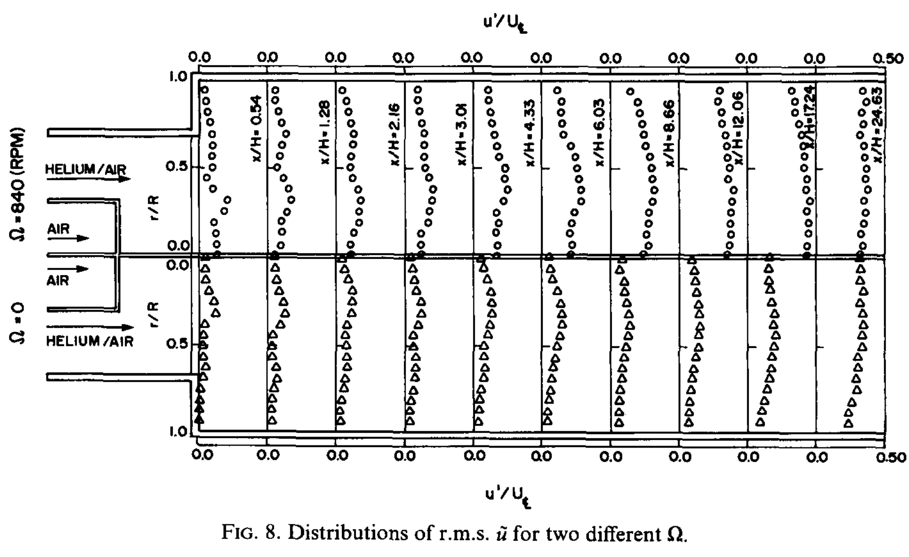

FIG. 8. Distributions of r.m.s. $\tilde{u}$ for two different Ω.

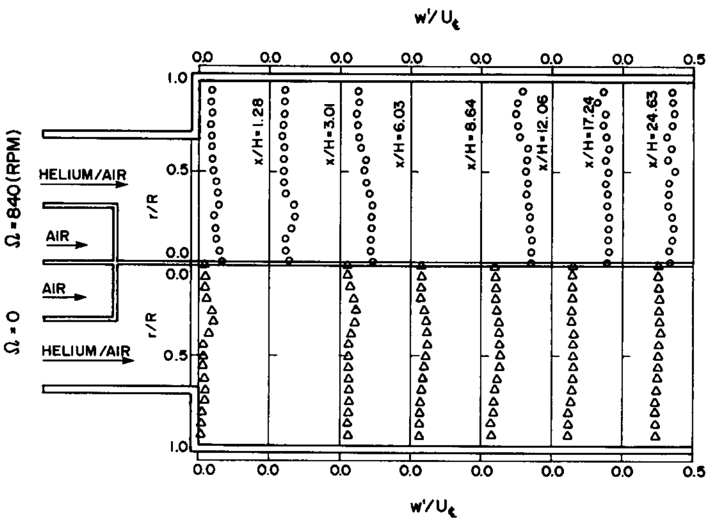

FIG. 9. Distributions of r.m.s. $\tilde{w}$ for two different Ω.

and viscosity effects in this region. The present results give two shear layers and thus two regions of fluid with fairly constant speed of rotation (Fig. 7). If the explanation of So and Ahmed [2] is reasonable, then the axial region where W overshoots ΩR would be quite large because the two shear layers remain rather distinct for quite a distance downstream of the sudden expansion. Figure 7 shows that W overshoots ΩR in the region $0 < x/H < 17$ and other measurements (U, $u'$and w') seem to lend credence to this argument.

5.2. *Scalar field*

The helium volume concentration measurements are shown in Figs. 10 and 11. For both the stationary and rotating cases, the scalar field approaches uniform distribution a lot sooner than the velocity field (compare Figs. 5 and 10). This implies that the turbulent mass diffusivity is larger than the turbulent momentum diffusivity. In other words, the turbulent Schmidt number is smaller than unity. The results also seem to indicate that as Ω increases, the turbulent Schmidt number decreases; thus suggesting that the present flow cannot be modelled by invoking a constant Schmidt number assumption.

