Rotation Effects on Axisymmetric Sudden-Expansion Flows

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The dump combustor of a ramjet propulsion system was simulated by a Plexiglas tube of 63.5 mm I.D. and 76.2 cm long. A convergent nozzle with an exit diameter of 43.2 mm was fitted to the inlet of the tube. Therefore, this arrangement provided a sudden expansion and gave a step height of 10.15 mm. Tube rotation effects on mixing in the dump combustor were examined by rotating the Plexiglas tube about its own axis at a constant speed. The flow downstream of the sudden expansion was studied using a one-color, one-component, laser-Doppler anemometer. Two conditions were investigated in detail, one with the tube rotating at 840 rpm and another with the tube stationary. In addition, three other experiments with different tube rotational speeds were carried out to determine the dependence of reattachment length on rotation. The average inlet velocity was set at ~ 10.6 m/s for all experiments. The results show that the primary reattachment length decreased as rotation increased because of the destabilizing effect due to the large shear created by the rotating tube wall. A detailed comparison of the flow characteristics with and without rotation present is made, and the effects of rotation on the flow are analyzed.

Nomenclature

d_1 = diameter at the sudden-expansion inlet
d_2 = diameter of downstream tube
$H = \frac{d_2 - d_1}{2}$ = step height
L = combustor length
M_i = inlet Mach number
N = tube rotational speed, rpm
r = radial coordinate measured from tube center
$R = \frac{d_2}{2}$ = tube radius
$R_o(x)$ = radial location of dividing streamline
$Re = \frac{U_i d_1}{\nu}$ = inlet flow Reynolds number
$T_i = (u'_o)_i / U_i$ = inlet centerline turbulence
$\tilde{u}$ = instantaneous axial velocity
u' = rms of fluctuating axial velocity
U = mean axial velocity
$\tilde{w}$ = instantaneous circumferential velocity
w' = rms of fluctuating circumferential velocity
W = mean circumferential velocity
$\overline{W} = \Omega R$ = rotation velocity of the tube
x = axial coordinate
x_L = reattachment length of primary recirculation region
x_s = reattachment length of secondary recirculation region
ν = fluid kinematic viscosity
$\psi = \int_o^R Ur\,dr$ = stream function
$\Omega = \frac{2\pi N}{60}$ = angular velocity of tube

Subscript
o = tube center

Introduction

THE basic ramjet engine, which is basically an expansion dump combustor, is one of the airbreathing propulsion systems being developed for volume limited missile applications. The air enters through the inlet duct upstream of the dump station and is used to carry fuel injected through the duct walls. Combustion occurs after the dump station and the flame are stabilized by the flow recirculation region just downstream of the dump station. The size of the recirculation region is crucial to the performance of the combustor because it serves to anchor the flame.

The dump combustor flowfield is very complex, involving turbulent mixing of fuel and air, flow separation, flow recirculation, shear flow reattachment, chemical reactions, etc. All these phenomena are affected by a host of parameters such as air velocity and temperature, inlet turbulence, inlet Mach number, sudden-expansion area ratio, fuel and air density ratio, wall rotational velocity, and fuel injection velocity. The objective of the present investigation is to seek further insight and understanding of the fluid mechanics of dump-combustor flows, especially the effect of wall rotation on the reattachment length x_L and the velocity and turbulence profiles in the combustor.

Although very little was known about the complex reacting flow phenomenon inside a dump combustor, a substantial amount of knowledge of the basic elements that make up this complex flow had been accumulated. Some of the more pertinent flow elements are flow over backward-facing steps, two-dimensional sudden-expansion flows, axisymmetric sudden-expansion flows, nonreacting flow through dump combustors, and swirler-induced rotation effects on flow behavior. A fairly complete review on flow over backward-facing steps and two-dimensional sudden-expansion flows was prepared by Eaton and Johnston.[1] Therefore, the following brief review summarizes recent results on axisymmetric sudden-expansion flows, reattachment length, and rotation effects on turbulent flow characteristics.

A systematic analysis of the effects of Re, d_2/d_1, H, T_i, M_i, and inlet and outlet geometries on x_L in axisymmetric sudden-expansion flows has been carried out by So.[2] He found that by far the most important parameter affecting x_L/H was T_i and that x_L/H decreased with increasing T_i. As a result, the widely scattered x_L/H measurements reported in the literature[3-12] could be explained on the basis of differences in the centerline turbulence intensities.

