Originally published in *Proceedings of the Fifth International Workshop on Compressible Turbulent Mixing*, ed. R. Young, J. Glimm & B. Boston.
ISBN 9810229100, World Scientific (1996).

Visualization of Shocked Mixing Zones Using Differential Interferometry and X-Rays

I. Galametz, G. Delouis, M.-H. Thorembey,
C. Rayer, G. Rodriguez and J.-F. Haas

Commissariat à l'Energie
Atomique/Vaujours-Moronvilliers
B.P. 7, 77181 Courtry, France

Abstract. We compare the behavior of continuous and discontinuous heavy-light interfaces between two gases, sulphur hexafluoride (SF_6)-air or xenon (Xe)-air, subjected to the acceleration by an incident upward propagating shock wave (Mach 1.45 in SF_6 and 1.4 in Xe) and the deceleration by up to 3 weaker reflected shock waves in a vertical shock tube. Continuous interfaces, obtained after the retraction of a separating diaphragm, have a smooth density profile with an initial thickness of 2.4 and 2.6 cm for SF_6-air and Xe-air respectively. Discontinuous interfaces are initially created by a plastic membrane 0.5 μm thick torn by the passage of the incident shock wave. The images are obtained by differential interferometry and, in the Xe-air case, by X-rays. The visualization illustrates the different development of shock-induced mixing for the two types of interfaces, and different modes of reflected shock propagation in a polyatomic gas (SF_6) and monatomic gas (Xe). From the X-ray method, profiles of Xe partial density are obtained in the planar region of the mixing zones for the two types of interfaces at all times. In contrast, the differential interferometry provides partial density profiles for continuous interfaces only and as long as the turbulent scales on the walls do not perturb the signature from the flow in the center. The continuous interfaces do not thicken and never turbulize. The discontinuous interfaces lead to turbulent mixing zones which thicken between reflected shocks. The shapes of average partial density profiles are similar for the two types of interfaces, for the two gas pairs and, in the continuous case, for the two diagnostics.

1 Experimental set-up and diagnostics

The vertical shock tube has been designed for the measurement of the Richtmyer-Meshkov (RM) instability of continuous heavy-light and discontinuous gas interfaces

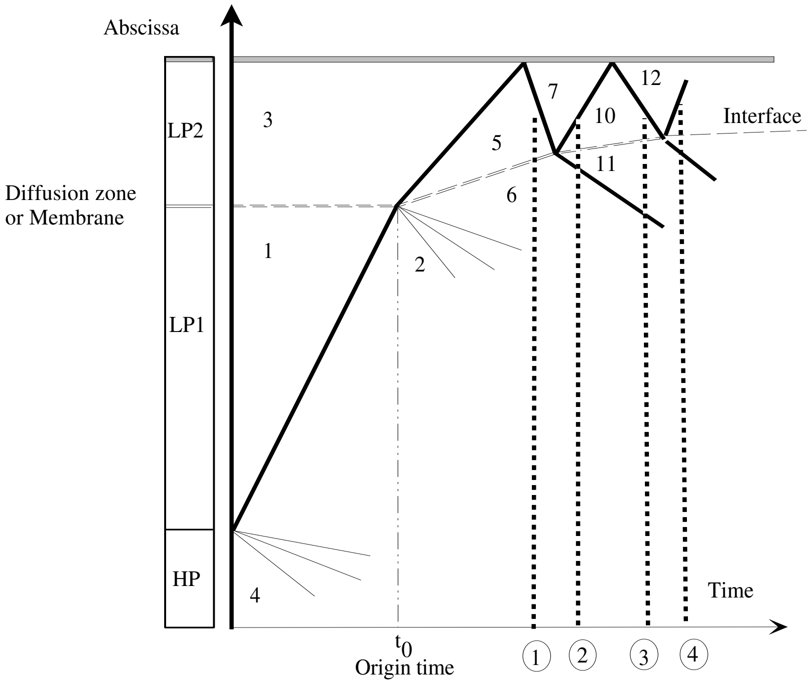


Figure 1: An x-t diagram of the experiment.

