Density Evolution within a Shock Accelerated Gaseous Interface

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The evolution of density profiles within a shock accelerated gaseous interface was investigated via a three-directional laser absorption diagnostic technique for negative, close to zero, and positive initial density jump of the interface. Results show that the direction of the shock wave acceleration could have a non-negligible effect on the mixing process development. Furthermore, the turbulent diffusion within the induced mixing zone is clearly identified from the thickening of the density profiles with time. [S0031-9007(96)02048-0]

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The instability mechanism which appears at an interface between two fluids of different densities when normally accelerated by a shock wave can give rise to turbulence and mixing between the two fluids. Such instability, known as the Richtmyer-Meshkov instability [1–3], is of current interest because of its importance in technological applications such as the inertial confinement fusion capsules, as well as astrophysical phenomena such as the overturn of the outer portion of the massive star collapsed core [4].

The purpose of the present experimental investigation is to follow, in a shock tube environment, the partial density profile evolution of one of the two constituents of a gaseous mixing zone originated from the instability of the small random perturbations present at the interface, when a shock wave crosses through it. Three series of tests were undertaken, where the initial experimental configuration was such as, crossing the interface, the shock wave passed from one gas (CO_2), in which the initial pressure, temperature, and density as well as the shock wave Mach number were kept constant, into another gas, the density of which was successively increased from series one to series three (He, Ar, and Kr). This allows the study of the evolution of the density within the shock induced mixing zone when the shock wave passes from the heavy gas to the light one (CO_2/He corresponds to the slow/fast interface), from one gas to another of close density (CO_2/Ar), and from the light gas to the heavy one (the fast/slow interface corresponds to the CO_2/Kr case), successively. Many questions concerning the development and process of the mixing are of current interest, and we hope to answer some of them with the help of the present results obtained from a suitable three-directional laser absorption diagnostic technique [5–7] applied to the investigations.

The shock tube test section and the diagnostic setup are schematically shown in Fig. 1. Experiments were conducted in an 8 m total length double diaphragm shock tube. The test chamber was an 8.5 by 8.5 cm square cross section and its length varied from 80 to 115 cm. The movable end wall of the shock tube allowed us to select the location of the mixing zone and the reflected shock wave interaction. The initial interface between the test gases was materialized by a thin plastic membrane (1.5 μm thick) resting over a 5×5 square wire grid (diameter 0.2 mm and spacing 17 mm). This allowed a regular rupture of the membrane and delayed the consequent particles which often perturbed the absorption measurements. In view of the satisfaction of the first tested grid, no other type or dimensions were used. The test gases were CO_2 upstream (on the left side of the membrane) because of its infrared spectroscopic properties, and helium, argon, or krypton downstream (on the right side of the membrane), because they presented no infrared absorption in the domain of our experiments, prevented from the formation of bifurcated reflected shock wave, and permitted study of the three general cases of initial density jumps across the interface, i.e., negative for CO_2/He, close to zero for CO_2/Ar, and positive for CO_2/Kr, respectively. The initial pressure of the test gases on both sides of the membrane was about 1500 Pa. The incident shock wave Mach number in the CO_2 was about 3.1, which induced transmitted shock wave Mach numbers of about 2.2, 3.0, and 3.5 in the helium (10% polluted with an air partial pressure), argon, and krypton, respectively. The corresponding mixing zone velocities measured behind the transmitted shock wave were about 830, 640, and 530 m/s, respectively. After the reflected shock wave mixing zone deceleration they were about 280, 55, and 8 m/s, respectively.

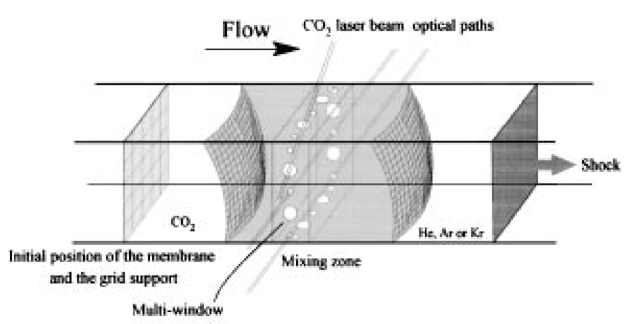

FIG. 1. Sketch of the three-directional laser absorption experimental setup through the shock tube cross section.