On the other hand, tube rotation effects on sudden-expansion flows have not been investigated. Related studies on swirling flows have, however, been reported by a number of researchers.[13-16] The studies of Rhode et al.,[13] Lilley,[14] and Johnson et al.[15] dealt with coaxial jets into a sudden expan-

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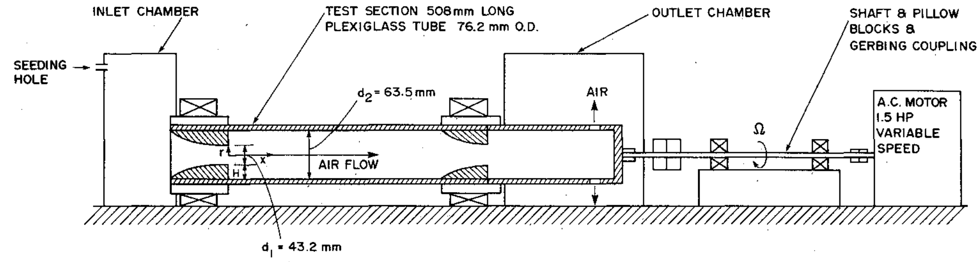

Fig. 1 Schematic of dump-combustor test facility.

sion chamber. In most of these studies, the outer annular jet was swirling while the inner central jet was not. As a result, the circumferential velocity created was rather uniform in the region near the tube wall and had a solid-body rotation behavior in the tube core. This kind of W distribution is quite different from the behavior in a rotating tube,[17,18] where W is maximum at the tube wall and decreases to zero at the tube center. The tube rotation gives rise to two countereffects on the flow: a destabilizing effect due to a large shear caused by the rotating tube wall, and a stabilizing effect due to the centrifugal force of the swirling velocity component of the flow.[18] Depending on the axial location in the tube, either one or both effects could be significant. For example, Kikuyama et al.[18] found that in a developing rotating pipe flow, the destabilizing effect was dominant near the inlet while the stabilizing effect prevailed far downstream. This behavior had not been observed in any of the other swirling flow studies[13-16] and could affect the formation of the recirculation region in a sudden-expansion flow.

The present experiments were formulated to investigate the effects of tube rotation on dump-combustor flows, with particular attention paid to x_L. Since literature data[2] showed such wide scatter in x_L/H, an accurate rotation effect on x_L/H could be assessed only if the nonrotating x_L/H was also measured in the same rig under the same flow conditions. Therefore, the corresponding nonrotating dump-combustor flow was also studied in detail to allow the rotation effects to be delineated.

Test Facility

The test facility was a simple rotating rig designed to conduct experiments on rotation effects on flow through sudden expansions (Fig. 1). It consisted of a Plexiglas tube of $d_2 = 63.5$ mm I.D. and 76.2 cm long supported by two pillow block bearings at each end. One end of the tube was fitted with a well-contoured nozzle made of aluminum. The nozzle was designed to slide in and out of the Plexiglas tube easily so that it could be used as either an exit or an inlet nozzle. This arrangement also allowed nozzles of different geometry and design to be tested. At the other end, another well-contoured aluminum nozzle was fitted into the Plexiglas tube and was located at exactly $L = 8d_2$ away from the first nozzle. A hollow aluminum cylinder with a closed end and eight air holes (6.35 mm in diameter) spaced at $\pi/4$ around the cylinder circumference was installed against this nozzle. A steel shaft was attached to the closed end of this cylinder. This shaft, in turn, was connected to the motor drive shaft through a Gerbing coupling. The drive shaft was also supported by two pillow block bearings. A speed controller not shown in Fig. 1 was used to control the speed of rotation of the three-phase, 1.5-hp motor. The motor had a large starting torque and a maximum speed of ~ 2500 rpm.

Details of the test section are shown in Fig. 1. The inlet nozzle had an I.D. of 43.2 mm, thus giving a $d_2/d_1 = 1.47$ and a step height of $H = 10.15$ mm. Two settling chambers were used to enclose the open end and shaft end of the assembly. A circular hole was cut through one side of these chambers, and a blower operating in the suction mode was connected to the chamber enclosing the shaft end. Therefore,

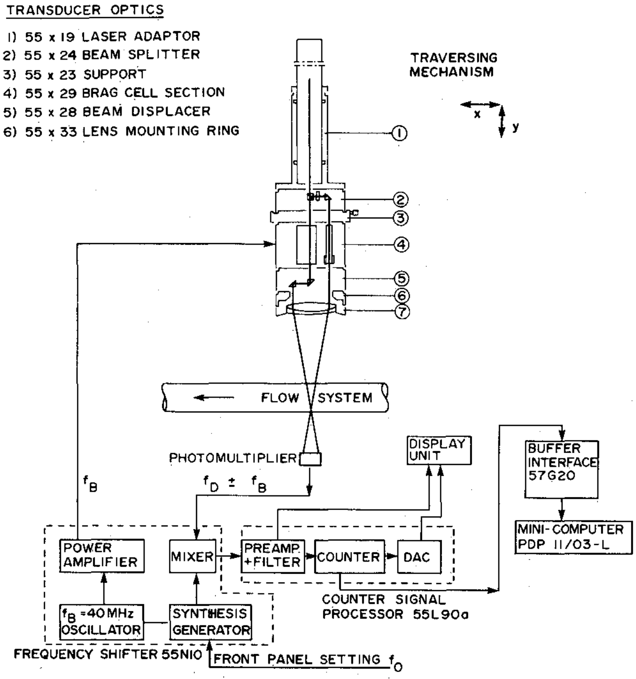

Fig. 2 Block diagram of the LDA and data acquisition system.

the air flowed through the tube as indicated in Fig. 1. Seedings for LDA measurements were deposited into the chamber enclosing the open end. The blower was capable of giving an average inlet velocity U_i of up to 16 m/s. Therefore, the test facility was capable of providing a flow with inlet Reynolds number $Re = U_i d_1/\nu$ up to 4.6×10^4 and a rotational speed up to 2500 rpm.