The helium concentration level in the near-wall region at $x/H = 1.30$ seems to increase for both the $\Omega = 0$ and 840 r.p.m. cases (Fig. 10). This suggests that helium is being trapped in the reversed flow region. Further downstream, the C distributions differ dramatically for the $\Omega = 0$ and 840 r.p.m. cases. For $\Omega = 0$, C tends to remain constant near the wall up to $x/H = 8.57$. On the other hand, C becomes quite uniform at $x/H = 8.57$ for the rotation case. The fact that the C distribution achieves uniformity so quickly for the $\Omega = 840$ r.p.m. case suggests that the recirculation region is much smaller when rotation is present.

There is only one peak in the c' profiles. It is associated with the mixing layer generated by the merging of the air and helium/air streams (Fig. 11). The other

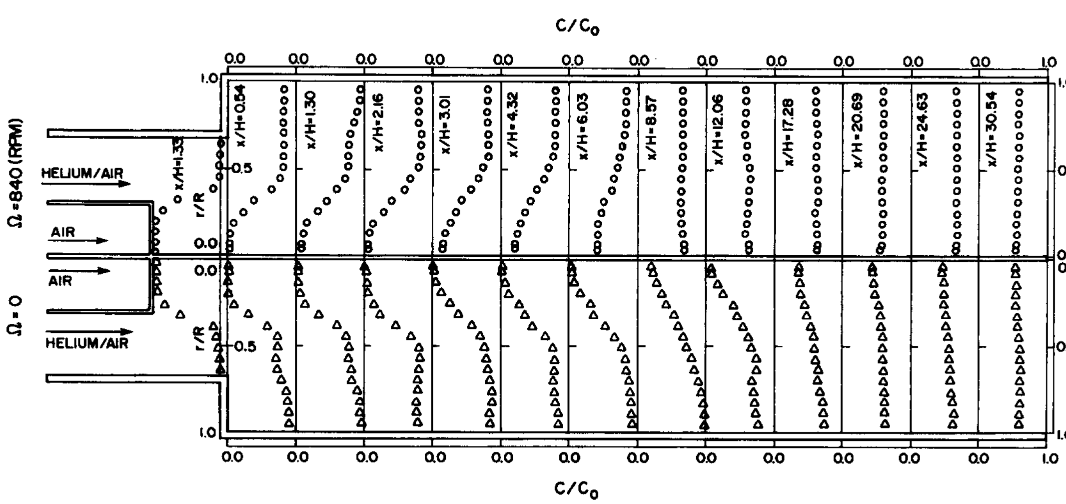

FIG. 10. Mean helium volume concentration distributions for two different Ω.

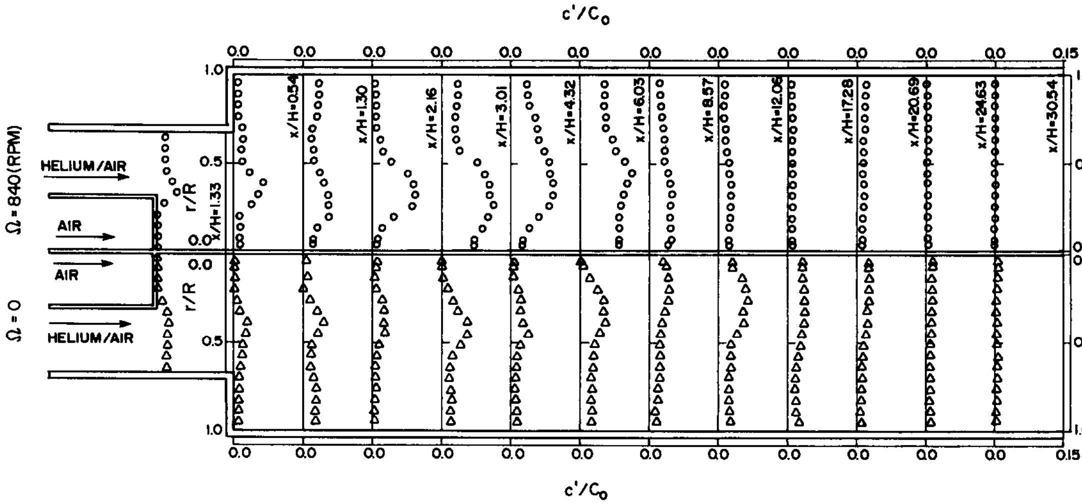

FIG. 11. Distributions of r.m.s. $\tilde{c}$ for two different Ω.