The multi-directional laser absorption principle of measurement was first theoretically introduced by Wang [5], and later experimentally undertaken and presented in the papers of Fortes *et al.* [6] (for the monodirectional case) and Houas *et al.* [7] (for the multidirectional setup). Details on very similar experimental conditions are given in the work of Jourdan *et al.* [8], in which it was shown that the mixing zone was strongly (or weakly) deformed by the wall boundary layer when it was turbulent (or laminar), and an optimal experimental Mach number, regarding both the flow parameters and the validity domain of the diagnostic method, was found to be close to 3. In the present work, focus is made on the investigation of the CO_2 partial density evolution in the direction of the shock wave acceleration.

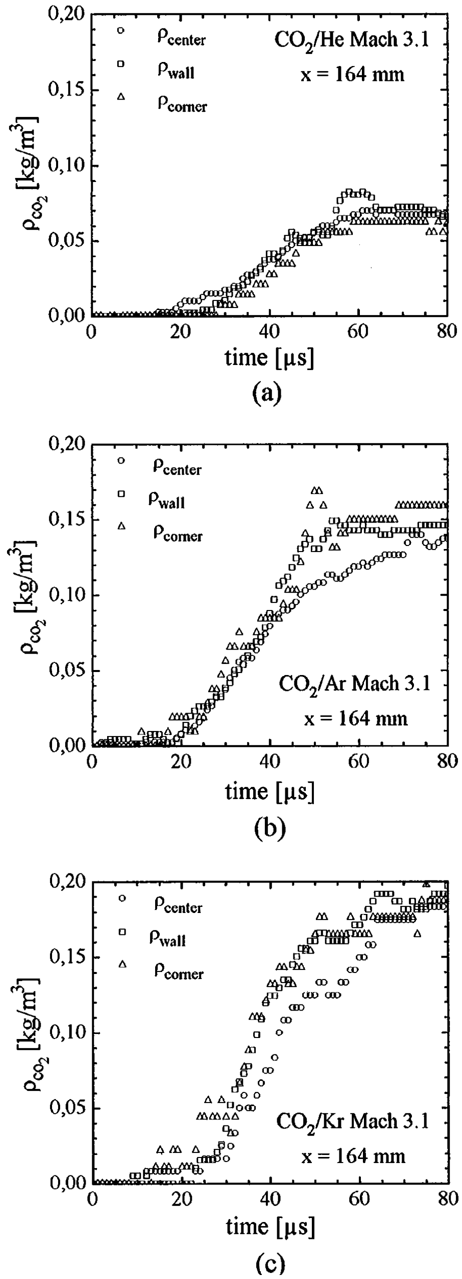

FIG. 2. Evolution of the partial CO_2 density versus the time within the (a) CO_2/He, (b) CO_2/Ar, and (c) CO_2/Kr mixing zones, respectively, in the center, near and parallel to the wall, and in a corner of the shock tube. The measurement location is $x = 164$ mm.

As has been demonstrated [6–9], the density profile within the mixing zone is directly obtained from both the deconvolution of the absorption signals and a suitable orderly data process. The diagnostic setup using a three-division laser probe allows a simultaneous comparison of the results found in the center, near and parallel to the wall, and in a corner of the shock tube.

We have plotted in Fig. 2 the evolution of the partial CO_2 density $\rho(\mathrm{kg/m^3})$ versus time (μs) within the (a) CO_2/He, (b) CO_2/Ar, and (c) CO_2/Kr mixing zones, respectively, for the first location of measurement ($x =$ 164 mm). The error bars were estimated to be less than 10%. The maximal value reached by CO_2 partial density behind the incident acceleration is in good agreement with the theoretical Rankine-Hugoniot calculations, which provide 0.065, 0.14, and 0.18 $\mathrm{kg/m^3}$ for CO_2/He, CO_2/Ar, and CO_2/Kr cases, respectively. Furthermore, the maxima are different in the corner, near the wall, and in the center of the shock tube. This indicates that the density is not constant along the shock tube cross section, probably due to the wall boundary layer perturbations, the effect of which is to deform the mixing zone [8]. At last, if the CO_2/He mixing zone presents three similar density progresses in the three characteristic regions, the differences between ρ_{center}, ρ_{wall}, and ρ_{corner} evolutions are more important for the CO_2/Kr case, which confirms the correlation between the mixing zone deformations and the development of a turbulent wall boundary layer [9]. However, in all cases the maxima margin remains less then 15%, which indicates that the disruptive effect of the boundary layer is influent but limited. Figure 3 presents the evolution of the normalized CO_2 partial density profile $\rho^*(L) = \rho(L)/\rho_{\max}$ within the mixing zone versus the thickness L (cm) for the three tested cases CO_2/He (a), CO_2/Ar (b), and CO_2/Kr (c), respectively. The experimental profiles have been centered at the geometrical center of the mixing and fitted by a law of the type