Instrumentation and Techniques

A standard DISA Model 55X laser Doppler anemometer (LDA) equipped with a DISA Model 55N10-1 frequency shifter was used to measure $\tilde{u}$ and $\tilde{w}$ employing the forward scatter mode as shown in Fig. 2. The coherent light source was provided by a 15-MW helium-neon laser (wavelength $\lambda = 632.8$ nm). A beam splitter was used to split the beam, and one beam was shifted 40 MHz, utilizing a Bragg cell so that high-turbulence and reversed flow in the axial direction could be detected. The focal length of the focusing lens was 80 mm. This allowed the beam separation to be chosen at 25.2 mm, and the beam intersection angle was 17.9 deg at the tube center. The resultant ellipsoidal sampling volume had dimensions of 0.26-mm length and 0.04-mm width. A DISA Model 55L90A signal processor was used to amplify and filter the signal fed by the frequency shifter as shown in Fig. 2. The signal from the counter/processor (55L90A) was then fed through a buffer interface (57G20) into a PDP11/03-L minicomputer for processing and analysis. Computer programs used by So et al.[16] to analyze LDA signals were also used to process the present velocity data. It should be pointed out that

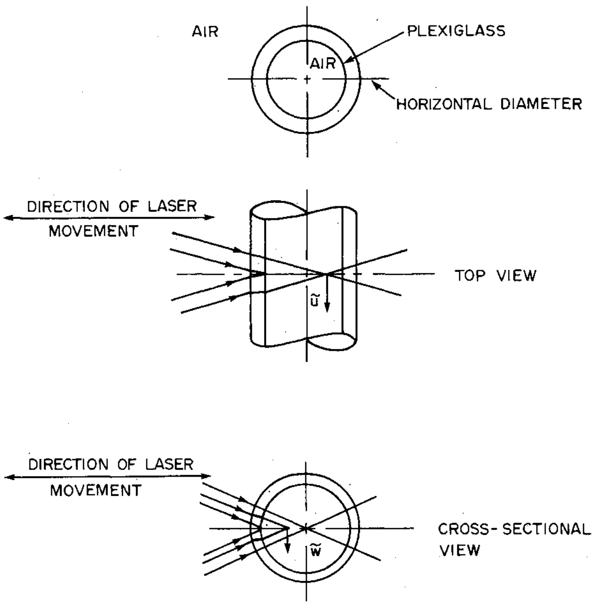

Fig. 3 Schematic showing LDA measurements of $\tilde{u}$ and $\tilde{w}$.

all velocity data were corrected utilizing resident time bias. Depending on the flow conditions, up to ten blocks of 1024 samples were used to resolve the velocity statistics.

All measurements across the tube were made along the horizontal diameter of the tube (Fig. 3). The instantaneous axial velocity $\tilde{u}$ was measured by orienting the laser beams on a horizontal plane passing through the tube axis. If the optics were rotated through an angle of $\pi/2$ rad, the laser beams would lie on the vertical plane perpendicular to the tube axis; thus, the measurements gave $\tilde{w}$ (Fig. 3). The complete LDA system was mounted on a two-dimensional manual traverse accurate to 0.20 mm in the radial direction and 0.5 mm in the stream direction. This assembly was mounted on a support totally independent of the table supporting the test facility. Therefore, motor vibrations were completely isolated from the LDA diagnostic system. Even then, excessive vibrations of the test section at high rotational speed prevented the proper focusing of the LDA signal. Consequently, experiments at rotational speed greater than 1200 rpm were not possible with the present rig.

To improve the LDA signal quality and frequency resolution, artificial seeding provided by a DISA Model 55L18 seeding generator was used. Liquid (50% water and 50% glycerine) droplets centered around 1 μm in size were generated. The droplets were carried into the settling chamber by an airstream, and their concentration was regulated by varying the air inlet pressure to the seeding generator. Rotational speed of the tube was measured by a stroboscope to ± 1 rpm. When the tube was rotating, only LDA was used to measure the flow inlet velocity across the tube at 3.5 mm downstream of the sudden expansion, and this measurement was taken to be the inlet flow velocity. For the no-rotation case, the inlet velocity was also independently checked by a pitot-static traverse at the exit plane of the sudden expansion. The LDA and pitot-static measurements were found to agree to within 2%.

