Characteristics of dump combustor flows

Ronald M. C. So and Saad A. Ahmed
Mechanical and Aerospace Engineering, Arizona State University,
Tempe, AZ 85287, USA

Received 28 January 1988 and accepted for publication 3 June 1988

Turbulent flows through dump combustors with different inlet geometries and flow conditions were investigated. The combustor was simulated by an axisymmetric tube with a sudden expansion geometry. Specifically two different inlet geometries were studied; one resembled an actual inlet, another a well-designed convergent nozzle. Furthermore two different step heights were examined. Finally, the effects of rotation on the flow behavior were also studied.

The results show that of all the geometric and flow parameters investigated, inlet turbulence and rotation have the greatest effect on the flow inside the combustor, in particular, the characteristics of the toroidal recirculating flow. Both parameters act to decrease the toroidal recirculation region and hence the reattachment length. The limited data available tend to show that the effects due to these two parameters are additive. On the other hand, inlet geometry only has an indirect effect on the combustor flow. It influences the flow characteristics because it creates different inlet turbulence at the sudden expansion.

Keywords: reattachment length; turbulence effects; rotation effects; dump combustor flows

Introduction

Dump combustor flows are of common occurrence in all kinds of air-breathing propulsion systems, particularly in liquid and solid fuel ramjets. Because of this, the flow characteristics in dump combustors are investigated extensively in order to perfect and optimize the design of dump combustors and to improve combustor performance. Such investigations can be broadly classified into two categories; one deals mainly with simulated mixing studies inside the combustor,[1,2] while another concentrates entirely on actual combustor flows.[3,4] Difficulties associated with the measurements of turbulent reactive flows are well known.[5] Therefore, in most actual dump combustor studies, the measurements are limited to combustor performance and the like, and detailed flow characteristics are not available.[3,4] Very often, detailed flow measurements have to be obtained from nonreacting, mixing experiments carried out in simulated dump combustors.[1,2] However, the usefulness of these simulated flowfield results has to be demonstrated by direct comparison with reacting flow data. Such comparisons were carried out by Drewry,[1] who found that simulated flowfield results could be used to predict the overall combustor performance trend for mixing-limited combustors. This means that the effects of various flow and geometric parameters on combustor performance can be examined by concentrating on the simulated flowfield studies only, where detailed flow measurements can be made reliably and accurately.

The present investigation chose to study the effects of flow and geometric parameters on the performance of dump combustors by examining the simulated, nonreacting flowfields inside dump combustors. These effects were investigated individually as well as simultaneously, and it was hoped that through this investigation a better understanding of dump combustor flows would be obtained and empirical guidelines could be developed for the design of such combustors.

The effects of inlet geometry (in terms of flameholders with different configurations) and variable-density mixing on dump combustor flowfields had been examined by Drewry.[1] However, Drewry made no attempt to control the inlet flow conditions. Therefore, different inlet flow conditions were associated with different flameholders. Consequently, the net effects observed in the measurements were the combined effects of changing inlet geometry and flow conditions. Other effects, such as inlet flow Reynolds number, expansion ratio, step height, inlet turbulence, etc., had also been investigated by researchers. A systematic analysis of these effects had been carried out.[6] In spite of the fact that two or more of the flow and geometric parameters were varied simultaneously in all data examined, So[6] found that inlet turbulence stood out as the most important parameter affecting dump combustor flows. In Ref. 6, inlet turbulence was defined as u_i'/U_i rather than $k_i^{1/2}/U_i$. The reason was that, among all the data examined, most reported measurements of u_i' only. Therefore, rather than make an assumption about the turbulence behavior at the sudden-expansion inlet, the reattachment length was correlated with u_i'/U_i. Specifically, the analysis revealed that as the inlet turbulence increased, the reattachment length decreased. Later, it was also found that rotation had the same effect on the reattachment length; namely, as the rotation of the combustor about its own axis increased, the reattachment length decreased.[7] The combined effects of rotation and variable-density mixing were also investigated,[8,9] and the result revealed that for a fixed rate of rotation, the reattachment length in the dump combustor was further decreased in the case of variable-density mixing.

In spite of all these studies, there is a lack of experiments designed to examine systematically the various effects individually as well as simultaneously. The present investigation proposes to fill part of this gap and specifically examines the effects of inlet geometry, step height, inlet turbulence and rotation, both individually and simultaneously, on the flowfields inside a dump combustor. In order to compare the present results with those in the literature, inlet turbulence is again taken to be u_i'/U_i.

© 1989 Butterworth Publishers

Experimental setup

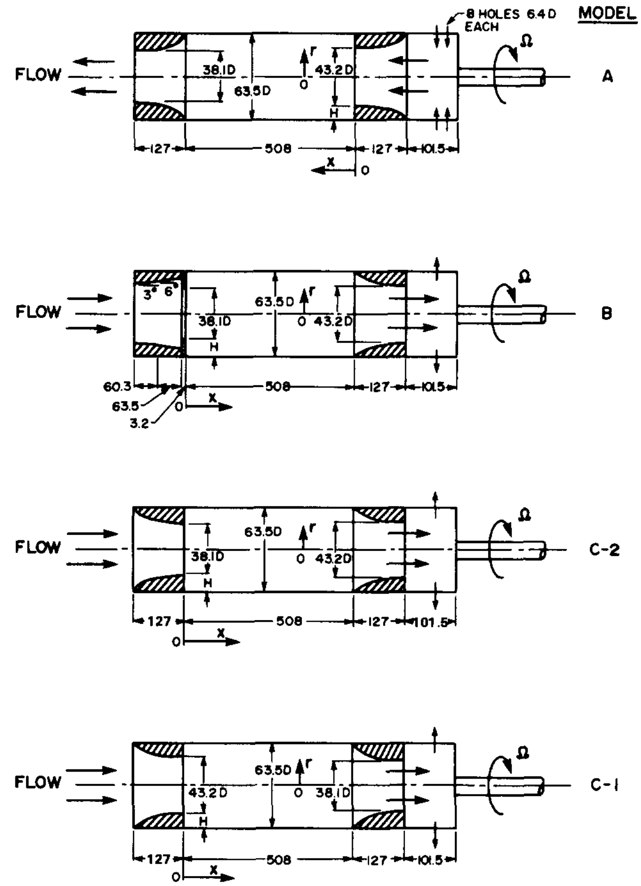
The rotating rig used in Ref. 7 was modified for the present experiments. In that facility, the motor drive shaft, supported by two pillow block bearings, was connected to a steel shaft attached to the dump combustor test model through a Gerbing coupling, so the motor directly controlled the rotational speed of the combustor. The dump combustor test model was also supported by two large pillow block bearings. A blower, operated in the section mode, was used to pull the flow through the dump combustor. Thus, the flow through the dump combustor was completely independent of the rotational speed and the rotational speed could be varied from 0 to about 2500 rpm at a fixed inlet flow Reynolds number. Details of the test facility can be found in Ref. 7.