$$\rho(L,t) = \frac{\rho_{\max}}{2}\left[1 - \mathrm{erf}\left(-\frac{L}{2\sqrt{Dt}}\right)\right],$$

which is a solution of the diffusion equation [10], and where t and D (mentioned on each graphic) represent the time passage of the mixing zone at the abscissa of measurements and the fitting parameter, respectively. Note that D ($\mathrm{cm^2/s}$) has a dimension of a diffusion coefficient and can be compared with the mean diffusion coefficients (25 °C, 1 atm) between the CO_2 and He, Ar, or Kr: $D_{CO_2/He}^{25\,^\circ C\,1\,atm} = 125\ \mathrm{cm^2/s}$, $D_{CO_2/Ar}^{25\,^\circ C\,1\,atm} = 35\ \mathrm{cm^2/s}$, and $D_{CO_2/Kr}^{25\,^\circ C\,1\,atm} = 25\ \mathrm{cm^2/s}$. We think that this kind of representation helps for a discussion about the physical processes which bring to both the thickening and the

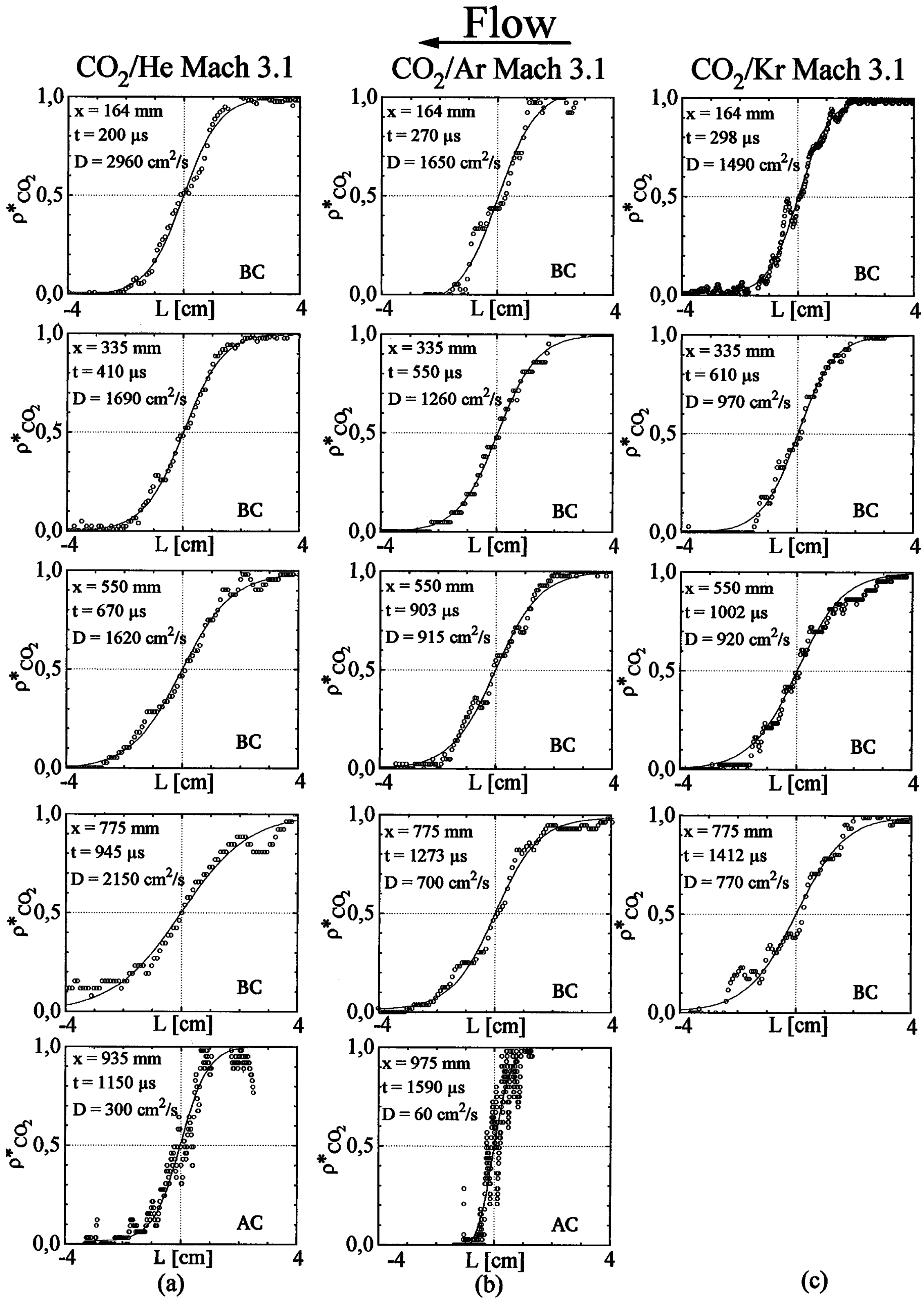

FIG. 3. Evolution of the normalized CO_2 partial density $\rho^*(L) = \rho(L)/\rho_{\max}$ within the mixing zone versus the thickness for the (a) CO_2/He, (b) CO_2/Ar, and (c) CO_2/Kr cases, before (BC) and after (AC) the compression by the reflected shock wave. x and t are the location and the time of the measurement, respectively, at $x = 0$ and $t = 0$ the shock wave is at the interface position.

symmetry (or not) of the mixing. The profiles obtained before and after the reflected shock compression of the mixing zone are noted BC and AC, respectively (no measurement of the compressed CO_2/Kr mixing zone was possible because of its total Taylorization). We observe that the smoothing curves issued from the solutions of the diffusion equation are a good fitting of the experimental results. On the other hand, the growth up of the turbulent diffusion between the two gases is clearly illustrated by the thickening of the density profile with time. But as time goes by the frontiers of the mixing are less and less definite, and the slope of the density profile near the monatomic gas (He, Ar, and Kr) grows up and remains similar near the CO_2. This shows that the mixing process, as complex it is, not symmetrical and could be dependent on the direction of the interface acceleration. After the compression of the mixing zone by the reflected shock wave (AC), a relative intensification of the density fluctuations is observed. However, in the CO_2/Ar mixing case these fluctuations could also be explained by the complex reflected shock-mixing zone interaction during which the interface is practically stopped (Taylorization). Moreover, the fact that the intensification develops more towards the CO_2 side is probably due to the turbulent boundary layer which grows in the CO_2 behind the transmitted shock wave. This problem points out the interest of the building of new shock tubes with a larger cross-sectional area [11].