Several methods are available for determining the reattachment length. Some are based on flow visualization[11] while others are based on detailed measurements of the flowfield behind the sudden expansion.[7,8,12] Flow visualization techniques tend to be more accurate because they do not rely on extrapolation to determine x_L. However, the present setup was not equipped for flow visualization experiments. Therefore, the following two techniques were used to determine x_L. One technique was based on the extrapolation of the locus of the zero mean axial velocity to the wall. In order to define the zero-U curve properly, at least five points in the flow direction were used. This technique was fast and convenient because it did not require detailed measurements of U in the recirculation region. Therefore, it was used to determine x_L at several tube rotational speeds. The other technique was based on the evaluation of the dividing streamline, which is defined as $\psi_d = \int_{R_o}^{R} Ur\,\mathrm{d}r = 0$. The dividing streamline approach was most suitable when detailed U profiles were available. Therefore, for the cases where detailed flow measurements were made, the x_L's were determined using both the zero-U locus and dividing streamline techniques. These two techniques had also been used by Yang and Yu,[12] and they found that the measured x_L/H's were in agreement to within $\pm 10\%$. Even though the x_L's thus determined are not as accurate as those given by flow visualization techniques,[11] the present approach is sufficient to delineate the dependence of x_L on N.

Results

All experiments in the sudden-expansion rotating flow rig were carried out at one inlet flow condition. The inlet velocity U_i at the tube centerline was measured at $x = 3.5$ mm downstream of the sudden expansion and was found to be quite uniform across the sudden-expansion inlet. Its value was determined to be $U_i \simeq 10.6$ m/s. Through the course of these experiments, U_i was found to vary by ± 0.5 m/s. Therefore, the volume flow rate obtained by integrating the U profiles was found to vary by as much as 6% of the mean volume flow rate based on a uniform inlet flow of 10.6 m/s. Based on this U_i, the nominal Re was 3.1×10^4. Altogether, five cases with $N = 0$, 420, 630, 840, and 1050 rpm, respectively, were investigated. The flow behavior for two cases was studied in detail: case 1 with $N = 0$ and case 2 with $N = 840$ rpm. The other three cases were examined for their x_L/H behavior only. Therefore, sufficient measurements were available for the determination of the dependence of x_L on N.

For the two cases where the flow was investigated in detail, ten profile measurements of $\tilde{u}$ were obtained in the x/H range of $0.69 \le x/H \le 17.13$. These profiles were used to construct the stream function plots and thus allowed the ψ_d curves to be extrapolated to the wall to give x_L. Simultaneously, the x_L's were also determined by extrapolating the zero-U locus to the wall. The x_L's determined by the two methods were found to agree to within $\pm 8\%$. The x_L's for the other three cases (i.e., $N = 420$, 630, and 1050 rpm) were determined using the zero-U locus method. As for the circumferential velocity $\tilde{w}$, five profiles were measured in the x/H range of $0.39 \le x/H \le 17.13$. Three profiles were obtained within the recirculation region, and two profiles were measured downstream of the reattachment point. Therefore, the change in W in the immediate region downstream of the sudden expansion can be clearly illustrated. Finally, flow symmetry for cases 1 and 2 was checked by making $\tilde{u}$ measurements across the whole tube at $x/H = 1.03$ and 4.8. The results show that the sudden-expansion flows with and without rotation were quite axisymmetric.

Behavior of Rotating Field

In principle, the air coming into the dump combustor should be aligned with the combustor axis. Therefore, the W velocity measured across the horizontal diameter should be approximately zero. In practice, the air flow may enter the dump combustor at a small angle of attack, which would give rise to a circumferential flow across the horizontal diameter. Consequently, the measured W will not be zero, even when $N = 0$. The W measurements obtained for case 1, where $N = 0$, are essentially a consequence of inlet flow misalignment (Fig. 4). It only takes an angle of attack of ~ 3 deg to give the results shown in Fig. 4. The inlet nozzle (Fig. 1) is too short (only 63.5 mm in length) to allow the inlet flow to be corrected before it enters the sudden expansion. However, the measurements show that this does not affect flow symmetry at $x/H = 1.03$ and 4.8. Therefore, it was assumed that a slight

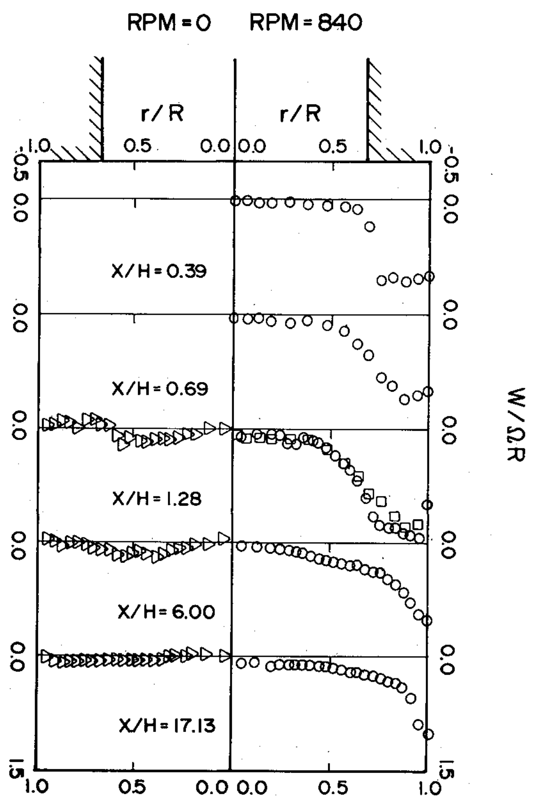

Fig. 4 A comparison of the normalized *W* profiles for cases 1 and 2.

misalignment in the inlet flow had little or no effect on the general flow behavior downstream of the sudden expansion.

