The instability mechanisms and mixing enhancement arising from the interaction of a compressible vortex ring with a normal shock wave were studied in a colinear, dual-shock tube. This flow geometry simulates features of the interaction of a shock wave with a jet containing streamwise vorticity, a configuration of significant interest for supersonic combustion applications. Flow visualization and quantitative concentration measurements were performed by planar laser Rayleigh scattering. For a given primary shock strength, interfacial instability is more evident in a weak vortex ring than in a stronger vortex ring. In all cases, the identity of the vortex ring is lost after a sufficiently long time of interaction. The probability density function of the mixed fluid changes rapidly from a bimodal distribution to a single peak upon processing by a shock wave. The most probable concentration decreases with time, indicating a rapid increase in mixing and dilution of the vortex fluid. The mixing enhancement is most rapid for the case of a strong vortex ring interacting with a strong shock wave, somewhat slower for a weak vortex ring and a strong shock wave, and significantly slower for the case of a strong vortex ring and a weaker shock wave. These observations are consistent with the earlier numerical predictions.

INTRODUCTION

Current interest in the interaction between compressible vortical flows and shock waves is largely motivated by the need to promote rapid, loss-effective mixing and combustion of hydrogen and hydrocarbon fuels for supersonic combustion applications [1]. While numerous previous studies have examined the penetration and mixing characteristics of transverse gas jets issuing into supersonic primary streams [2, 3], relatively little is known about the interaction of these jets with compression waves. Of specific importance for mixing is the impact of shock waves on the streamwise vortical structure that appears to play an essential role in the mixing process of transverse jets in compressible flow [3, 4].

Previous research on the interaction of compression waves with vortical flows has examined the density field, shock propagation, and the pressure amplification of acoustic waves, with much of the research being motivated by the need for noise reduction from high-speed jets [5, 6]. Earlier experimental studies of the interaction between a vortical ring and a shock wave have also indicated a strong turbulization due to the interaction, suggesting a potential impact on mixing [7]. More recently, detailed numerical simulations have examined shock structure and vorticity amplification resulting from the interaction of shock waves and vortex pairs [8, 9]. The results suggest that the most pronounced vorticity amplification occurs for the case of a strong vortex interacting with a strong shock. Somewhat less vorticity amplification is predicted for the case of a strong shock wave combined with a weak vortex; considerably less amplification is seen for the case of a weak shock and strong vortex. Experimental verification of these trends is one focus of the current work.

A key feature of the vortex/shock interaction is the vorticity generated by the misalignment of the adverse pressure gradient associated with the shock and the density gradient between the vortex ring and the surrounding flow [4, 10, 11]. The action of this baroclinic torque in compressible flow has been studied numerically [11-13] and experimentally
[11, 14–16]. Yet to be established is how the vorticity generated by shock passage interacts with the existing vorticity in a vortex ring, and what the implications of the instabilities and vortex interactions for fuel/air mixing might be. The instability characteristics of an accelerated volume of light gas and one of heavy gas can differ by more than simply the sign of the vorticity generated by baroclinic torque [14]. For example, acceleration of regions of heavier gas can lead to inertial (Rayleigh–Taylor) instabilities and strong, non-uniform acceleration can lead to shear (Kelvin–Helmholtz) instabilities [14, 15]. Thus the growth of actual disturbances may be a combined result of several instability mechanisms. Achieving an increased understanding of these phenomena is of obvious and direct importance to scramjet applications, given the inevitability of shock waves and regions of non-uniform density in a scramjet combustor.

The current research examined the instabilities and mixing enhancement induced by the passage of a normal shock wave through a compressible vortex ring consisting of propane gas injected into air. The visualization of the vortex structure and quantitative measurements of jet gas concentration during and after shock passage allowed study of the time evolution of the resulting instabilities and their impact on fuel/air mixing. The current work followed a study in the same facility of the mixing enhancement resulting from the interaction between shock waves and axial turbulent jets [17].