The present experiments were carried out in the same test facility but with different dump combustor models. These models are described below.

The combustor models

The flowfields in three dump combustor models were investigated in the present experiments. These models, designated A, B, and C-2, are shown in Figure 1. The dump combustor model investigated in Ref. 7 is also shown in Figure 1 and is designated C-1. All models were made of Plexiglas, the detailed dimensions of which are clearly specified in Figure 1. Each model was equipped with an inlet nozzle and an outlet nozzle, both made of aluminum. The two nozzles were installed at exactly eight tube diameters apart to simulate the flowfield inside an actual ramjet combustor. Well-contoured nozzles of the same design were used to simulate the combustor exit geometry, so the exit conditions for the four combustors studied were identical. The airflow entered the open end of the combustor and exited through the shaft end for combustors B, C-2, and C-1. On the other hand, the airflow was from the shaft end to the open end for combustor A. Thus designed, the different combustors allowed the various flow and geometric parameters to be investigated separately or in various combinations.

Combustors A and C-1 are identical, except for the flow direction. The inlet turbulence to the dump combustor was relatively low for model C-1. However, it was quite high for model A. Therefore, a comparison of the flowfields in these two combustors will undoubtedly contribute to an understanding of inlet turbulence effects. The inlet nozzles of combustors B and C-2 are totally different. Model C-2 has an idealized inlet, where the inlet turbulence is expected to be low. The inlet nozzle of model B was designed to resemble the actual inlet geometry of a solid fuel ramjet combustor, where the inlet turbulence is expected to be high. In spite of these differences, the sudden-expansion step heights of B and C-2 are the same. Therefore,



ALL DIMENSIONS IN mm

Figure 1 Details of combustor models

a comparison of the flowfields between these two combustors will reveal the combined effects of inlet geometry and inlet turbulence on the dump combustor flow. The sudden-expansion step heights of combustors C-1 and C-2 are different; otherwise, the two combustors are essentially identical. For model C-1, $H/d_1=0.23$, while for model C-2, $H/d_1=0.33$. Therefore, a comparson of the flowfields in these two combustors will give the effects of step height on dump combustor flows.

The flow at the entrance of combustor models B, C-1, and C-2 is nonrotating for both the stationary and rotating cases. This nonrotating character is maintained throughout the combustor for the stationary case. On the other hand, the flow acquires a rotation component near the surface of the sudden-

Notation

d_1	Diameter at combustor sudden-expansion inlet
d_2	Diameter of combustor
H	Step height $\equiv (d_2-d_1)/2$
k_i	Inlet turbulent kinetic energy
r	Radial coordinate measured from combustor centerline
R	Combustor radius $\equiv d_2/2$
Re	Inlet flow Reynolds number $\equiv U_i d_1/\nu$
T_i	Inlet centerline turbulence $\equiv u_i'/U_i$
u	Instantaneous axial velocity
u'	Rms of fluctuating axial velocity
u_i'	Inlet centerline value of u'
U	Mean axial velocity
U_i	Average inlet axial velocity to combustor
w	Instantaneous circumferential velocity
w'	Rms of fluctuating circumferential velocity
W	Mean circumferential velocity
x	Axial coordinate measured from combustor sudden expansion inlet
x_L	Reattachment length of primary recirculation region
ν	Fluid kinematic viscosity
ψ	Stream function $\equiv \int_0^r Ur\,dr$
Ω (rpm)	Rotational speed of combustor

expansion inlet in the rotating case. This rotation is confined to the wall boundary layer, and the flow outside is still nonrotating. Since the sudden-expansion inlet length for these three combustors is 127 mm (Figure 1), the rotating boundary-layer development is limited by this short distance. For combustor A, the situation is slightly different. The eight radial jets that supplied air to the combustor give rise to a slight rotation component in the inlet flow even for the stationary case. When the combustor rotates, the radial jets become circumferential jets and this imparts a high rotation component to the flow at the entrance to the combustor.

Since the flow inside model C-1 at two different Ω's had been investigated in detail,[7] the present investigations were also carried out at the same Ω's. This way, direct comparison of the measurements can be made, and the separate and combined effects of inlet geometry, step height, inlet turbulence, and rotation can be evaluated.

Instrumentation

The one-color, one-component laser Doppler anemometer (LDA) system of Ref. 10 operating in the forward scatter mode was used to measure the flow properties inside the different combustors. Components of the system consisted of a DISA model 55X LDA, model 55N10-1 frequency shifter, model 55L90A counter/processor equipped with a model 57G20 buffer interface, a 10-mW helium-neon laser (wavelength = 632.8 nm), and a model 55K18 seeding generator. The laser beam was split, and one beam was shifted 40 MHz, using a Bragg cell to allow accurate measurement of high turbulence and reversed flow in the axial direction. As before, the beam separation and beam intersection angle were chosen to give an ellipsoidal sampling volume with dimensions of 0.26 mm length and 0.04 mm width. The entire LDA system was mounted on a two-dimensional manual traverse, which was, in turn, mounted on a support separate from that of the rotating test rig. Therefore, the LDA system was isolated from vibrations stemming from the test rig. The manual traverse was accurate to 0.2 mm in the radial direction and to 0.5 mm in the axial direction. The seeding generator produced liquid (50% water and 50% glycerine) droplets with average size of 1 μm. These droplets were carried into the combustor by an airstream. The LDA signal quality could be improved by adjusting the droplet concentration, which was controlled by the air inlet pressure to the seeding generator. Finally, the speed of rotation of the combustor was measured by a stroboscope accurate to ± 1 rpm.