In the inlet nozzle, the air at the nozzle surface rotates at the same speed as the surface because of the no-slip condition. The air adjacent to the surface then rotates at a lower speed. Eventually, this speed decreases to zero away from the near-wall region, where viscous effects are important. Therefore, the separating shear layer leaving the inlet nozzle is expected to have a rotational velocity equal to $0.68\overline{W}$, because $d_1/d_2 = 0.68$. If the inlet nozzle is long enough, the rotational velocity of the sudden-expansion inlet flow would resemble a solid-body rotation, and vortexing of flow outward would become an important phenomenon of the rotating sudden-expansion flow. However, such behavior was not measured in the present experiment. The measured W profiles at five different x/H for case 2 are shown in Fig. 4. At $x/H = 0.39$, the measured W is essentially zero from $r/R = 0$ to $r/R = 0.6$ and $W = 0.28\overline{W}$ at $r/R = 0.68$. This shows that fluid rotation is confined to the separating shear layer. Inside the recirculation region, W rises quickly to $\overline{W}$ and overshoots $\overline{W}$ by about 6% at $r/R = 0.88$. This behavior is a direct consequence of the slow-moving fluid and viscous effects in the recirculation zone. Similar W profiles are measured at $x/H = 0.69$ and 1.28, except that the overshoot gradually increases to ~10% at $x/H = 0.69$ and then to ~30% at $x/H = 1.28$. Further downstream, at $x/H = 6.0$ and 17.13, the overshoot disappears and W reaches $\overline{W}$ at the tube wall as expected. One possible cause of the overshoot was measurement error. This prompted a repeat measurement at $x/H = 1.28$, which is also shown (square symbol) in Fig. 4. Surprisingly good agreement is obtained in the region $0 < r/R < 0.7$, but some discrepancy is noticed in the recirculation zone. The reason for the discrepancy can be explained as follows. Since the W traverse was carried out across the horizontal diameter as shown in Fig. 3, the beam intersection angle varied from the tube centerline to the tube wall. The beam intersection angle was determined to be 17.9 deg at the centerline and decreased to 17.1 deg at the wall. Based on this variation, the percentage error in the measured W was estimated to be less than 5%.

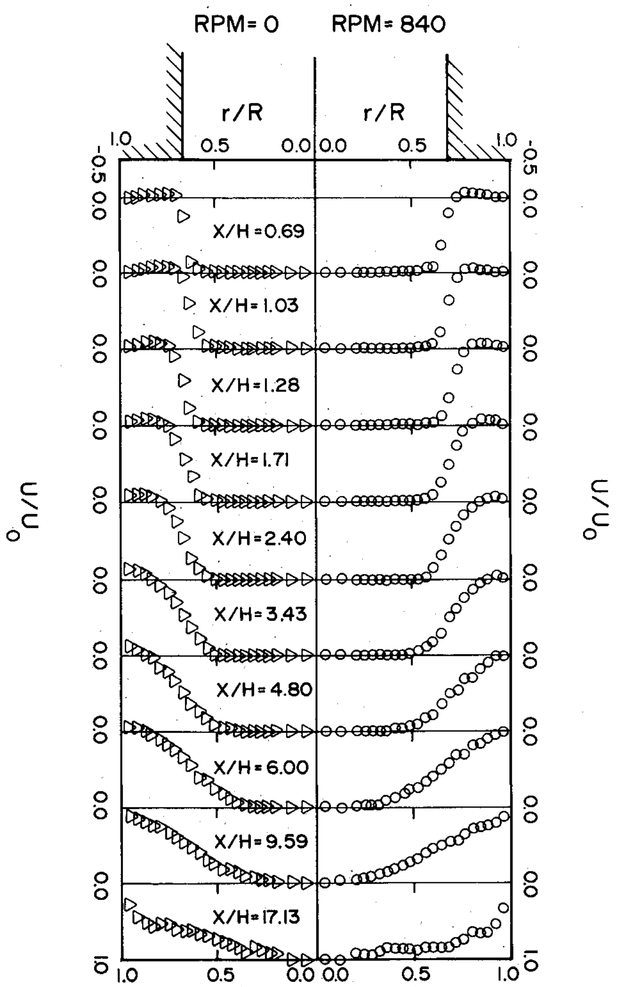

Fig. 5 A comparison of the normalized *U* profiles for cases 1 and 2.

This compares with a percentage error estimate of < 2% for U.[10] Therefore, the measured overshoot in W is real and cannot be explained away by measurement error.

