Study of Compressible Mixing Layers Using Filtered Rayleigh Scattering Based Visualizations

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Introduction

EXPERIMENTAL and theoretical results have confirmed a reduction in growth rate, changes in turbulence levels, and evolution of the large-scale structures of the compressible mixing layer with increasing compressibility [characterized by $M_c = (U_1 - U_2)/(a_1 + a_2)$, where U is the freestream velocity, a is the speed of sound, and subscripts 1 and 2 denote the high-speed and low-speed streams, respectively].[1-6] This Note provides a brief presentation of Rayleigh scattering-based flow visualization results of compressible planar free shear layers performed as a first step in an effort to obtain quantitative information such as density and velocity.
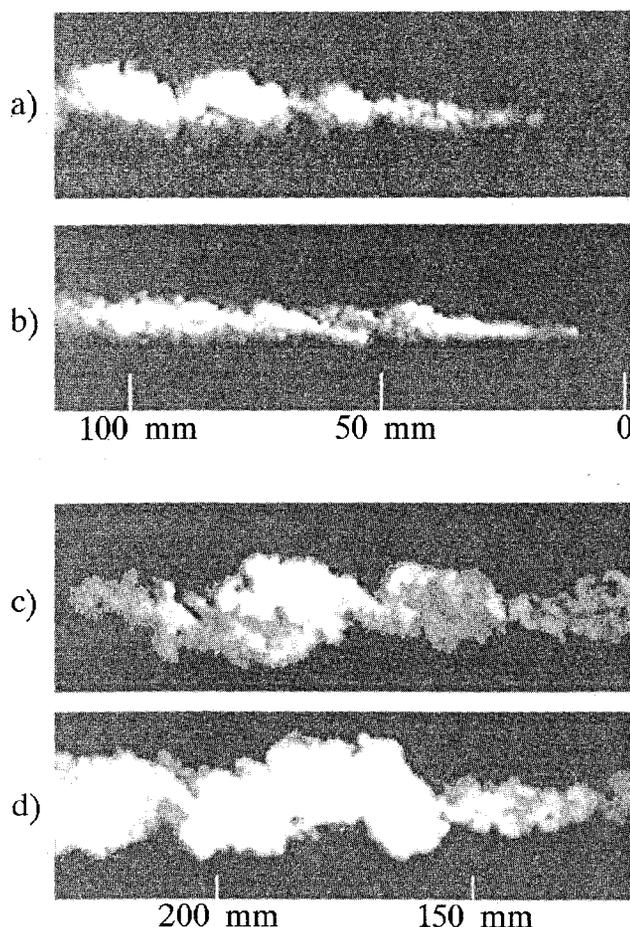

Fig. 1 Streamwise (X-Y; streamwise-transverse) view in the developing (a and b) and fully developed (c and d) regions for $M_c = 0.51$.

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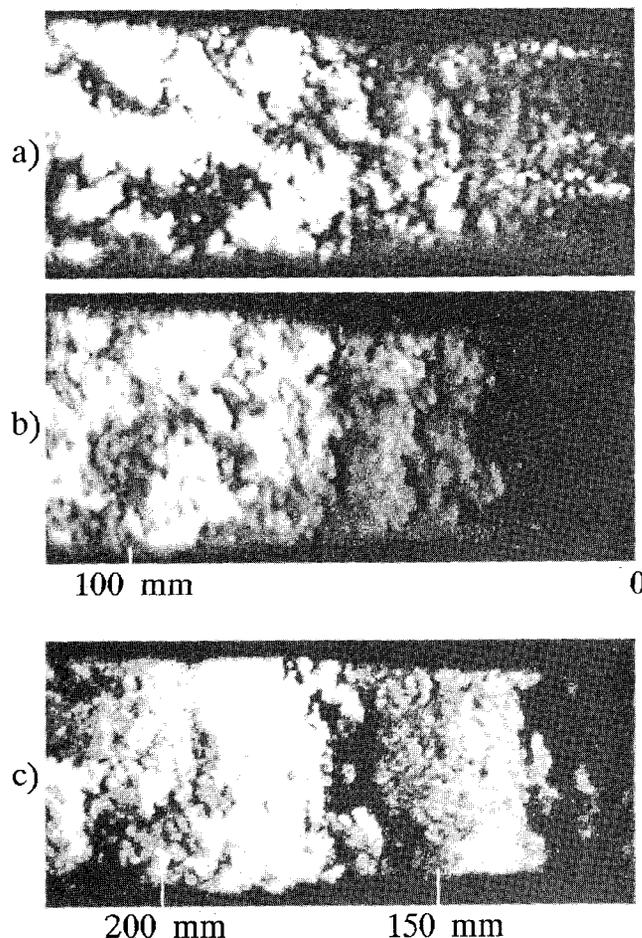‡Graduate Student, NSF Fellow, Department of Mechanical Engineering. Student Member AIAA.