**EXPERIMENTAL APPARATUS**

**Flow Facility**

The test facility consisted of two colinear, opposed shock tubes as shown in Fig. 1. A circular shock tube of 10 mm inside diameter with a driven section 325 mm in length was used to generate the compressible vortex ring. The open end of the vortex shock tube was situated within the test section of a larger, primary shock tube 50 × 50 mm in internal cross section, in which a normal shock wave was generated. The test section of the primary shock tube was fitted with quartz windows for optical access and discharged vertically upwards to the atmosphere. The driven and test sections of the primary shock tube had a combined length of 1.9 m. The diaphragm of the primary shock tube, consisting of Mylar film of either 25 or 76 μm in thickness, was burst by impulsively charging the driver section with compressed air. The diaphragm of the vortex shock tube consisted of either a single or double sheet of 5-μm-thick Mylar film placed in contact with a pair of 50-μm-diameter copper wires. Synchronization of the vortex ring generation with the arrival of the primary shock wave was achieved by rupturing the diaphragm of the vortex shock tube, after an appropriate time delay, by discharging an electric current through the upper wires.

Piezoelectric pressure transducers, situated in the wall of the primary shock tube 35 cm upstream and downstream of the test section window, allowed determination of the primary shock wave velocity. A third transducer situated 127 cm upstream of the test section window served as the timing reference for the vortex shock tube, laser pulse, and the imaging system. A fourth pressure transducer was situated in the wall of the vortex shock tube at the tube exit, allowing determination of the time-of-flight of individual vortex rings from the exit of the vortex tube into the test section. The driven section of the vortex shock tube was purged with propane, which was then expelled into the surrounding test section air, giving rise to the vortex. A slow air co-flow was employed to keep the test section clear of propane prior to the initiation of the vortex ring.

**Diagnostics**

Planar Rayleigh scattering was employed to provide visualization of the flow structure and detailed quantitative measurements of the degree of mixing between the propane vortex and the surrounding air. The significantly higher Rayleigh scattering cross section of propane relative to that of air allowed measurements of vortex fluid concentration. The utilization of Rayleigh imaging as a quantitative, spatially and temporally resolved means to determine mixing has been demonstrated by earlier investigators [16–18].
Illumination for Rayleigh scattering was provided by a pulsed Nd:YAG laser (Continuum YG-681-10) at its third harmonic wavelength of $\lambda = 355$ nm with a pulse energy of 120 mJ. The nominal 10 ns duration of each laser pulse was sufficiently fast to effectively freeze the flow. Quartz cylindrical optics were used to form the laser beam into a 0.1-mm-thick light sheet of roughly 30 mm breadth at the test section centerline. A single Rayleigh scattering image for each test run was acquired by an image intensified CID camera (Xybion ISG-204-U-2) equipped with a Poynting Products frame grabber. Corrections for nonuniform laser illumination, optical system response and background were made for all images.

Flow Conditions

The Mylar primary shock tube diaphragms were burst at pressures of 3.0 and 6.4 atm, producing average measured primary shock Mach numbers in the test section of $M_s = 1.21$ and 1.44, respectively. These will be referred to as the "weak" ($M_s = 1.21$) and "strong" ($M_s = 1.44$) shocks. The primary shock Mach numbers were generally repeatable to within 5%. For all runs the initial temperature of all gases was 300 K. The diaphragms of the vortex shock tube were burst at 2.4 and 4.4 atm, producing average Mach numbers of the shock waves in the tube of 1.03 and 1.1, respectively. The resulting vortex rings are referred to here as "weak" and "strong." The average convective velocity of a vortex ring, $U_0$, was calculated from the position of the forward stagnation point of the vortex ring and the time difference between the illuminating laser pulse and the initiation of the vortex ring as determined from the pressure transducer at the vortex tube exit. For the region imaged (approximately 2 to 5 cm downstream of the tube exit), the convective speed of the vortex ring ranged from $U_0 = 44$ to 170 m/s for the weak vortex and $U_0 = 71$ to 286 m/s for the strong vortex. The corresponding Reynolds numbers, based on the distance between the cores of the vortex pair and the gas properties of propane, were $5 \times 10^4$ to $19 \times 10^4$ for the weak vortex ring and $8 \times 10^4$ to $32 \times 10^4$ for the strong one respectively.