The reasons for the overshoot in the recirculation zone are not clear. However, two lines of reasoning can be put forward. One explanation for the transfer of energy from the axial to the circumferential direction could be turbulent shear and pressure. Another could be the fact that the separating shear layer is already rotating at the plane of the sudden expansion, and this rotation could further enhance the rotation of the air in the recirculation zone. Since the axial velocity in the recirculation zone is very small, the air in this region tends to rotate at constant W. This constant W, plus the enhancement due to the rotating separating shear layer, would lead to an overshoot in W. If this second line of reasoning is correct, then the W profiles outside of the recirculation region should not show any overshoot at all. The measured W profiles at $x/H = 6.0$ and 17.13 essentially verify this observation. This means that the reattachment point is located at $x_L/H < 6.0$, which is substantiated by the determination of x_L using the zero-U locus method. Therefore, the results tend to validate the second conjecture.

Rotation Effects on Reattachment

The axial velocity profiles normalized by U_o for cases 1 and 2 are compared in Fig. 5, while a more detailed comparison of U inside the recirculation zone is given in Fig. 6. Essentially, rotation had no effect on the flow in the combustor core (Fig. 5). A very uniform flow was generated by the inlet nozzle, and this uniformity was not affected by rotation. In both cases, the uniform core flow extends to $x/H = 6.0$. Rotation effects were mainly noticed in the recirculation region (Fig. 6) and down-

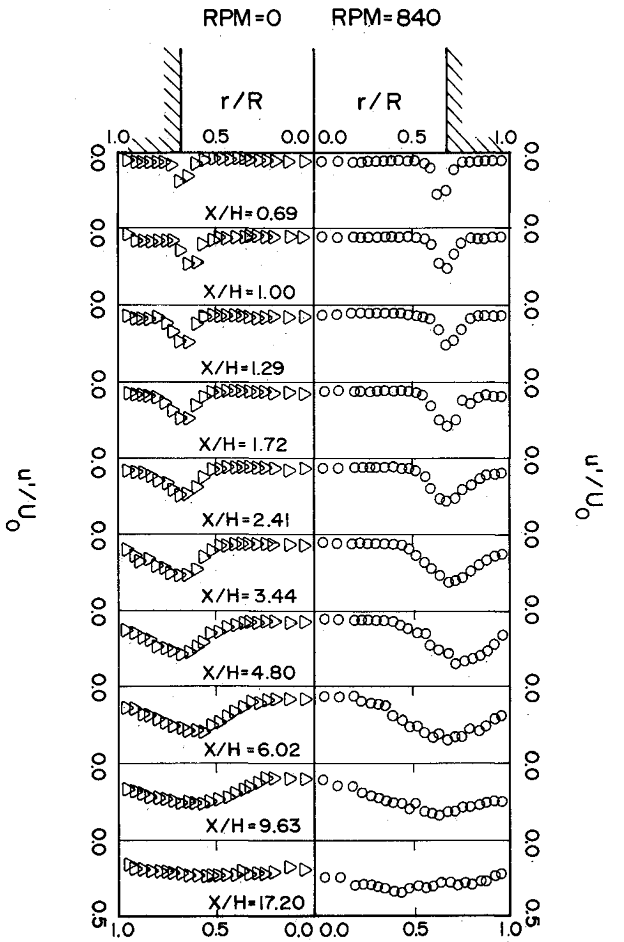

Fig. 6 Detailed plots of U in the recirculation zone for cases 1 and 2.

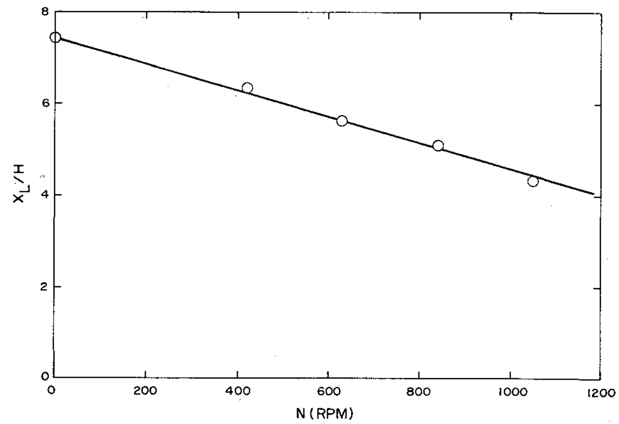

Fig. 7 Variation of the primary reattachment length x_L/H with rotational speed N.