Measurement and analysis techniques

Only u and w were measured using the LDA system. These were measured separately. Therefore, the measurements yielded one-point velocity statistics only, and one-point velocity cross-correlations were not available. The measurements of u and w were carried out along the same horizontal diameter of the combustor. The data processing and analysis programs of Ref. 10 were used to process and analyze the velocity measurements. All velocity data were corrected by utilizing resident time bias, and up to 10 blocks of 1024 samples were used to resolve the velocity statistics. This way, the maximum percentage errors on the measured U and W are 2% and 5%, respectively. Details of the mesurement and analysis techniques are given in Refs. 7 and 10; therefore, they are not discussed further.

As before, the measured U's were used to construct stream function plots,[7] and the dividing streamline, $\psi = 0$, was extrapolated to the wall to give x_L. When complete U profiles were not available, x_L was determined by extrapolating the zero U locus to the wall. Even though flow visualization techniques tend to be more accurate because they do not rely on extrapolation to determine x_L, the present setup was not equipped for flow visualization experiments, and techniques based on extrapolating $\psi = 0$ and $U = 0$ to the wall had to be used. These extrapolation techniques had also been used by other researchers,[2] and they found that the two extrapolation techniques were in agreement to within 10%.

Discussion of results

A complete set of experiments has been carried out on combustor C-1 in Ref. 7. Therefore, the present experiments were mainly concerned with combustors A, B, and C-2. However, data from Ref. 7 will be used to compare with the present results to illustrate clearly the effects of flow and geometric parameters on the flowfield inside dump combustors. The experiment on combustors A, B, and C-2 were carried out at two different rotational speeds: $\Omega = 0$ and 840 rpm. Other inlet conditions are summarized in Table 1, where the corresponding test cases from combustor C-1 are also listed. Since the study of Ref. 6 indicated that Reynolds number (Re) was not an important parameter as far as x_L was concerned, the present study was carried out with approximately the same Re. However, because of the importance of inlet turbulence, all experiments on combustors A, B, and C-2 were carried out with approximately the same inlet turbulence for the $\Omega = 0$ and $\Omega = 840$ conditions for each combustor model. The U_i and T_i were measured at $x = 3.5$ mm downstream of the combustor sudden expansion. Profiles of U_i and u_i' at this location were found to be quite uniform. Detailed measurements of u and w were made of the flow in both combustors B and C-2 for the two Ω's tested. As for combustor A, only the $\Omega = 0$ case was studied in detail; the $\Omega = 840$ case was examined for x_L/H behavior only.

Since the primary objective is to study the effects of the various parameters on flow reattachment behind the sudden expansion, the emphasis of the presentation is placed on the u

Table 1 Summary of test conditions and x_L/H results

Combustor model	A		B		C-2		C-1 (Ref. 7)	
d_1 (mm)	43.2		38.1		38.1		43.2	
D (mm)	10.15		12.7		12.7		10.15	
Ω (rpm)	0	840	0	840	0	840	0	840
U_i (m/s)	15.5	15.5	12.5	15.6	14.1	14.1	10.55	10.55
$Re \times 10^{-4}$	4.5	4.5	3.2	4.0	3.6	3.6	3.1	3.1
$T_i \times 10^2$	13.7	13.7	17.6	17.3	4.6	5.5	5.7	5.7
x_L/H	5.4	3.4	4.0	2.2	8.3	4.9	7.4	5.1

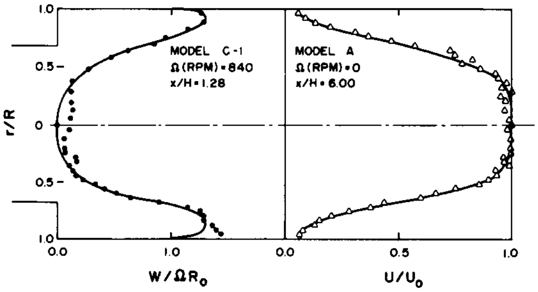


Figure 2 Symmetry check for combustors A and C-1

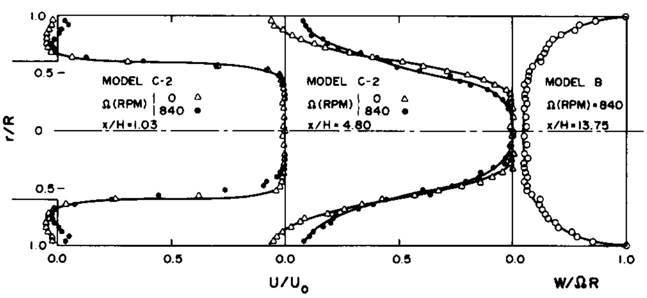


Figure 3 Symmetry check for combustors B and C-2

measurements. This does not mean that the w measurements are neglected. On the contrary, the circumferential velocity is examined carefully in all the rotating cases and at select stream locations in all the stationary cases. However, not all the circumferential velocity mesurements are reported. Select W and w' measurements are discussed if they contribute to a further understanding of the flow behavior. This does not dilute the significance of the present study because the omitted W and w' information do not contribute to a more penetrating understanding of the structure of the toroidal recirculation region. Neither do they provide further insight into the behavior of the turbulence field. If these phenomena were to be examined, a complete study of the turbulence behavior in the toroidal recirculation region has to be carried out. This would at least require the use of a two-color LDA system. Such an LDA system is not presently available, and the effort has to be postponed.

The stream velocity measurements were used to analyze (a) the effect of inlet geometry, (b) the effect of inlet turbulence, (c) the effect of step height, and (d) the combined effects of inlet turbulence and rotation on the flow inside dump combustors. A detailed discussion of each of these effects is given below.