peak associated with the mixing layer generated by the sudden expansion is barely noticeable at $x/H \leqslant 1.30$ and quickly disappears as the flow moves downstream. This observation is true for the $\Omega = 0$ and 840 r.p.m. cases and suggests that, as far as the scalar field is concerned, the mixing behavior is dominated by the shear layer generated by the merging of the annular and central jets. Since helium is a lot lighter than air, once it is trapped in the reversed flow region, it does not mix with the external air stream. As a result, the shear layer generated by the sudden expansion has no effect on the mixing of $\tilde{c}$ in the near-wall region, and this leads to fairly constant C and near zero c' in the recirculation region of both the $\Omega = 0$ and 840 r.p.m. cases. It can, therefore, be concluded that there is only one scalar shear layer, even though there are two velocity shear layers in this type of sudden-expansion co-axial-jet flows.

5.3. *Recirculating flow and reattachment*

With both U and C available, the mean mixture density ρ can be calculated from equation (2) and the stream function ψ from equation (1). The normalized plot of ψ/ψ_{cl} is shown in Fig. 12. Several points should be noted about this plot. Firstly, the reattachment length x_L/H determined from the locus of $\psi = 0$ for the $\Omega = 0$ case is ~ 9.7. This is substantially different from the reattachment lengths determined from Habib and Whitelaw's [8] measurements, which are $x_L/H = 18.6$ and 20.2 for the $U_j/U_0 = 1$ and 1/3 cases, respectively. On the other hand, $x_L/H = 9.7$ for the present stationary case is similar to that measured by So and Ahmed [2] and other axisymmetric sudden-expansion flow data examined by So [3]. Therefore, this result seems to suggest that variable-density jet mixing in a sudden-expansion flow tends to decrease the reattachment length. Secondly, the recirculation

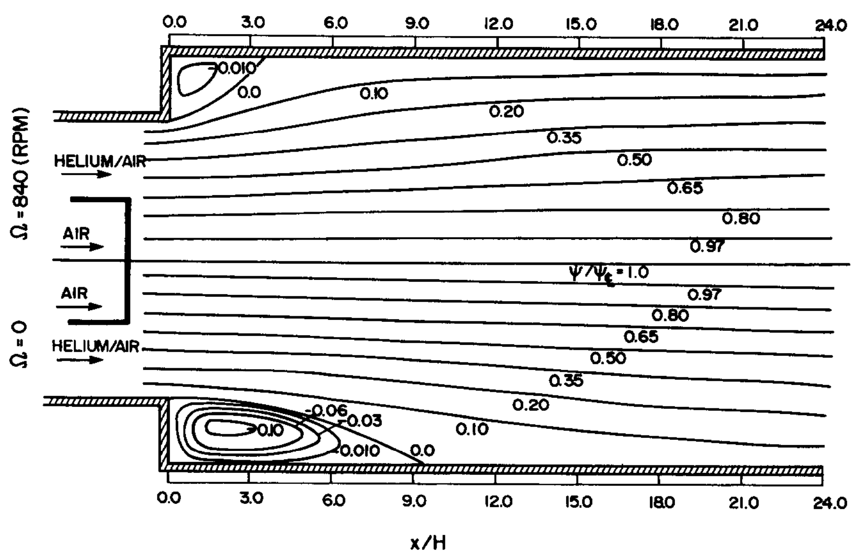

FIG. 12. Normalized stream function plots for two different Ω.

region in the $\Omega = 840$ r.p.m. case is much smaller and x_L/H is only ~ 3.5. This is 1/3 of that in the $\Omega = 0$ case and 30% less than the corresponding rotation case without density variation (Fig. 1). The reduction is essentially a consequence of the combined effect of rotation and density difference between the two streams. Based on these results, one can conclude that density variation has a greater effect on the reattachment length than rotation. By similar reasoning, one can expect the same conclusion to emerge even if the annular stream is heavier than the central air stream. This will not be beneficial to flame anchoring in a combustor. Finally, no secondary recirculation is measured for either the $\Omega = 0$ or 840 r.p.m. case. This result is in contrast to the data examined by So [3] and to the measurements of So and Ahmed [2] on rotating sudden-expansion flows.