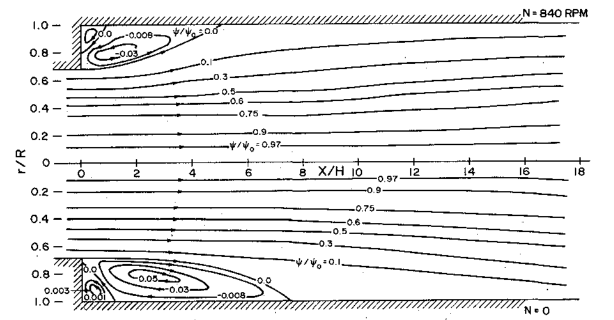

Fig. 8 A comparison of the stream function plots for cases 1 and 2.

stream of the reattachment point in the near-wall region (Fig. 5). When $N = 0$, the maximum reversed flow was observed at $x/H = 3.43$. This position was shifted to $x/H = 1.28$ when $N = 840$ rpm. Furthermore, substantial reversed flow was noticed at $x/H = 4.8$ for the $N = 0$ case, but no reversed flow was observed at the same location when $N = 840$ rpm (Fig. 6). A forward flow was observed near the wall at $x/H = 0.69$ and 1.03 for case 1 and at $x/H = 0.69$ only (Fig. 6) for case 2. Even accounting for measurement errors in U (which are $< 2\%$), the present results suggest the existence of a secondary recirculation near the corner. The existence of this secondary recirculation zone had been inferred by Baughn et al.[5] from their heat-transfer measurements. It had also been measured by Durrett et al.[10] using an LDA technique, and they found that the dimensions of the secondary recirculation extended from $x/H = 0$ to $x/H \simeq 1$ in the stream direction and from $r/R = 1$ to $r/R \simeq 0.7$ in the radial direction. The present results show that the axial extent of the secondary recirculation is $x_s/H > 1$ for case 1 and $x_s/H < 1$ for case 2. Therefore, the x_s/H result of case 1 is similar to that measured by Durrett et al.,[10] even though their H is about twice as large as the present H.

The reattachment points were determined according to the two methods discussed in the third section. Both methods (extrapolation of the $U = 0$ or $\psi_d = 0$ curve to the wall) give approximately the same result; their values agree to within 8%. Based on these determinations, the normalized reattachment points (x_L/H) are 7.4 ± 0.5 for case 1 and 5.1 ± 0.4 for case 2. The measured x_L/H for case 1 is consistent with those reported in the literature.[2] Therefore, it can be concluded that rotation decreases x_L/H and the reduction is greater than 30% when $N = 840$ rpm.

In order to determine the behavior of x_L/H with rotational speed, the x_L/H of three more cases, $N = 420$, 630, and 1050 rpm, were measured. For these three cases, the x_L/H's were determined by extrapolating the $U = 0$ curve to the wall, and therefore, there was no need to measure the complete U profiles. Figure 7 shows that the reattachment point decreases linearly with increasing N. The reason for the decrease is the fast spreading of the separating shear layer, and this rapid spreading is primarily caused by the destabilizing effect due to the large shear created by the rotating tube wall.

According to Kikuyama et al.,[18] tube rotation gives rise to two countereffects on the flow. One is destabilizing and is due to the large circumferential shear created by tube rotation. Another is stabilizing and is the result of centrifugal force due to fluid rotation. At the inlet of a rotating pipe, the wall boundary layer is thin, and fluid rotation is essentially confined to the boundary layer, where the rotation velocity decreases from ΩR to zero. In this region, the rotation effect is destabilizing as a result of the large circumferential shear.[18] In the present experiments, the inlet boundary layer was unstable because of the destabilizing effect created by the rotating inlet nozzle. When this boundary layer left the inlet nozzle to form the mixing layer, the additional destabilizing effect caused the mixing layer to spread faster, leading to a reduced recirculation region.

In order to clearly illustrate the recirculation regions and their sizes, stream function plots for cases 1 and 2 were constructed using the measured U profiles. The results are shown in Fig. 8, with ψ normalized by ψ_o, the stream function along the axis of the sudden-expansion tube. These results clearly show the shortening of the recirculation region by rotation. At the same time, the plots also show the existence of a secondary recirculation zone near the corner. For case 1, this secondary recirculation zone extends from $r/R = 1$ to $r/R \simeq 0.8$ and from $x/H = 0 \text{–} \sim 1.2$, where the secondary reattachment point occurs. Since the present measurements were not fine enough to resolve the size of the zone for case 2, its approximate dimensions could not be determined, but its axial extent was found to be $x_s/H < 1$ (Fig. 6). In general, it can be seen that rotation also tends to shorten the secondary reattachment length (Fig. 6).

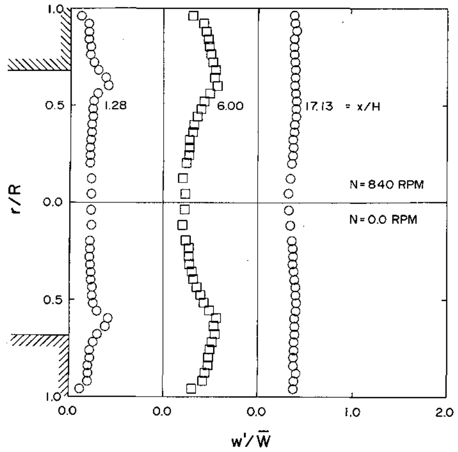

Fig. 9 A comparison of the normalized w' profiles for cases 1 and 2.

