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SHOCK ENHANCEMENT AND CONTROL OF HYPERSONIC MIXING AND COMBUSTION

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Abstract

The possibility that shock enhanced mixing can substantially increase the rate of mixing between coflowing streams of hydrogen and air has been studied in experimental and computational investigations. Early numerical computations indicated that the steady interaction between a weak shock in air with a coflowing hydrogen jet can be well approximated by the two-dimensional time-dependent interaction between a weak shock and an initially circular region filled with hydrogen imbedded in air. An experimental investigation of the latter process has been carried out in the Caltech 17 Inch Shock Tube in experiments in which the laser induced fluorescence of byacetyl dye is used as a tracer for the motion of the helium gas after shock waves have passed across the helium cylinder. The flow field has also been studied using an Euler code computation of the flow field. Both investigations show that the shock impinging process causes the light gas cylinder to split into two parts. One of these mixes rapidly with air and the other forms a stably stratified vortex pair which mixes more slowly; about 60% of the light gas mixes rapidly with the ambient fluid. The geometry of the flow field and the mixing process and scaling parameters are discussed here. The success of this program encouraged the exploration of a low drag injection system in which the basic concept of shock generated streamwise vorticity could be incorporated in an injector for a Scramjet combustor at Mach numbers between 5 and 8. The results of a substantial computational program and a description of the wind tunnel model

and preliminary experimental results obtained in the High Reynolds Number Mach 6 Tunnel at NASA Langley Research Center are given here.

Introduction

The aim of this work is to demonstrate, both experimentally and computationally, the enhancement of the mixing rate between hydrogen and air through the generation of strong streamwise vorticity introduced by the interaction of a weak shock with the unmixed medium of non-uniform density. This paper describes the basic investigations in the Caltech 17-inch Shock Tube, in the Vortex Channel facility, and our progress on a model injector-mixer being carried out in the High Reynolds Number Mach 6 Tunnel at the NASA Langley Research Center.

Earlier experiments of Haas and Sturtevant (1988), which were initially directed toward a study of shock diffraction in a medium of non-uniform density, suggested that the vorticity generated at the interface between helium and air resulted in a rapid distortion of the interface and, later, rapid mixing between the two gases. When the very exacting requirement for very rapid mixing and combustion of hydrogen and air in the Supersonic Combustion Ramjet (SCRAMJET) became clear, we proceeded to investigate, Marble, Hendricks and Zukoski (1987), the details of the mixing process induced by shock interaction with a jet of hydrogen in air.

The experimental and computation results obtained in the Shock Tube Program and the Contoured Wall Injector will be discussed separately in the following paragraphs.

Shock Tube Program

The general concept of the process being studied is illustrated in Figure 1 where a weak shock, generated in the air stream by a turn in the bottom wall, intersects a hydrogen jet flowing parallel to the air stream and the wall. The interaction between the

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shock and the strong density variations present in the flow generates strong longitudinal vorticity in the interface between the hydrogen stream and the air, and this vorticity rapidly distorts the interface. This distortion greatly increases the interfacial area and hence will greatly increase the rate of mixing. In this picture, the vorticity produced by the longitudinal velocity differences between the air and hydrogen streams has been ignored, but it will also act to increase the rate of mixing.

Numerical computations, based on a linearized treatment of the flow, confirmed that the interaction of a weak oblique shock, such as that shown in Figure 1, with a cylindrical hydrogen jet moving parallel to an airstream at high supersonic speeds can be represented quite well by the two-dimensional time-dependent interaction of a weak normal shock with an initially circular region of hydrogen immersed in air. The primary difference is that one of these flows develops in the streamwise direction whereas the other develops in time.

Experiments

This result has led to a program of shock tube experiments in which a cylindrical jet of helium, connecting vertically in the working section of a shock tube, was used to model the hydrogen cylinder. A shock wave was produced in the tube which propagated in a direction normal to the axis of the cylinder, as shown in Figure 2. During the ensuing interaction process, the concentration of helium was determined by measuring the laser induced fluorescence of by-acetyl dye which was mixed with the helium. The intensity of the fluorescence was measured with an enhanced video camera and calibration of the camera-shock tube system allows quantitative estimates to be made of the local concentration of the dye. In these experiments, the laser sheet cuts a cross section of about 0.5 mm thickness, normal to the cylinder axis, with a time resolution of about 2 microseconds and the interaction process could be followed for times of up to two milliseconds after shock impingement. Details of the experiment and experimental results, given in a report by J. Jacobs (1990), are reviewed here.

A set of photographs illustrating the interaction process for a 1 millisecond period are shown in Figure 3 where the region within which the concentration is above about 20% of the original value is shown in

black, for the purposes of this paper. Color enhanced treatment of these data, Jacobs (1989), gives a much more detailed picture of the distribution of the dye than can be given here in black and white.

The experiments show that the interaction process initially breaks the cylinder of helium into a vortex pair connected by a thin umbilical cord that soon mixes. As the flow develops, each vortex breaks up into two distinct regions which can be clearly defined in the color photographs and in shadowgraphs of the flow. These are a region called the front lobe, which develops into what appears to be a strongly stratified vortex pair, and the back lobe which mixes rapidly with the surrounding air and disappears.