The present investigation measurements have been obtained within the fully developed turbulent regime of the mixing. In fact, the first abscissa that we can probe (164 mm) corresponds to a time of about 200 to 300 μs following the respective tested mixings CO_2/He to CO_2/Kr, and at those moments the linear bubbles and spikes dominant regime is not present anymore. However, it is interesting to correlate our results with the work of Mikaelian [12], even if it has been done with the hypothesizes of both a linear mixing zone thickness and density law evolutions with time, Mikaelian showed that the turbulent kinetic energy generated after the shock wave passage through the interface is proportional to the square of the Atwood number (the Atwood number is defined as $A = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ where ρ is the respective density of the gas, CO_2, He, Ar or Kr, taken just after the shock wave passage from gas 1 to gas 2). In other words the efficiency of the mixing increases with A^2. If we compare the margin between the experimental points and the symmetrical fitted curves (here just considered as a good fitting function), we can see that the CO_2/He profiles are the closest, and the CO_2/Kr ones present the more numerous fluctuations even if they keep a good fitting on the whole. Could we conclude that the CO_2/He mixing is the most homogeneous and the CO_2/Kr the least? If we consider the small experimental volume of measurement (a cylinder of about 1.5 mm^3 volume and 28 mm long), this hypothesis is possible regarding the fact that $A^2_{CO_2/He} = 0.53$, $A^2_{CO_2/Ar} = 0.096$ and $A^2_{CO_2/Kr} = 0.0025$. Consequently, we find that the higher A^2 is, the higher turbulent kinetic energy generated after the shock wave passage through the interface is, and the more efficient the mixing is.

In summary, an experimental investigation of the evolution of the density profile within a shock accelerated gaseous interface has been undertaken for negative, close to zero, and positive initial density jumps at the interface, within the nonlinear regime. Results show that the mixing process does not develop symmetrically and the direction of the shock wave acceleration has probably a non-negligible influence on it. Furthermore, it has been shown that, for a given shock wave Mach number, the homogeneity of the mixing decreases with the density jump across the interface. Finally, the efficiency of the mixing as well as the turbulent diffusion seem to follow the square evolution of the Atwood number.

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