In the following, weak and strong vortex ring interactions with a strong shock wave and the strong vortex ring interaction with a weak shock wave are described. Due to the relatively large variations in the weak vortex and the weak shock speeds, the reliable imaging of weak vortex/weak shock case was not possible.

RESULTS

Vortex Ring Stability and Structure

Planar Rayleigh scattering images of a weak vortex ring interacting with the strong normal shock wave are shown in Fig. 2. Each of the
Fig. 2. Planar Rayleigh images of weak vortex ring/strong shock interaction. Black and white correspond to minimum and maximum intensities, respectively. The shock position is shown by the arrows. (a) before interaction; (b) during interaction ($\Delta t = 37 \mu s$, $\xi = 0.29$). Typical regions for the pdf computations are shown as dashed rectangles.

Three images shown was taken during a different test run. In all cases, the direction of vortex ring propagation is from top to bottom and the shock propagation is from bottom to top. Each imaged region corresponds to $2.7 \times 2.7$ cm in physical space, with the exit of the vortex shock tube 2.2 cm above the top edge of each image shown. The vortex ring prior to interaction with the normal shock is shown in Fig. 2a, in which the vortex structure is clearly visible. While significant mixing had taken place in the vortex cores, there is a region of relatively high propane concentration in the forward stagnation region.

Two parameters are utilized here to characterize the "age" of the interaction. $\Delta t$ is the elapsed time from the first contact of the normal shock with the vortex ring. The nondimensional parameter $\xi = \Delta t/(R/U_0)$ is obtained by normalizing $\Delta t$ by a characteristic time of the large-scale circulation of the vortex ring, $R/U_0$, where $R$ is half the distance between the visible vortex cores. $\xi$ serves as a rough measure of the number of rotations undergone by the vortex cores during the period of the shock/vortex interaction. An image taken after the interaction ($\Delta t = 37 \mu s$, $\xi = 0.29$) is shown in Fig. 2b. Although the vortex structure is still recognizable, there appears to be increasing instability and turbulization at the flanks of the vortex. The decrease in overall signal intensity (especially after correction for pressure and temperature, not performed in the images shown) is suggestive of increased mixing. The degree of mixing enhancement appears greatest at the flanks and least in the stem region immediately beyond the vortex ring. The turbulization of the vortex ring increases with increasing time, with the vortex ring eventually losing its identity. The lateral extent of the vortex does not appear to be greatly influenced by the interaction, in agreement with previous experimental and numerical results [7, 8].

A series of interaction images for the case of a strong vortex ring/strong shock wave is shown in Fig. 3. In this case, the normal shock wave is of the same strength as the previous case (Fig. 2) but the vortex ring is stronger. The qualitative features of the strong vortex (Fig. 3a) are similar to its weaker counterpart, although somewhat more mixing appears to have taken place in the vicinity of the vortex cores. In Fig. 3b, the shock wave has propagated past the vortex cores, as indicated ($\Delta t = 31 \mu s$, $\xi = 0.31$). This appears to have resulted in flattening of the vortex ring. In addition, there is a crescent-shaped region characterized by relatively high signal strength, suggestive of high propane concentration. The relatively lower signal strength in the region behind the leading edge of the vortex ring indicates that the region of high intensity is not entirely an...
artifact of the density rise due to the passage of the normal shock wave. An image corresponding to $\Delta t = 45 \mu s$, $\xi = 0.55$ is shown in Fig. 3c. In the case a "Y-shaped" secondary structure consisting of relatively poorly mixed propane is apparent in the stem region of the vortex ring.