Jacobs studied the two-dimensional mixing process quantitatively by measuring the change in areas of these two regions. The rapid drop in area of the back lobes is shown in Figure 4 in which the areas of both lobes, normalized by their values at about 0.5 ms, are plotted as a function of time. The back and front lobes are already clearly defined in the 0.488 ms photograph of Figure 3 and the back lobe has substantially disappeared by 0.988 ms.

By the 0.988 ms time frame, about 60% of the initial helium has been mixed with air to form a mixture with less than a 10% helium concentration.

Computations

A detailed numerical analysis of this flow has been carried out by Hendricks and Marble (1990) using the Flux Corrected Transport method developed by Boris, Book and Haim (1975, 1976) and a modified form of the computational code developed by Picone and Boris (1988). Because the time scales involved in the process of interest here are a few milliseconds, viscous effects do not play an important role in the evolution of the flow field and an inviscid Euler code was used to model the flow field. The results of these computations have been very important in guiding the experimental work and in explaining features of the flow field that have not been measured.

The mixing augmentation mechanism under consideration here results from the vorticity generated when pressure and density gradients in a fluid are not aligned. The rate of change of the vorticity, ω , generated in the fluid in this manner is given by the right hand side of the vorticity equation written in terms of the the pressure p and density ρ as:

$$\rho \frac{D}{dt} \left(\frac{\bar{\omega}}{\rho} \right) = \frac{1}{\rho^2} \bar{\nabla} p \times \bar{\nabla} \rho$$

As the shock wave passes over the cylinder, the maximum rate of generation of vorticity occurs as the shock wave passes over the major diameter of the cylinder where the pressure and density gradients are perpendicular, and because of the $(1/\rho)$ term in this equation, vorticity will be preferentially generated on the light gas side of the density gradient rather than on the air rich side. Hence, most of the vorticity will be generated in the light gas and little in the surrounding air and the subsequent development of strongly stratified light gas vortices is reasonable.

Computations have been carried out for a wide range of initial values for the parameters of the system including: Mach number of the shock; specific heat ratios; density ratios between the light gas and the ambient fluid; thickness of the density gradients between light gas and the ambient fluid; the geometry of the interface; and the number and relative positions of cylinders of light gas. Only the conclusions drawn from the basic flow will be discussed here.

Although some vorticity production does occur after the passage of the shock over the light gas cylinder, the calculations show that the circulation around the upper or lower half of the flow is almost constant after the shock has passed and that for weak shocks scales as

$$\frac{\Gamma}{a_1 d} \sim \frac{2}{\gamma_1 + 1} (M_s^2 - 1) \frac{\sqrt{\frac{\gamma_1 \rho_1}{\gamma_2 \rho_2} - 1}}{\sqrt{\frac{\gamma_1 \rho_1}{\gamma_2 \rho_2} + 1}}$$

Here, d is the diameter of the light gas cylinder, and a is the speed of sound in the ambient fluid, γ is the specific heat ratio, and ρ , the gas density. The subscripts 1 and 2 refer to the ambient air and light gas properties and M_s is the Mach number of the gas motion normal to the shock wave.

The subsequent development of the distortion is then almost totally due to the self-induced flow produced by the vorticity generated by the passage of the shock. One aspect of this motion is that the structure moves through the ambient gas with a velocity which varies from about 75% of the gas speed behind the shock early in the development to roughly 15% later on. This relative velocity is of little import for the shock tube experiments, but can be important in a fuel injector design.

Results of a single computation, taken from Hendricks and Marble (1990), for a Mach 1.10 shock strength and three different times are shown in Figure 5 for a flow similar to that shown in the photographs of Figure 3. The data in Figure 5a, b, and c, are density contours, and that in 5d is the pressure contour corresponding to 5c. The time t^* directly enters the formulation of the computations and it is a dimensionless time defined as (ta/d) . The time given in the Figures is obtained by using experimental values for a and d .

The mechanism by which the vorticity is redistributed during the development to the later configuration is of particular interest. The two relevant mechanisms are the convective transport and the barotropic generation and annihilation. The first is possible because the vorticity is initially deposited in the thin layer where the composition gradient is large. Because this may involve only a small fraction of the helium, the helium carrying the vorticity may migrate toward the front and leave the less vortical portion in the rear part of the structure. The barotropic generation is important because significant pressure gradients remain in the field after passage of the original shock. The relative stability of the stratified vortex which appears in the late stage of development may be inferred from the colinearity of the density and pressure contours exhibited in Figures 5c and 5d.

The development and separation of the front and back lobes is clear from the density plots, and the circular pressure distribution indicates that a stable vortex has developed by 2.19 ms. Vorticity plots, see Hendricks and Marble 1990, confirm our interpretation of the density field, that a stable vortex pair is produced. The good agreement between the experimentally determined density fields and the computational results indicates that we have a good understanding of the distortion produced by the interaction of the shock with the light gas cylinder.