Symmetry check

A major feature of an axisymmetric sudden-expansion flow is the creation of a toroidal recirculation region attached to the wall of the sudden-expansion tube. The extent of this recirculation region defines the reattachment length. Under most conditions, the recirculation region is weak and the velocities within the region are small compared to the inlet average velocity. As a result, the formation of this toroidal recirculation region, and hence the reattachment length, may also be affected by flow asymmetry as well as by the various parameters discussed earlier. In order to ascertain the effects of flow asymmetry, symmetry check on the flow was carried out on all combustor models before the actual experiments. The check was in the form of U and W measurements across one diameter at select stream locations along the combustors. In general, the check was concentrated in the region, $1<x/H<14$, where reversed flow is most likely to be found, and was carried out for both the stationary and rotating cases. Some sample plots of U/U_0 and $W/\Omega R$ across one diameter for all four models tested are shown in Figures 2 and 3. It can be seen that, within experimental measurement error, the sudden-expansion flow is axisymmetric for all cases studied. Consequently, any measured change in reattachment length cannot be attributed to flow asymmetry because it is essentially nonexistent in all the flow cases investigated.

Effect of inlet geometry

Combustors B and C-2 are similar in every respect, except inlet design. A well-contoured nozzle is used to guide the flow into combustor C-2. Therefore, the inlet turbulence at the plane of the sudden expansion is relatively low (Table 1). On the other hand, combustor B's inlet consists of a diffuser followed by an orifice. This inlet geometry produces separated flow upstream of the orifice and generates high inlet turbulence to the dump combustor (Table 1). In view of this, a comparison of the dump combustor flow between B and C-2 for the case $\Omega=0$ will give the effect of inlet geometry. The results of this comparison are shown in Figures 4–6.

The mean axial velocity results are shown in Figure 4, while the axial turbulence u' is plotted in Figure 5. In general, the trend of the flow development in combustors B and C-2 is essentially very similar, the only differences being in the recirculation region and the relatively early reattachment of the separating shear layer in combustor B (Figure 4). Forward flow across the whole combustor is noticed at $x/H=4.8$ for combustor B. This compares with $x/H=9.63$ for combustor C-2. As for u', the turbulence level is, in general, a lot higher for the flow inside combustor B compared to the flow inside combustor C-2 (Figure 5). The inlet turbulence at the combustor centerline of B is more than three times higher than in C-2 (Table 1). This trend persists until $x/H\simeq 10$. The u' distribution at the inlet of B is also about three times greater than the corresponding distribution in C-2, which means that the inlet geometry of B is very effective in promoting mixing and in the generation of turbulence. This increased mixing activity is still very evident at $x/H\simeq 14$. Similar behavior is also observed for w'. Therefore, the results suggest that the effect of inlet geometry is to produce an inlet flow with different inlet turbulence, which, in turn, promotes or hinders mixing and, according to Ref. 6, influences the reattachment of the mixing layer.

The effect of inlet geometry on the reattachment length x_L is shown in Figure 6, where the stream functions of the flow

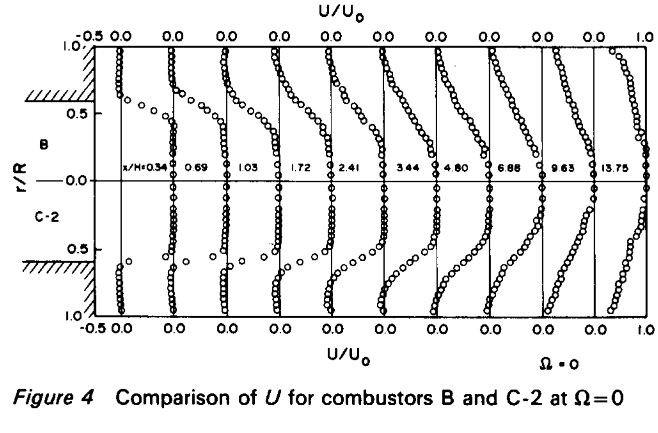


Figure 4 Comparison of U for combustors B and C-2 at $\Omega=0$

inside combustors B and C-2 are plotted. If the $\psi=0$ curve is extrapolated to the wall to give x_L, then x_L for combustor B is approximately half that for combustor C-2. The x_L's reported in Table 1 represent the average value determined from extrapolating the $\psi=0$ and $U=0$ curves to the wall. This reduction in x_L is consistent with the observations that increasing T_i causes x_L/H to decrease,[6] and further suggests that the actual effect of inlet geometry is to create different T_i's at the entrance to the sudden expansion.

Effect of inlet turbulence

Combustors B and C-2 have vastly different inlets. As a result, the inlet turbulence T_i also differs considerably. Even though it is argued that the effect of inlet geometry is to create different T_i's, therefore, the differences observed in flow behavior and x_L between combustors B and C-2 are directly attributable to T_i; a convincing case that T_i is the only important parameter in the determination of x_L has not been made. In order to do so, the flow behavior in the same dump combustor with different T_i's has to be examined. Such a comparison is made possible by considering the flow in combustors A and C-1 at $\Omega=0$.

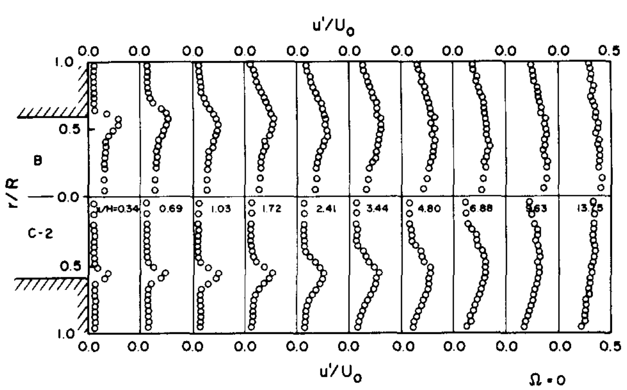


Figure 5 Comparison of u' for combustors B and C-2 at $\Omega=0$

The geometries of combustors A and C-1 are identical from inlet to outlet. However, the flow direction is different. For combustor A, the air was drawn in through the shaft end via radial jets. This created an inlet flow with high turbulence. Unfortunately, it also created an inlet flow with a small W component. On the other hand, the airflow was from the open end to the shaft end for combustor C-1. Since the flow entered the dump combustor mainly through the captured stream tube, a relatively low T_i was achieved for this combustor. Even then, because of inlet flow misalignment,[7] a small but significant W was also measured at the inlet. This small W slowly disappeared as the flow moved downstream. So and Ahmed[7] showed that this small inlet W component had little or no effect on the flow development inside the dump combustor. Consequently, the small inlet W effect on dump combustor flows can be ignored in the analysis of the effect of inlet turbulence.