Fig. 2 Plan (X-Z) view in the developing (a and b) and fully developed (c) regions for $M_c = 0.51$.

Experimental Facility and Instrumentation

The experiments were conducted at the Aeronautical and Astronautical Engineering Research Laboratory at Ohio State University. The convective Mach numbers investigated were 0.51 and 0.86, with flow parameters given previously.[2,3] The light source was a Quanta Ray GCR-4 frequency-doubled (532 nm) Nd:YAG laser with a pulse width of 9 ns, which was injection seeded to provide a narrow line width and ~ 50 GHz tuning capability. A sheet of light ~ 0.1 mm thick was used. The images were recorded with a Princeton Instruments intensified CCD camera. An iodine molecular filter was used to eliminate background scattering from walls and windows. The details of a similar filter and the filtered Rayleigh scattering technique are given by Miles et al.[7]

Scattering was collected from condensed particles of water vapor present in the supply air of one or both free streams. Two types of particle formation, previously employed by Clemens and Mungal[5] with ethanol vapor, were used with water vapor. The product formation technique marks regions in the flow where sufficient mixing has occurred for the water vapor in the subsonic stream to condense. In the passive scalar technique, condensation occurs in the supersonic freestream, allowing the evolution of the supersonic fluid in the shear layer to be visualized. Concerns about the size of the particles formed and the response time of their formation have been previously addressed, and the particles are believed to accurately represent the features of the shear layer.[4]

Results and Discussion

Figure 1 shows streamwise (X-Y) views of the developing and fully developed regions for $M_c = 0.51$ at unrelated instants. Many images in the developing region of the $M_c = 0.51$

case (Fig. 1a) show the evolution and growth of "roller-type" large-scale structures with distinct braid and core regions. At other instants (Fig. 1b), the large-scale structures have few similarities with the well-defined rollers. Figures 1c and 1d show the structures in the fully developed region. Again the flowfield is dominated by rollers with the well-defined core and braid regions of the Brown and Roshko type (Fig. 1c), but their presence is not as distinct in all images (Fig. 1d). Similar structures were also observed by Clemens and Mungal.[5]

Plan (X-Z) views of the $M_c = 0.51$ free shear layer are shown in Fig. 2. Figures 2a and 2b are plan view images in the middle and upper edge in the developing region, respectively. Product formation seems to begin almost immediately after the end of the splitter plate, with streamwise streaks present in the first 30 mm of the flow. The streaks resemble streamwise vortices observed in incompressible shear layers that are attributed to the amplification of upstream disturbances.[8] Although little two dimensionality is observed in plan views in the middle of the developing region, it is more evident in plan views located slightly higher near the edge of the shear layer, in both the developing (Fig. 2b) and fully developed (Fig. 2c) regions.

Figure 3 presents spanwise views from the developing and fully developed regions of the $M_c = 0.51$ shear layer for different streamwise locations. The streamwise streaks in the plan view initially appear as dots (Fig. 3a) that grow larger and perhaps merge (Fig. 3b) as they convect downstream. Figure 3c shows a spanwise view cutting through a braid region, and Fig. 3d shows a spanwise cut through a core region.

Figure 4 presents streamwise (X-Y) views for the $M_c = 0.86$ case. Upstream (Fig. 4a), the mixing region marked by the product formation is separated from the passive scalar signal in the top freestream. This is an effect of the higher temperature in the boundary layer of the high-speed side formed on
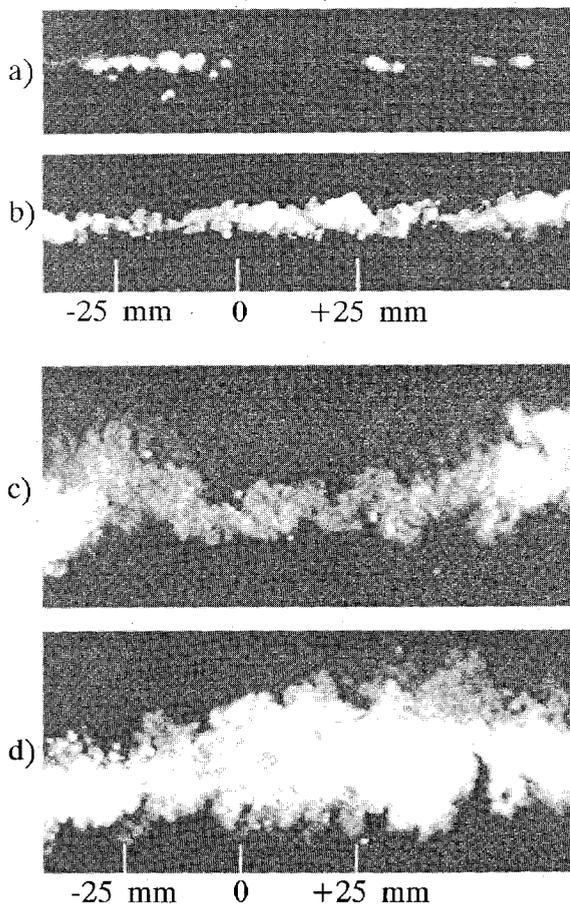