Analysis of the flow generated by the interaction suggest that the characteristic scaling time (τ) for the distortion process is given by

$$\tau = \frac{d^2}{\Gamma} \propto \left(\frac{d}{a_1} \right) \left(\frac{1}{M_s^2 - 1} \right)$$

The strong dependence on the shock Mach number is important since it gives us a sensitive control over the time required to enhance the mixing process.

For the experimental conditions used in obtain-

ing the data discussed above, the value for (τ) is about 0.9 milliseconds which is fortuitously close to the observed time of about 1 millisecond for the disappearance of the back lobe. For an engine moving at Mach 10 with a combustion chamber Mach number of 6, shock Mach number of 1.10, diameter of the hydrogen jet of 2 cm, and a hydrogen injection temperature of 1600 K, the characteristic time is about 0.3 milliseconds.

This scaling result demonstrates that the time required for the development of the mixing process described above is short enough to be of interest in a SCRAMJET engine even for a very weak shock. By increasing the shock Mach number from 1.10 to say 1.30, for which the total pressure losses are still small, the scaling time can be reduced by a factor of three, or to about 100 microseconds for this example. Given the expected residence time for air in the SCRAMJET engine of 1 to 2 milliseconds, these times are relatively short.

The computations confirm that the light gas remaining in the front lobes forms a strongly stratified vortex pair which continues to persist in an unmixed condition for times larger than that available in the experimental apparatus. Because these vortices are stratified, they are particularly stable and we expect that continued mixing of this material with air will be slow. Hence, we must rely on mixing due to either the longitudinal shear or some other shock interaction to rapidly mix this material with the surrounding air. The influence of mixing induced by shear and the possibility that a second shock can destabilize the vortices pair are being studied now in experimental and computational programs.

Contoured Wall Injector

The success of the shock tube experiments in demonstrating the effectiveness of shock enhanced mixing in fields of non-uniform density encouraged the search for a configuration incorporating the shock-enhancement principles as well as being compatible with the requirements and limitations of a Scramjet combustion chamber. Such a configuration was conceived in April 1987 and, through the efforts of Dr. Dennis Bushnell, NASA-Langley Research Center, arrangements were made in early May for Caltech to design and construct a model to be tested in the Langley High Reynolds Number Mach 6 Tunnel.

The concept for the injector is illustrated in Fig-

ure 6. The injector consists of alternate compression ramps and expansion troughs, of 5 degrees each, for the Mach 6 air stream. The end of each ramp houses a nozzle discharging helium (hydrogen) at an appropriate pressure level. At the same streamwise location the flow in each trough is turned back to the free stream direction, forming a weak oblique shock. This shock moves away from the combustor wall and under the helium jet, thus providing a shock impingement on the light gas stream corresponding to that in the shock tube, and lifting the helium flow away from the combustor wall and into the air stream.

In the computations and experiments discussed here these ramps extend 6 inches in the axial direction, the injector face is 1 inch high and 0.5 inches deep, and the ramps are 1.63 inches wide. The shock begins to impinge on the injected fluid at the bottom of the injector face and proceeds across the injectant as suggested in the sketch of Figure 6.

Computations

Computations have been carried out for this system over a domain which extends from a position 3 injector heights (i.e. 3h) upstream from a 5 degree ramp which is 6h long, to a point 30h downstream of the injector plane. The region covered is 4h high and deep, and it covers the region from the centerline of the injector which is 0.5h wide to the center of the expansion ramp which is 1.63h deep.

Two codes have been used to model the flow. The first was developed by Hendricks from a code obtained from J.P. Boris and E.S. Oran at the Naval Research Laboratory, and the second by Waitz from a Navier-Stokes code obtained from the Computational Branch, NASA Langley RC. Computing support was obtained from NAS Facility at NASA Ames RC, the JPL/Caltech Cray, and the San Diego Supercomputer Center, NSF.

Contour maps of the density profiles in planes perpendicular to the air flow, from Hendricks and Marble 1990, are shown in Figure 7 for positions near the end of the ramp, and at several positions downstream of the injector face. The ramp and injector widths are equal here. In 7a,b and c the plane is at 0.5, 1 and 2 injector heights downstream of the injector face, the development of the shock produced by the turning of the flow at the end of the ramp can be traced in the air and helium streams. The distortion of the helium jet at a point 2 injector heights is

shown in 7c and here the distortion begins to look very much like that observed in the shock tube experiments. (Rotate the contours shown in Figure 7 through 90 degrees in the counter clockwise direction and compare with contours shown in Figure 3 and 5.)

A set of density contours obtained by Waitz for larger downstream distances and with the NASA based code is shown in Figure 8 for helium injected into a Mach 6 air stream with the nozzle exit pressure matched with the free stream pressure and with a nominal exit Mach number of 1.7. The density contours shown are similar in appearance and develop in the same manner as those shown earlier for the shock tube experiments.