Since the velocity measurements in combustors A and C-1 were not carried out at the same x locations, a comparison of the flow behavior is best achieved by examining the ψ plots (Figure 7). In addition, the u' distributions at some common locations are also compared (Figure 8). It is observed that the flow reattaches earlier for combustor A, and the u' level is, in general, higher than that in combustor C-1. The similarities and differences observed in this comparison are essentially identical to those seen in the comparison between combustors B and C-2. Even the reattachment length x_L follows the same trend noted in the earlier comparison of combustors B and C-2. Therefore, it can be concluded that the observed differences in flow behavior and x_L between the various combustors examined are primarily caused by the different T_i's. Other geometric parameters, such as inlet geometry, do not contribute to the observed differences in flow behavior and x_L in the dump combustors investigated.

Effect of step height

Another geometric parameter is step height. In order to isolate this parameter for investigation, the flow in two combustors (C-1 and C-2) of similar design, except for the step height, were investigated. The flow in C-1 had been examined in detail.[7] If

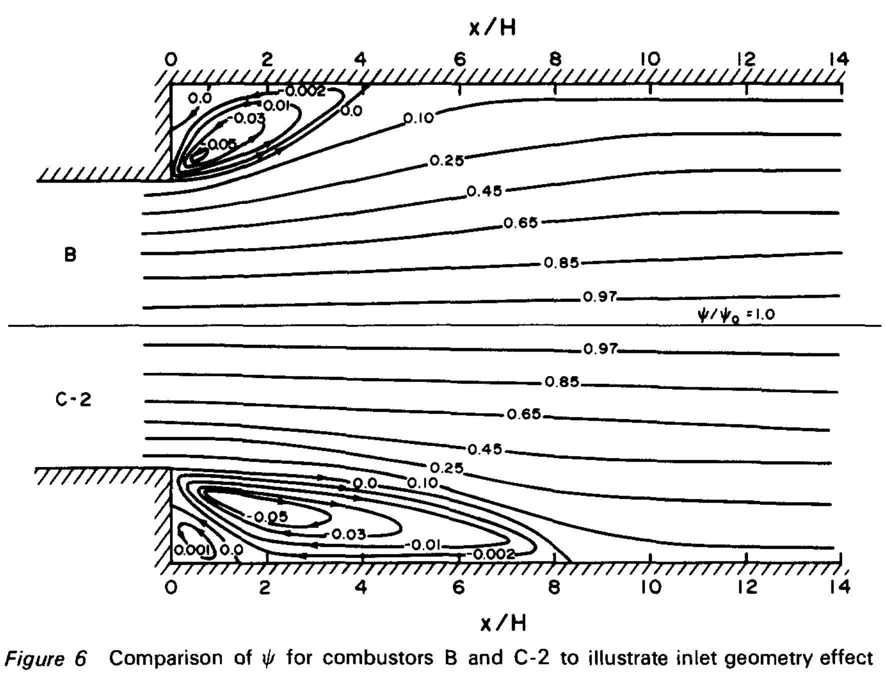


Figure 6 Comparison of ψ for combustors B and C-2 to illustrate inlet geometry effect

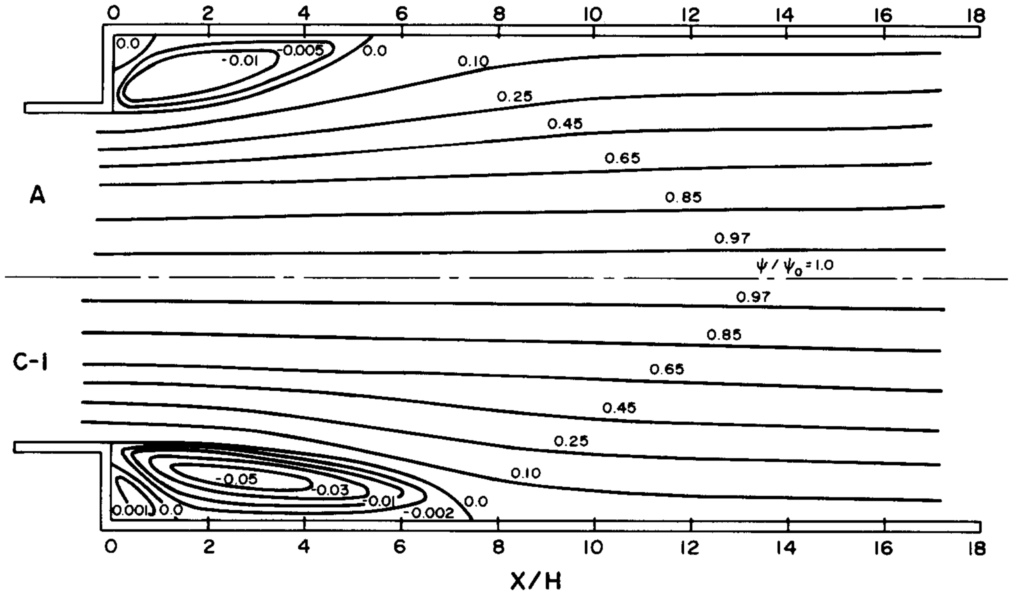


Figure 7 Comparison of ψ for combustors A and C-1 to illustrate inlet turbulence effect