6. CONCLUSIONS

The following conclusions emerge from this study.

(1) Sudden-expansion flow with density difference tends to promote mixing and shorten the reattachment length.

(2) The scalar field mixes faster than the velocity field; thus suggesting that the turbulent Schmidt number is smaller than unity.

(3) Rotating the flow about the sudden-expansion tube axis promotes further mixing and a drastic reduction of the recirculation region. Consequently, the reattachment length is reduced by a factor of three compared to the non-rotating case.

(4) Another consequence of rotation is the rapid mixing of the scalar field; thus suggesting that the turbulent Schmidt number decreases with increased rotation.

(5) The secondary recirculation normally observed in an axisymmetric sudden-expansion flow is missing in the present flow, with and without rotation. This result could be a consequence of the enhanced mixing due to the density difference between the two streams.

(6) Finally, similar physical reasonings would lead to the same conclusions even if the annular stream is heavier than the central stream.

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EFFETS DE LA ROTATION SUR LE MELANGE DANS LES ECOULEMENTS AXISYMETRIQUES A ELARGISSEMENT BRUSQUE

Résumé—On étudie expérimentalement les effets de la rotation sur le mélange d'un jet à densité variable coaxial à une géométrie comportant un élargissement brusque. Un jet central d'air entouré par un jet annulaire hélium/air est injecté dans un tube circulaire avec une section droite élargie. On examine deux cas en détail; l'un stationnaire, l'autre avec une vitesse constante de rotation de 840 tr min^{-1}. Des résultats montrent que le mélange entre l'hélium et l'air est fortement augmenté par la rotation. En conséquence la région de recirculation en aval de l'expansion brusque est raccourcie et la longueur de recollement est diminuée selon un facteur trois. Néanmoins l'écoulement à 30 fois la hauteur de la marche, en aval de l'expansion est essentiellement identique pour les deux cas étudiés.

ROTATIONSEINFLUSSE AUF DIE INHOMOGENE MISCHUNG IN ACHSENSYMMETRISCHEN STRÖMUNGEN MIT PLÖTZLICHER ERWEITERUNG

Zusammenfassung—Die Rotationseinflüsse auf die Mischungsvorgänge in einem koaxialen Strahl variabler Dichte in einer achsensymmetrischen Anordnung mit plötzlicher Erweiterung werden experimentell untersucht. Ein zentraler Luftstrahl, umgeben von einem ringförmigen Helium–Luft-Strahl, wird in ein kreisförmiges Rohr mit einer Querschnittserweiterung eingeblasen. Dabei wurden zwei Fälle untersucht: Eine stationäre Anordnung und der Fall einer konstanten Rotation (840 UPM) um die Rohrachse. Die Ergebnisse zeigen, daß die Mischung zwischen Helium und Luft durch Rotation stark begünstigt wird. Folglich wird die Rezirkulationszone nach einer plötzlichen Erweiterung kleiner, und die Länge bis zum Wiederanlegen der Strömung verringert sich um etwa den Faktor 3. Jedoch ist die Strömung 30 Schrittweiten hinter der plötzlichen Erweiterung für den stationären Fall und den Fall mit Rotation grundsätzlich identisch.

ВЛИЯНИЕ ВРАЩЕНИЯ НА НЕОДНОРОДНОЕ ПЕРЕМЕШИВАНИЕ В ОСЕСИММЕТРИЧНЫХ ВНЕЗАПНО РАСШИРЯЮЩИХСЯ ПОТОКАК

Аннотация—Экспериментально исследовано влияние вращения на перемешивание коаксиальных струй переменной плотности в осесимметричном внезапно расширяющемся потоке. Центральная воздушная струя, находящаяся внутри кольцевой невоздушной струи, вдувалась в круглую трубу с внезапным расширением. Подробно рассматриваются два случая: течение в неподвижной трубе и течение в трубе, вращающейся вокруг своей оси с постоянной скоростью, равной 840 об/мин. Результаты показывают, что вращение существенно усиливает перемешивание гелия и воздуха. Как следствие, сокращается область рециркуляции ниже внезапного расширения, а длина зоны повторного присоединения уменьшается примерно в три раза. Однако в обоих случаях структуры течений на расстоянии 30 калибров ниже внезапного расширения практически совпадают.