Although the rate of mixing is our primary figure of merit for these systems, the rate at which the helium stream drifts away from the wall is another and it can be determined from plots of the type shown in Figure 8. A qualitative measure of the degree of mixing is shown for this example in Figure 9 where the fraction of the total mass flux of helium in the stream with a specified mass fraction of helium is shown as a function of downstream distance. Again, rapid mixing of a considerable part of the flow occurs close to the nozzle and then the mixing rate slows down; this is similar to that observed in the shock tube experiments and calculations and again emphasizes the importance of dealing with the stable vortex pair formed by the interaction.

The degree of similarity between the computations of these two flows as well as with the shock tube measurements is encouraging and suggests that the process we are investigating will lead to a considerable enhancement of the mixing process and further that the computations can be used to guide the experimental program and, perhaps, for design purposes.

Experimental Results

In the experiment the injector block is mounted on a flat plate model of the same width which extends about 30 inches up and down stream of the injector section. This plate has an aerodynamic boundary layer trip near the leading edge which can produce turbulent boundary layers at the beginning of the ramps which are from 0.2 to about 2.0 injector heights thick. A number of injector blocks have been constructed which allow both the scale of the injectors and the ratio of the spacing between injectors to

the injector height to be changed by a factor of two. Instrumentation includes total temperature, pressure and concentration probes, spark schlieren photography, surface oil flow patterns, and Rayleigh scattering system for instantaneous measurement of helium density.

Preliminary tests with this model started briefly in the spring of 1989, and tests were started in June of 1990 and will continue through August of 1990. Data obtained in the preliminary test and more recently in the ongoing test program indicate that the calculations described above give a good representation of the flow over the model. The importance of the ramp width to nozzle height and the boundary layer thickness to nozzle height ratios has been demonstrated. The test matrix will include changes in the geometric parameters of the injector, the boundary layer thickness and Reynolds number of the flow, the injector Mach number, and pressure ratio at the injector exit.

Conclusions

The degree of similarity between the two computed flow fields and between these computations and the shock tube and wind tunnel measurements is encouraging and suggests that the basic features of the process under investigation are understood and can lead to a considerable and rapid enhancement of the mixing process. Further, we have found that the computations can be used to guide the experimental program and, perhaps, for design purposes. Finally, some mechanism for destabilizing the vortex must be incorporated into the injector design to ensure complete mixing of the light gas with air.

Acknowledgements

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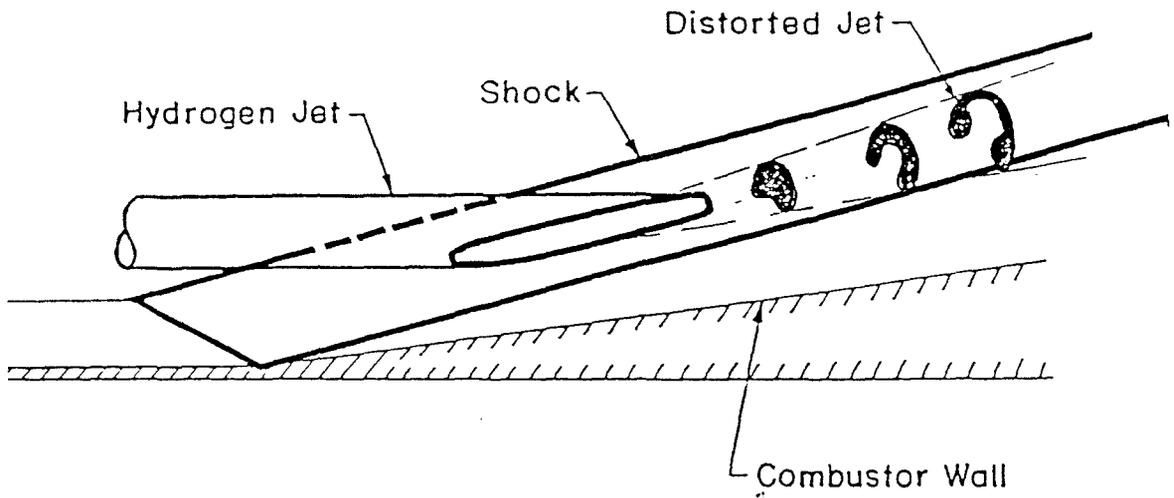