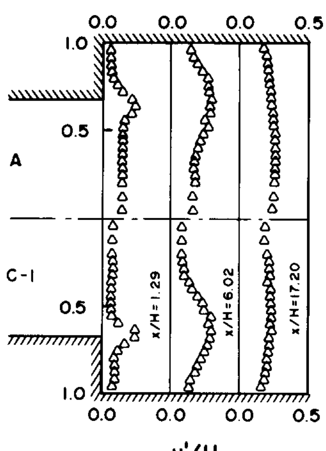


Figure 8 Comparison of u' for combustors A and C-1 at $\Omega=0$

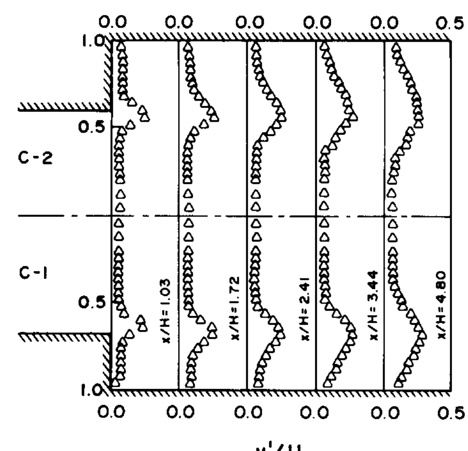


Figure 9 Comparison of u' for combustors C-1 and C-2 at $\Omega=0$

the same inlet conditions were also maintained in the experiment on combustor C-2, the results can be compared with those of C-1 to delineate the effect of step height on dump combustor flows. The inlet conditions for these two cases are approximately the same (Table 1). In order to examine the effect of step height alone, only the measurements for the condition $\Omega=0$ are examined. The stream function plots for combustors C-2 and C-1 are already given in Figures 6 and 7. A comparison of these two figures reveals that the flow inside these two combustors is essentially the same and the x_L's determined are very consistent. Even though there is a difference of $0.9H$ between the two x_L's, this difference is within the error margin of the reattachment length measurement. The distribution of u' at select x locations are shown in Figure 9. Just as in the mean field, identical u' behavior is also observed. This shows that step height has little or no effect on dump combustor flows and further substantiates the analysis that d_2/d_1 is not an important parameter as far as x_L is con[illegible]d.[6]

Combined effects of inlet turbulence and rotation

So and Ahmed[7] found that combustor rotation had the same effect on x_L as T_i did, namely, increasing Ω caused x_L/H to decrease. They explained the decrease based on the rotating boundary layer work of Refs. 11 and 12. Combustor rotation creates a very large shear in the flow near the wall, thus giving rise to a strong destabilizing effect on the separating shear layer and causing it to spread faster and reattach sooner compared to the stationary flow case. Since inlet turbulence also causes the separating shear layer to spread faster by energizing the flow and promoting mixing, the flow reattaches sooner compared to the low T_i case. This similarity between the two effects suggests that they might be additive. Therefore, it is important to investigate the combined effects of these two parameters together. This is achieved by comparing the flow inside combustors B and C-2 for the condition $\Omega=840$ rpm.

Unlike the case where $\Omega=0$, U actually approaches uniform distribution faster for combustor C-2 even though the reattachment length x_L is larger for combustor C-2 than for combustor B (Figure 10). However, x_L for both combustors rotating at $\Omega=840$ rpm is smaller than the corresponding x_L at $\Omega=0$ (Table 1). This means that inlet turbulence and rotation combine to effect a faster spread of the separating shear layer, thereby causing it to reattach sooner. The width of the separating shear layer in combustor B is clearly evident in the

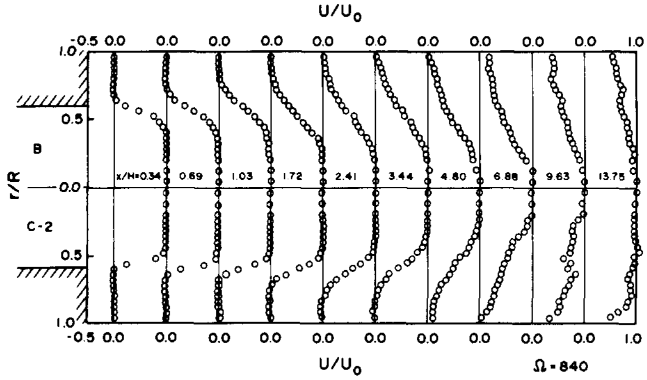


Figure 10 Combined effects of inlet turbulence and rotation on U

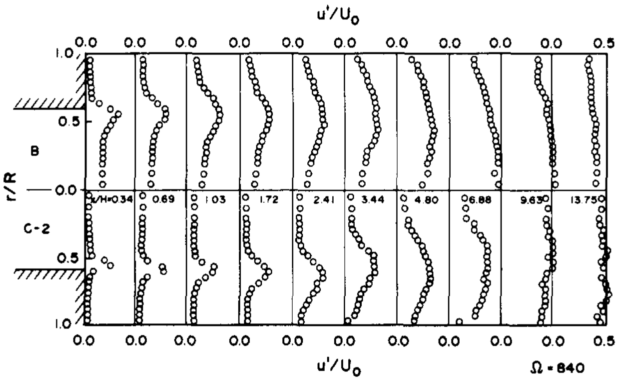


Figure 11 Combined effects of inlet turbulence and rotation on u'

U plots shown in Figure 10. Further evidence of the increased width of the separating shear layer can also be found in the u' profiles (Figure 11). There, the high level of turbulence in the combustor core and in the recirculation region of combustor B is clearly shown. This means that the mixing activity is greatly increased for the flow in combustor B, even in the recirculation region. A consequence of this increased mixing activity is the reduction in x_L.