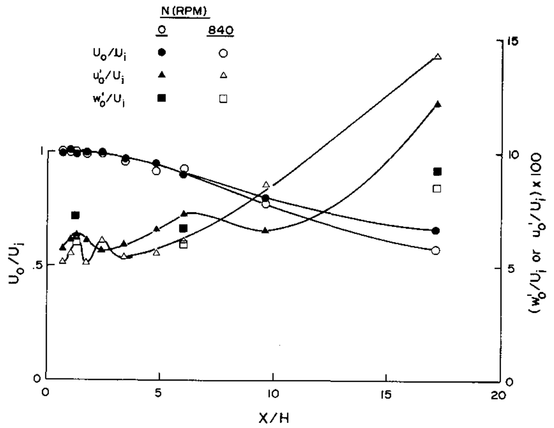

Fig. 11 Centerline behavior of U_o, u_o', and w_o' for cases 1 and 2.

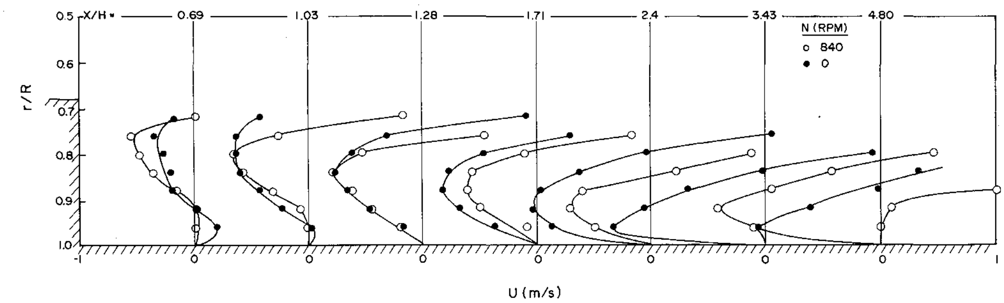

Fig. 10 A comparison of the normalized u' profiles for cases 1 and 2.

Rotation Effects on the Turbulence Field

The radial distributions of w' and u' are shown in Figs. 9 and 10, respectively. Rotation does not seem to have an effect on w' because the distributions obtained at $x/H = 1.28$, 6.00, and 17.13 are essentially the same for both cases 1 and 2. Even the location and magnitude of the maxima are identical. Downstream of the reattachment point, w' becomes more and more uniform. At $x/H = 17.13$, the variations of w' across the tube are practically zero.

On the other hand, rotation affects the distribution of u', both within the recirculation region and downstream of the reattachment point. The effects in these two regions are essentially the same; namely, the maximum u' is affected by rotation but the location of the maximum u' is not. This behavior is essentially a consequence of the destabilizing effect created by the large circumferential shear. According to the rotating pipe flow investigations of Kikuyama et al.,[18] the destabilizing influence will disappear in the downstream flow when W becomes more and more fully developed. A point will be reached when the stabilizing centrifugal force will prevail over the destabilizing effect. At this point, the turbulence intensities will start to decrease until ultimately they fall below those in a stationary pipe. In the present experiments, this flow state was not reached, and u' for case 2 is still larger than that measured in case 1 at $x/H = 17.13$. Therefore, the flow at this location was still dominated by the destabilizing effect. Since most ramjet combustors have a L/d_2 ratio of 4 to 5, the present results suggest that the flow inside a rotating ramjet combustor is essentially dominated by the destabilizing effect of the large shear created by the rotating combustor wall.

The area ratio of the sudden expansion is $(d_2/d_1)^2$ or 2.15. Therefore, when the flow becomes uniform again downstream of the reattachment point, its average velocity U should be $0.47U_i$. At $x/H = 17.13$, U_o/U_i measured for cases 1 and 2 are 0.66 and 0.58, respectively (Fig. 11). This, together with the U profiles shown in Fig. 5, indicates that rotation promotes mixing, thus leading to a faster approach to uniform flow across the tube. The centerline measurements for case 2 show that u_o' is greater downstream of the reattachment point. Upstream of the reattachment point, u_o' is smaller. Furthermore, u_o' increases with x/H and does not reach a local maximum near the reattachment point, as shown by the measurements of case 1 and the data of Yang and Yu.[12] This result is in agreement with the results shown earlier and further shows that the destabilizing effect is most dominant in the near-wall region.

Conclusions

Based on these results, the following conclusions can be drawn:

1) Tube rotation creates a very large shear in the flow near the wall. This gives rise to a destabilizing effect on the separating shear layer, thus causing it to spread faster and reattach sooner compared to the stationary flow case. When $N = 840$ rpm, the reattachment length was observed to decrease by more than 30%.

2) The flow in the dump combustor was essentially dominated by the destabilizing effect because the combustor was not long enough for the stabilizing centrifugal force to influence the flow.

3) The primary reattachment length decreases linearly with the rotational speed N for the range $0 \leq N < 1200$ rpm investigated.

4) A secondary recirculation zone was also observed near the corner. This exists with and without rotation of the combustor. The size of the secondary recirculation zone for case 1 is estimated to be the same as that measured by Durrett et al.,[10] even though their sudden-expansion geometry is different.

5) Finally, tube rotation promotes mixing, and this leads to a fuller U profile and a faster approach to uniform flow downstream of the reattachment point.

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