Fig. 1. Sketch illustrating the Shock Induced Mixing Concept

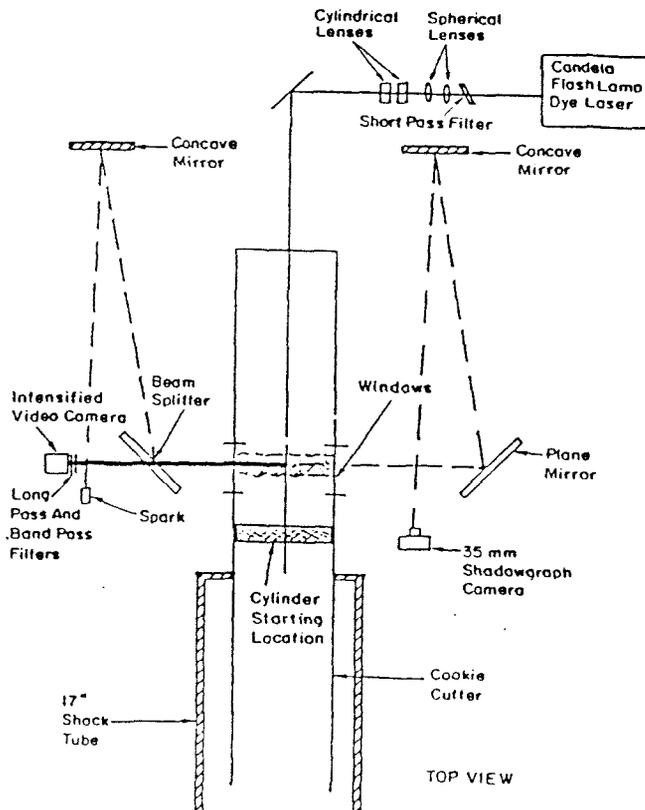


Fig. 2. Sketch of Shock Tube Experimental Apparatus

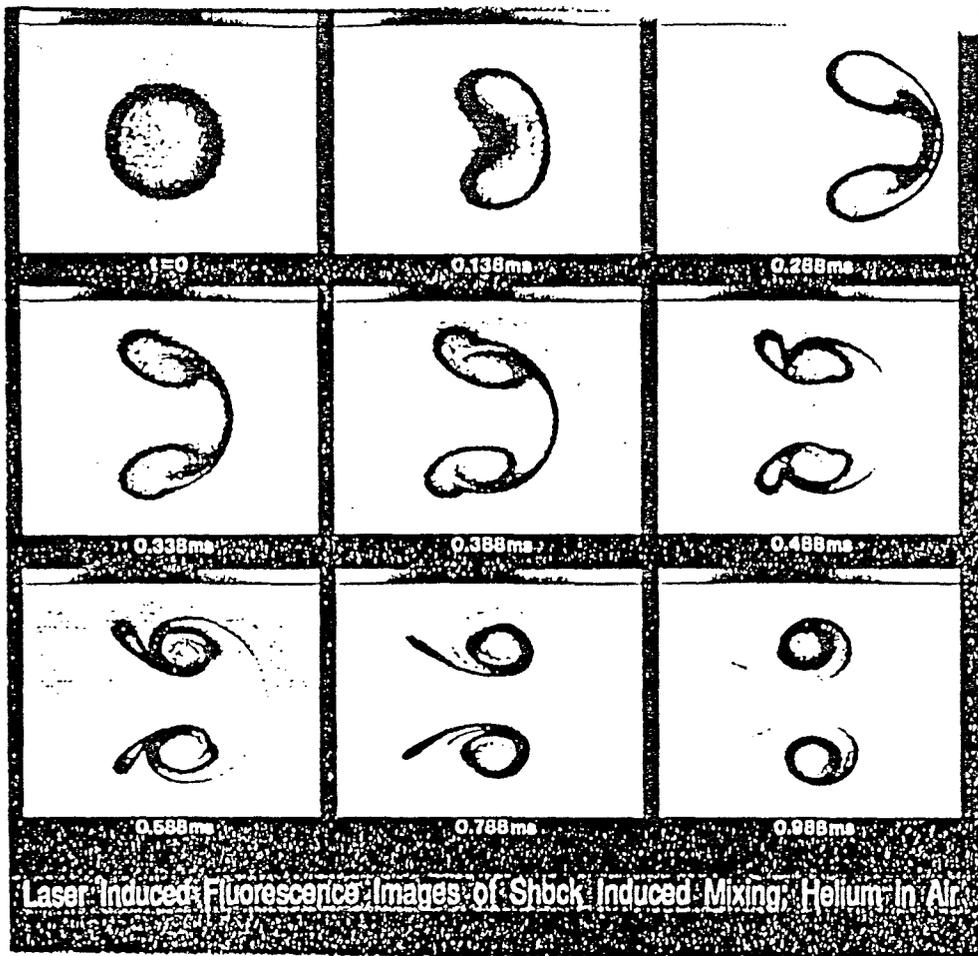


Fig. 3. Photographs showing the Development of Density Field with time for a shock Mach number of 1.0