Lastly, a single interaction image for the case of a strong vortex ring and a weak shock wave is shown in Fig. 4. In this case, the vortex ring is of the same strength as the previous case (Fig. 3) but the normal shock wave is weaker ($M_s = 1.21$). The structure for this post-shock case ($\Delta t = 81 \mu s$, $\xi = 1.06$) does not exhibit the secondary "Y-shaped" structure similar to that for the case of a stronger shock strength. At earlier interaction times (not shown), a flattening of the vortex ring, accompanied by a crescent-shaped region of high propane concentration, is observed as in the previous case of the strong vortex ring/strong shock interaction.

The baroclinic torque resulting from the density gradient in the vortex ring and the shock pressure rise acts in a direction to augment the vorticity in the vortex cores. Although the higher density of the propane vortex ring gas relative to the surrounding air suggests that the vortex ring is Rayleigh–Taylor unstable, that the relatively smooth caps of the vortex rings persist well into the shock/vortex ring interaction suggest that this instability grows relatively slowly. Thus the structural fea-
tures and mixing characteristics, observed during the vortex ring/shock wave interaction and described qualitatively above, are likely to result from a combination of shear instability and baroclinic torque.

Spatial Probability Density Functions of Concentration

Representative probability density functions (pdf's) of the mixture fraction of propane are shown in Figs. 5-7. A value of $C = 0$ corresponds to pure air; $C = 100$, to pure propane. The character of a spatial pdf naturally depends on the selected region. All pdfs presented here were obtained in regions completely containing the vortex ring but excluding the far stem region, as shown in Fig. 2.

Pdfs for the case of a weak vortex ring interacting with a strong shock are shown in Fig. 5. The pdf of the weak vortex ring prior to the shock interaction is characterized by two peaks, one at low and another at high concentration. The low-concentration mixed fluid peak is believed to correspond to the vortex core regions, while the higher peak is due to the relatively less mixed forward stagnation region. The two peaks are of comparable height which is indicative of the similar extents of these regions. Upon processing by the shock wave, the nature of the pdf changes dramatically, with the bimodal pdf of the undisturbed vortex ring rapidly changing to a pdf with a single peak. This shift is indicative of a rapid increase in mixing and dilution of the vortex fluid. For the case of the weak vortex, the peak mixed fluid concentration is found to have a value of roughly 30% for times in the range of $\Delta t = 31-37 \mu s \ (\xi = 0.21-0.29)$.

The pdfs for the case of a strong vortex pair interacting with a strong shock are shown in Fig. 6. The pdf of the mixed fluid in the vortex ring before the shock interaction is quantitatively very similar to that of the weak vortex. The pdf of the strong vortex also shows a rapid change to a single peak. The location of the peak is seen to clearly march towards increased mixedness (i.e., lower values of $C$) with time. Specifically, the peak mixed fluid concentration decreases from approximately 26% at a time of $\Delta t = 31 \mu s \ (\xi = 0.31)$ to 20% at a time of $\Delta t = 45 \mu s \ (\xi = 0.55)$. This amount of decrease appears to be somewhat greater than that exhibited by the pdfs from the weak vortex ring/strong shock case shown in Fig. 5, suggesting that, for a given shock strength, more rapid mixing occurs for the case of a strong vortex than for a weaker one.

Finally, sample pdfs for the case of a strong vortex pair interacting with a weak shock are presented in Fig. 7. This interaction appears to be characterized by a considerably slower rate of mixing than the case of either the strong or the weak vortex rings interacting with a strong shock. For example, at a relatively long time of $\Delta t = 86 \mu s \ (\xi = 1.06)$, the pdf of the weak
shock case still exhibits remnants of the two peaks characteristic of the undisturbed vortex ring, including a significant fraction of mixed fluid concentration with values exceeding 40%. These trends are in qualitative agreement with numerical predictions of the same phenomena [8]. It should be noted that for the experimental results presented here, the strength of the vortex ring differed by roughly 60% between the strong and weak vortex rings, while the difference in shock Mach numbers amounted to only about 15%. This underscores the observation that the mixing is impacted to a much greater extent by shock strength than by vortex strength.