The w profiles were measured at three x locations only. Just as in the case of combustor C-1,[7] W shows an overshoot inside the recirculation region of the flow in combustor C-2 (Figure 12). This overshoot slowly disappears as the flow moves downstream of the recirculation region. At $x/H=13.75$, the W profile is typical of one found in the entry flow region of a pipe rotating about its own axis.[11,12] Even though the same W profile is measured at $x/H=13.75$ for the flow in combustor B, an overshoot in W is not observed in any region of the flow in combustor B (Figure 12). According to the measurements of Ref. 7, the overshoot inside the recirculation region was a real phenomenon and was established right at the entrance of the sudden expansion. The overshoot increased to a maximum before disappearing downstream of the reattachment point. A plausible explanation was offered in Ref. 7. The overshoot was attributed to the enhancement of W, which was approximately constant and equal to ΩR in the recirculation region, by the rotating separating shear layer. If this line of reasoning is true, it could also explain the lack of an overshoot in W for the flow in combustor B. Since the mixing activity inside the recirculation region of combustor B is greatly increased by high T_i, the W distribution in this region cannot be equal to ΩR. On the other hand, it should behave like the W profile in the entry boundary-layer flow of a rotating pipe. Under this condition, even the enhancement of the rotating separating shear layer is not sufficient to augment W to beyond ΩR. However, it can be seen that W is fairly high inside the recirculation region of the flow in combustor B (Figure 12). A higher level of w' is also noted for the flow in combustor B, but at $x/H=13.75$ the w' distribution across the combustor is about the same for combustors B and C-2.

An alternative explanation to the overshoot in W should also be considered. If the streaklines show an inward movement at the plane where the overshoot is observed, then conservation of angular momentum dictates an increase in W. In order to test this hypothesis, a plot of $Wr/\Omega R^2$ versus r/R at $x/H=1.03$ for combustor C-2 is shown in Figure 13. The result shows that the overshoot is still there. Therefore, the overshoot could not have been due to an inward movement of the streaklines. From this plot, we can also infer that $\partial(Wr)/\partial r$ changes from negative near the wall to positive away from the wall. This means that the flow near the wall is unstable, and further substantiates

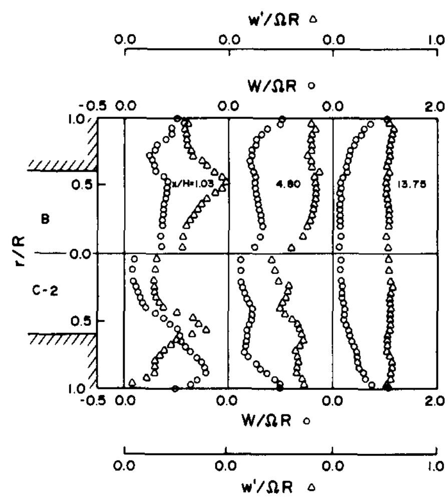


Figure 12 Combined effects of inlet turbulence and rotation on W and w'