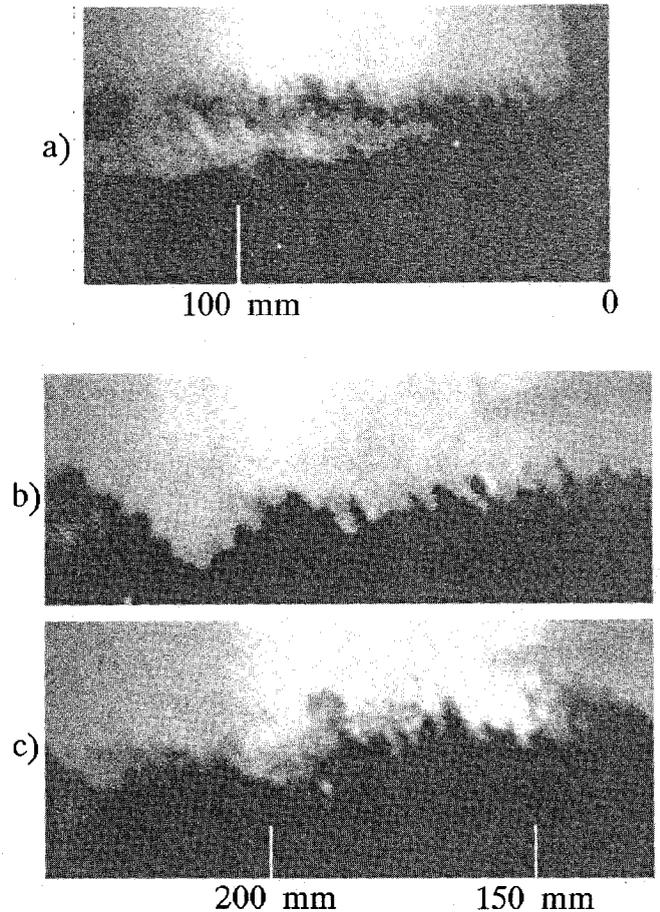Fig. 4 Streamwise (X-Y) view in the developing (a) and fully developed (b and c) regions for $M_c = 0.86$.

Fig. 3 Spanwise (Y-Z) view in the developing (a and b) and fully developed (c and d) regions for $M_c = 0.51$.

the splitter plate. Product formation in this case gives no indication of the core and braid regions seen earlier in the $M_c = 0.51$ case. Figures 4b and 4c present the streamwise images using only the passive scalar technique in the fully developed region for the $M_c = 0.86$ case. There is little evidence of core and braid regions, but less organized large-scale structures are still observed in most images. As with $M_c = 0.51$, small-scale structures seem to be embedded in the larger ones.