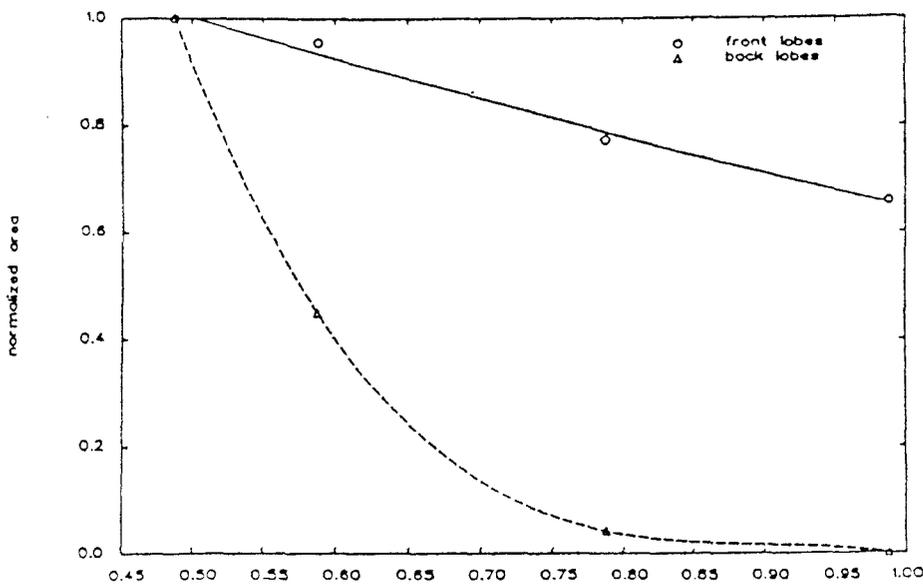


Fig. 4. Change in Normalized Areas of Front and Back Lobes with time, based on areas with a 50% or higher concentration of Helium.

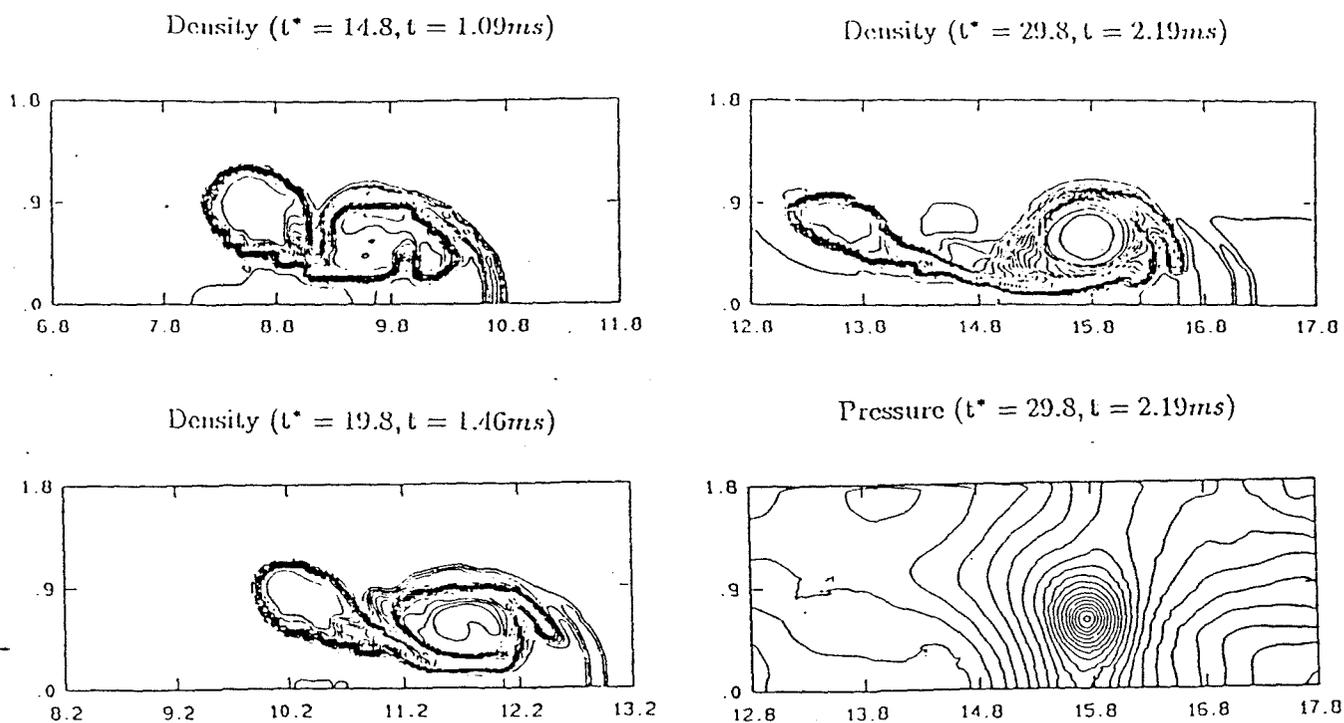


Fig. 5. Density and Pressure field computed (Hendricks and Marble 1990) for a shock Mach number of 1.10 at three times.