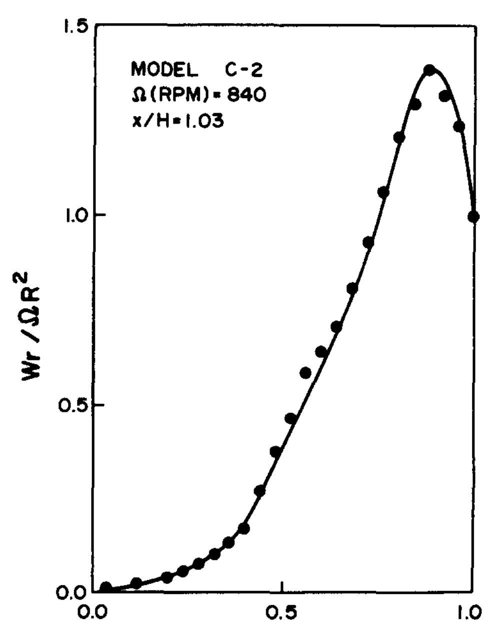


Figure 13 A plot of $Wr/\Omega R^2$ versus r/R for combustor C-2

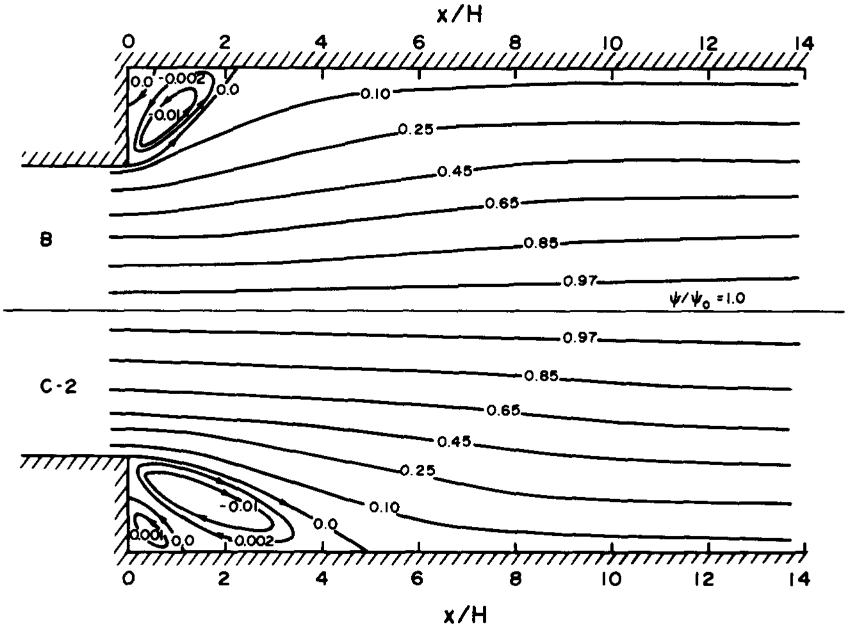


Figure 14 Combined effects of inlet turbulence and rotation on ψ

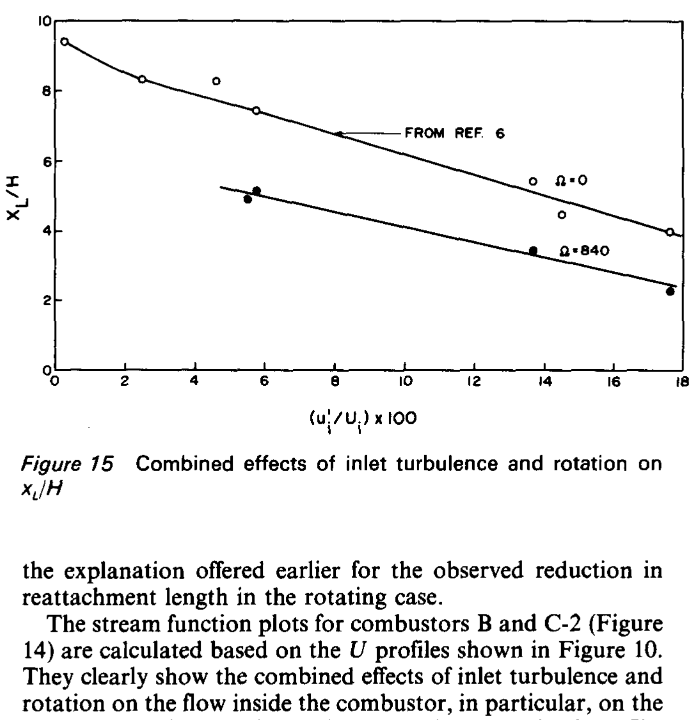


Figure 15 Combined effects of inlet turbulence and rotation on x_L/H

the explanation offered earlier for the observed reduction in reattachment length in the rotating case.

The stream function plots for combustors B and C-2 (Figure 14) are calculated based on the U profiles shown in Figure 10. They clearly show the combined effects of inlet turbulence and rotation on the flow inside the combustor, in particular, on the recirculation flow and on the reattachment behavior. The x_L/H's listed in Table 1 again represent the average value obtained from extrapolating $\psi=0$ and $U=0$ to the wall. Therefore, together these results seem to indicate that the effects of inlet turbulence and rotation on x_L/H are additive.

Further evidence that this is indeed the case can be obtained by plotting x_L/H versus T_i for the condition $\Omega=840$ rpm and compared to the result presented in Ref. 6 for the condition $\Omega=0$. This comparison is shown in Figure 15. It can be seen that x_L/H also varies linearly with T_i for $\Omega=840$ and, in general, is lower than the corresponding value for $\Omega=0$. Over the range of T_i examined, the two lines are approximately parallel, thus suggesting that the effects of inlet turbulence and rotation on x_L/H are indeed additive. This is a reasonable conclusion because both effects cause the separating shear layer to spread faster.

Conclusions

Based on the results presented, the following conclusions can be drawn.

(1) The combustor flow in all the cases considered is quite axisymmetric. Therefore, flow asymmetry could not have been a factor in the observed behavior of the reattachment length.
(2) The only effect of this class of inlet geometries is to create an inlet flow with different T_i's.
(3) When all inlet geometric and flow parameters except step height are kept constant, the net effect of step height on the flow in the combustor is negligibly small. This further substantiates the finding that this class of inlet geometries only affects T_i and has no other direct influence on the flow in the combustor.
(4) Inlet turbulence has a direct and significant effect on the flow in the combustor, particularly on the toroidal recirculation region. It increases mixing in the flow and energizes the separating shear layer, thus causing the shear layer to reattach sooner.
(5) In the rotating case, the flow near the wall is unstable. This promotes mixing and leads to a shorter toroidal recirculation region.
(6) Combustor rotation has the same effect on the flow as does inlet turbulence. When inlet turbulence and rotation are investigated together, their combined effects are found to be additive. The result is a drastic reduction of the reattachment length compared to the flow in a stationary dump combustor with relatively low inlet turbulence.
(7) The observed overshoot in W inside the toroidal recirculation region is not due to an inward movement of streaklines. Rather, it is the combined consequence of the effects of viscosity, rotating inlet boundary layer, and turbulent energy transfer from the axial to the circumferential direction.

Acknowledgment

This research was conducted under contract No. N60530-85-C-0191, supported by Naval Weapons Center, China Lake, CA 93555 and sponsored by the Defense Advanced Research Projects Agency.

References

1 Drewry, J. E. Fluid dynamics characterization of sudden-expansion ramjet combustor flowfields. *AIAA J.*, 1978, **16**, 313–319

2 Yang, B. T. and Yu, M. H. The flowfield in a suddenly enlarged combustion chamber. *AIAA J.*, 1983, **21**, 92–97

3 Stull, F. D., Craig, R. R., and Hojnacki, J. T. Dump combustor parametric investigations. Air Force Aero Propulsion Lab., AFAPL-TR-74-90, 1974

4 Stull, F. D. and Craig, R. R. Investigaton of dump combustors with flameholders. Air Force Aero Propulsion Lab., AFAPL-TR-76-15, 1976

5 So, R. M. C., Whielaw, J. H., and Lapp, M. *Experimental Measurements and Techniques in Turbulent Reactive and Non-Reactive Flows*, ASME Special Publication AMD-66, 1984

6 So, R. M. C. Inlet centerline turbulence effects on reattachment length in axisymmetric sudden-expansion flows. *Exp. Fluids*, 1987, **5**, 424–426

7 So, R. M. C. and Ahmed, S. A. Rotation effects on axisymmetric sudden-expansion flows. *J. Prop. Power*, 1988, **4**, 270–276

8 So, R. M. C., Yu, M. H., Otugen, M. V., and Zhu, J. Y. Rotation effects on inhomogeneous mixing in axisymmetric sudden-expansion flows. *Int. J. Heat Mass Transfer*, 1987, **30**, 2411–2421

9 Zhu, J. Y., So, R. M. C., and Otugen, M. V. Turbulent mass flux measurement using a laser hot-wire technique. *Int. J. Heat Mass Transfer*, 1988, **31**, 819–829

10 So, R. M. C., Ahmed, S. A., and Mongia, H. C. Jet characteristics is confined swirling flow. *Exp. Fluids*, 1985, **3**, 221–230

11 Murakami, M. and Kikuyama, K. Turbulent flow in axially rotating pipes. *J. Fluids Eng.*, 1980, **102**, 97–103

12 Kikuyama, K., Murakami, M., and Nishibori, K. Development of three-dimensional turbulent boundary layer in an axially rotating pipe. *J. Fluids Eng.*, 1983, **105**, 154–160