**SUMMARY**

The instability mechanisms and mixing enhancement arising from the interaction of a normal shock wave with a compressible vortex were studied in a colinear, dual-shock tube. Planar laser Rayleigh scattering was employed to provide flow visualization and quantitative measurements of the vortex fluid concentration.

Flow visualization suggests that, for a given primary shock strength, interfacial instability is more evident in a weak vortex ring than in a stronger vortex ring. The stronger vortex ring however appears somewhat more subject to
deformation during the interaction than the weaker vortex ring. In all cases the identity of the vortex ring is lost after a sufficiently long time of interaction.

The probability density function of the mixed fluid of vortex rings changes rapidly from a bimodal distribution to a single peak upon processing by a shock wave. The value of the peak concentration further decreases with time, indicating a rapid increase in mixing and dilution of the vortex fluid. The mixing enhancement is most rapid for the case of a strong vortex ring interacting with a strong shock wave, somewhat slower for a weak vortex ring interacting with the same shock wave, and significantly slower for the case of a strong vortex ring and weaker shock wave. These observations are consistent with earlier numerical predictions [8].

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REFERENCES


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Comments

E. Hasselbrink, Stanford University, USA. I think that it has been too hastily suggested that mixing has occurred where the propane concentration is low. Even if the mixture fraction of propane is unity at a given spatial location, the propane scattering may be low due to low gas density. This explanation is consistent with the images: the signal is low in the cores where pressure is low and the signal is high at the front stagnation point, where the pressure is expected to be high. My own estimates for the density variation in such a vortex ring arc ~ 20% (references: D. W. Moore, Proc. Roy. Soc. Lond. A., 1989; Mandella, Ph.D. Thesis, Stanford U., 1987; two papers in Fluid Dyn. Res., v. 12, 1993). Therefore, caution must be exercised in drawing conclusions about mixing from the concentration data and PDFs. For example, your interpretation of high mixing in the vortex ring core contrasts previous studies of turbulent vortex rings (Glezar, 1981, Ph.D Thesis Caltech; Maxworthy 1974 & 1977, J. Fluid. Mech.) which find very thin, persistent, stable cores that mix little with outside fluid.

Authors' Reply. It is true that the pressure variations in a compressible vortex will lead to variations in the strength of the Rayleigh scattering signal. For the shock/vortex ring interactions studied here, however, we believe that
this effect is considerably smaller than the variations in signal due to the concentration field. An examination of images presented in Fig. 2b help support this view. In this case, the pressure ratio across the shock wave is about 2.3, leading to a change in Rayleigh scattering signal much in excess of that due to the expected 10–20% pressure variation in the vortex ring. In addition, examination of Figs. 2 and 3 suggests that the regions of low signal strength in the vortex cores represent only a small fraction of the imaged flow field. Lastly, it should be noted that the two studies cited (Glezer and Maxworthy) were carried out in liquids, where mass diffusion rates are much smaller than those of gases. In summary, we believe that the qualitative features of the pdfs and the quantitative changes in mixed fluid concentration upon shock interaction are not greatly influenced by pressure variation in the vortex rings prior to the interaction.

E. J. Gutmark, Naval Air Warfare Center, USA. The PDFs, comparing fuel concentration in the vortex before and after the interaction with the shock, are not consistent with the conservation of fuel. The data show more fuel in the mixing domain before the interaction than after it. What is the explanation for this apparent inconsistency?

Authors' Reply. As stated in the article, each spatial pdf was obtained in a similar region encompassing the vortex ring. The quantitative comparison of the total amount of injectant between individual pdfs is complicated by the existence of large peaks corresponding to either pure injectant gas or pure (or nearly pure) ambient air. These peak values would, in many cases, be off-scale if included in the PDFs shown in Figs. 5–7, and thus some injectant fluid may not be fully accounted for in the PDFs shown. There may also have been some shot-to-shot variations in the quantity of the injected gas. In any case, these uncertainties do not affect the conclusions regarding the changed nature of the PDFs or the rapid shift in mixed fluid to lower values of concentration resulting from the shock/vortex interaction.