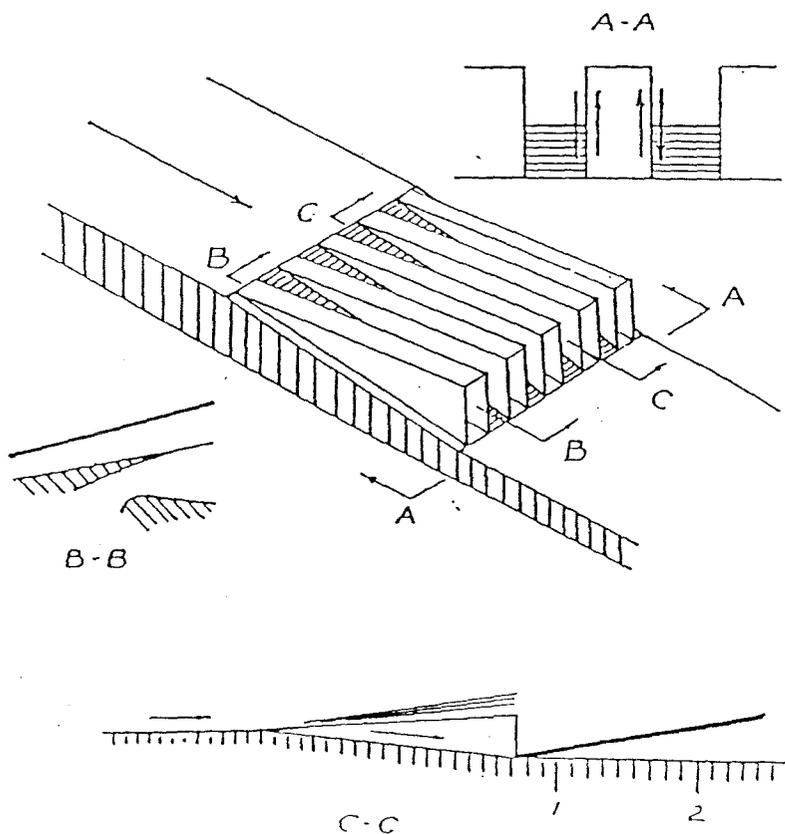


Fig. 6. Sketch illustrating the Contoured Nozzle Injector Concept

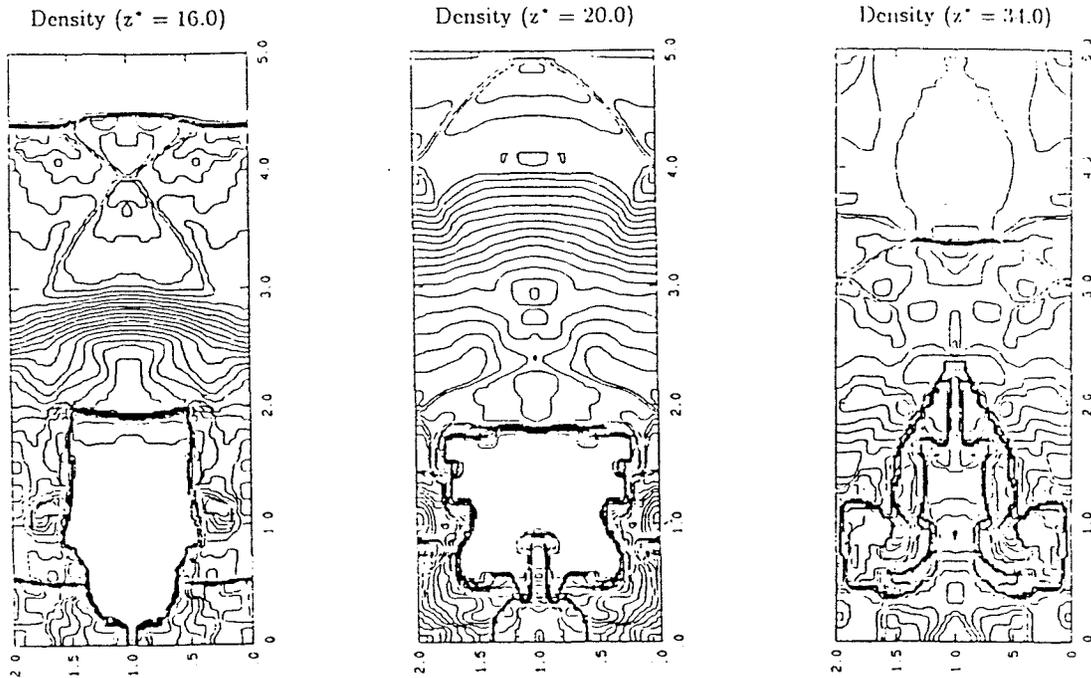


Fig. 7. Density and Pressure field computed (Hendricks and Marble 1990) for a Mach number 6 flow at planes 2, 4, and 8 injector heights downstream of nozzle exit face.