Figure 5 shows plan (X-Z) views for the developing and fully developed regions for $M_c = 0.86$. Figure 5a shows product formation in the middle of the shear layer. Although no clear organization is seen, one thing that is observable is the delay of product formation until ~ 25 mm downstream, probably due to the lack of mixing of the cold supersonic and moist subsonic streams at this higher compressibility level. There was no indication of the streamwise streaks shown in the $M_c = 0.51$ case, suggesting that the streaks could perhaps be an important mechanism in the decreasing growth rate with increasing compressibility level. Figures 5b and 5c present two passive scalar plan views for the fully developed region. Oblique structures are not as well defined as the two-dimensional ones shown earlier for $M_c = 0.51$, but two types of spanwise oblique structures typically occur. First there are images (Fig. 5b) that show oblique branching from a streamwise core. Another type of obliquity is seen in Fig. 5c, where an entire large-scale structure appears with oblique orientation in the shear layer. Sandham and Reynolds[6] predicted the presence of these oblique structures for high compressibility levels in their stability analysis and numerical simulations. Experimental space-time pressure correlation results have also shown that, for the $M_c = 0.86$ case, large-scale structures become more oblique relative to the $M_c = 0.51$ case.[3]
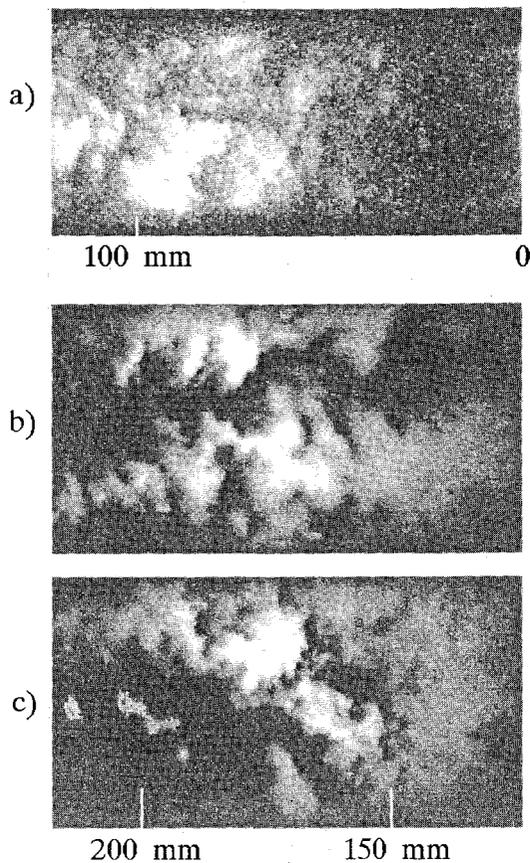
a)

100 mm   **0**

b)

c)

200 mm   **150 mm**

Fig. 5 Plan (X-Z) view in the developing (a) and fully developed (b and c) regions for $M_c = 0.86$.

Conclusions

Filtered Rayleigh scattering-based flow visualizations were used in compressible mixing layers. The lower compressibility case ($M_c = 0.51$) displays well-defined roller-type spanwise structures and streamwise streaks (perhaps indicative of streamwise vortices). The structures of the high compressibility case ($M_c = 0.86$) are more three dimensional and oblique. Work is currently underway to obtain quantitative information using this planar technique.

References

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Double Piston Shock-Wave Valve

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Introduction

THE shock tube is a useful tool for simulating shock-wave phenomena. In its early applications, it was used as a supersonic wind tunnel by utilizing the high-speed flow induced behind the incident shock wave. Recently, it has been used to generate plane shock waves since there has been a growing interest in the evolution and propagation of such shock waves.

There are many different methods for generating shock waves that produce high-speed gas flow, including using diaphragms, shock-wave valves, the free-piston gun tunnel, ballistic range (light gas gun), the Ludwieg tube, and electromagnetic systems. Of these various approaches the use of the diaphragm is the simplest and easiest to handle. However the production and changing of diaphragms is tedious and time consuming and causes various difficulties. Furthermore, during experiments part of the diaphragm might fly off into the shock-tube channel and test section, thereby disturbing the event to be observed (e.g., the shock-wave front and the air flow behind it). When this happens, the shock tube must be disassembled, the debris left from the diaphragm removed, and the apparatus reassembled. If metal diaphragms are used, damage to the shock-tube wall, observation windows, and/or test models may occur in extreme cases. When a poisonous gas is used as the test gas, or when there is a chemical shock tube, the rupture of the diaphragm can be extremely troublesome since the gas inside the shock tube may diffuse into the laboratory space when the ruptured diaphragm is being replaced for the following run. Replacing the lost gaseous atmosphere inside the tube can also be time consuming.

Diaphragm rupture is not always spontaneous; in many cases a needle is used to burst the diaphragm. In such cases, the shock-wave speed cannot be adjusted precisely since the velocity of the needle cannot be kept constant. However, precise wave-speed adjustment is essential for weak shock-wave research. This requirement is difficult to achieve when using a normal diaphrapm system.

A shock-wave valve is a suitable solution to the problem. Recently, some research regarding the development of shock-wave valves has been reported.[1-3] In the early types of shock-wave valves, the flow was forced to make a 180-deg turn at the valve. Subsequently, a system was proposed using a piston and valve arrangement such that the flow area at the valve remained constant[1,2]; thus the pressure losses were significantly reduced. However, this system was too complicated for easy and reliable use.

The purpose of the present Note is to introduce a new concept for a shock-wave valve. This valve has a simple structure, is easy to operate, and is suitable for large-scale shock tubes. It also generates very little turbulence in the flowfield produced.

Valve Design and Structure

The proposed shock-wave valve system is placed at the diaphragm position as shown in Fig. 1. This system is an independent unit, constituting a partition between the high-pressure chamber on one side and the low-pressure channel on the other side. It is different from the previous shock wave valve in that it can use whatever shock creating systems were

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