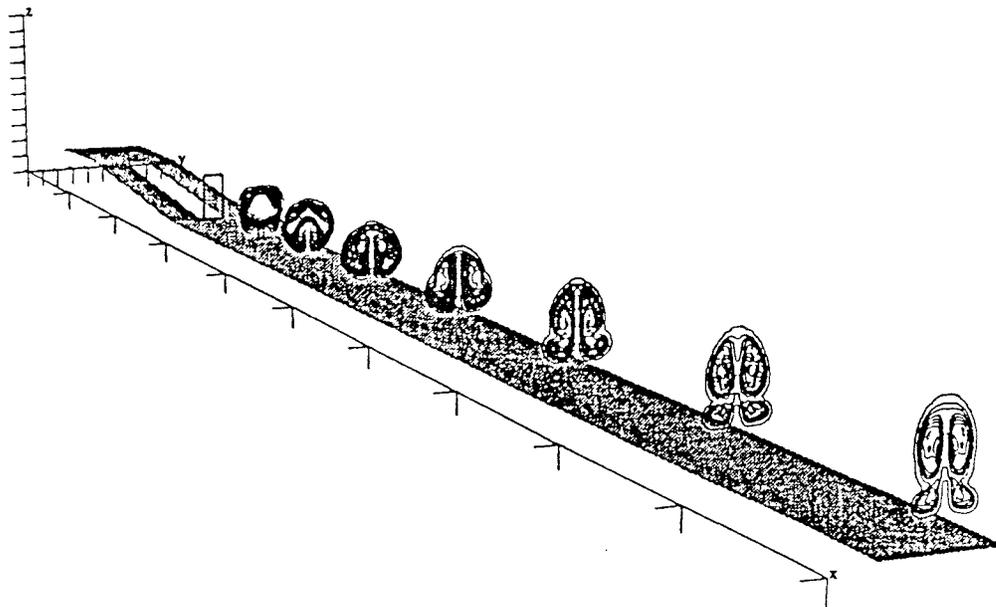


Fig. 8. Density field computed by Waitz for Mach 6 flow at planes 1, 2, 4, 8, 15, 22 and 30 injector heights downstream of nozzle exit.

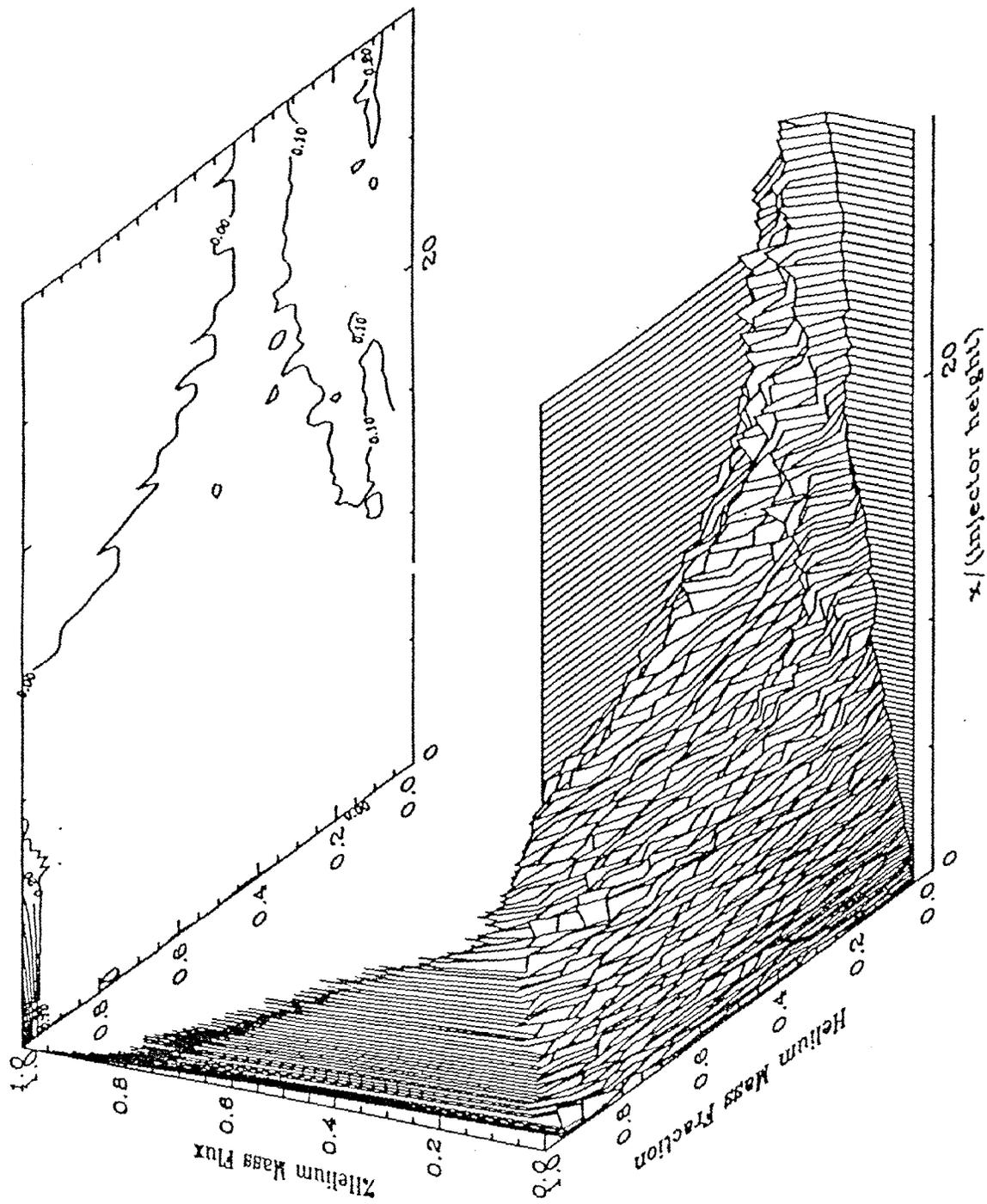


Fig. 9. Mixing Contours for the flow of Figure 8.