subjected to weak shock waves [1]. It has a square cross section (8 by 8 cm^2) and the distance between the initial interface position and the end plate has been set to 30 cm in the experiments described here. For the shadowgraph or schlieren visualization of the mixing zones arising from the RM instability we normally use a Cordin high-speed framing camera. Images are recorded at times ranging from 1.1 ms, shortly before the arrival of the first reflected shock waves to 2.7 ms, after passage of the third reflected shock (Figure 1). For higher quality visualization and measurement of the density averaged along the optical axis, we have adapted to the gas mixing problem (with strong density gradients) the differential interferometry method developed for compressible aerodynamics [2]. Figure 2 schematizes the optical set-up for the white-light differential interferometer. As it provides pictures in which the colors correspond to optical path differences proportional to the gradient of optical index, this set-up can be considered a quantitative schlieren system. As we are interested in mostly horizontal shock waves an mixing zones, the two Wollaston biprisms have the same angle of 1 or 0.5° and are rotated so that the vertical density gradient is measured. The single color image recorded per shot is digitalized using a triple CCD camera (for the colors

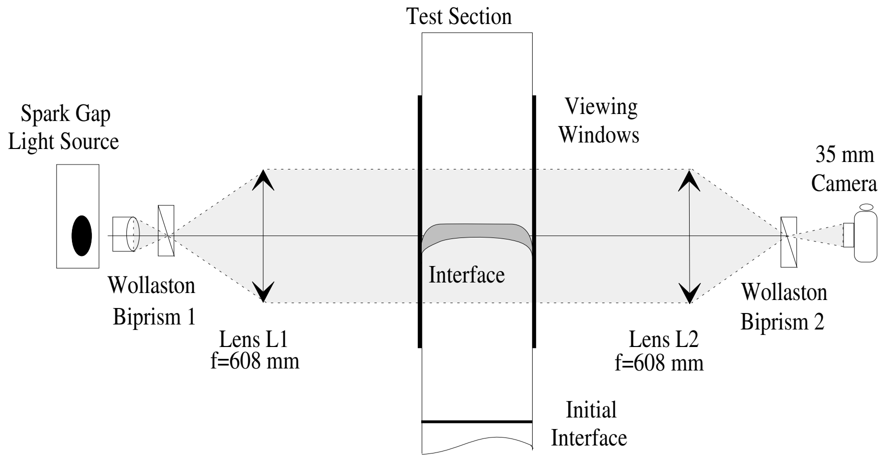


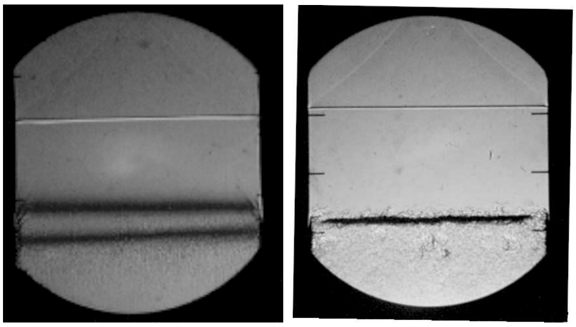
Figure 2: Optical set-up for the differential interferometer.

red, green, and blue). The colors are then automatically matched to the optical index and density gradient. By integration from a position of known density, we deduce the partial density and mass concentration in the mixture. The X-ray technique [3], for which only Xe significantly absorbs the low-energy (≤ 60 keV) X-ray photons, has been used previously to obtain the Xe partial density. As both techniques integrate the three-dimensional flow field on a two-dimensional image, wall effects are always present and perturb the density measurement at late times.

2 Visualization

The mixing zones arising from the shock interaction with discontinuous (using thin membranes) or continuous (diffusive zone) interfaces for the gas pairs (Xe-air or SF_6-air) have been visualized using the differential interferometer and the X-rays. As X-ray pictures were presented previously [4], we show only a few interferometric images for the case of SF_6-air. Unfortunately they appear here in black and white.

Figure 3a shows the SF_6-air continuous interface recorded at time denoted 1 in the x-t diagram (Fig. 1). The discontinuous interface at time 1 is shown on Fig. 3b. One sees from top to bottom the downward-propagating reflected shock wave in air and the upward-moving mixing zone with SF_6 on the bottom. The horizontal layers in Fig. 3a indicate that the diffusion zone is still laminar and the grainy pattern below it is the signature of fine-scale mixing in the boundary layer. The contact surface seen on Fig. 3b displays a dark line which is the signature of the ruptured membrane. The turbulent mixing seen a little above and much further below probably lies along the



(a) (b)

Figure 3: SF_6-air interface time 1: (a) continuous; (b) discontinuous.

walls because the membrane has ruptured there at shock passage. Far from the walls the membrane may be still intact and thus prevents gas mixing at this early stage. Figures 4a and 4b recorded at time 2 show the bifurcation of the reflected shock as it refracts into the multiatomic SF_6. A *bubble* can be seen on the walls between the shock and mixing zone which is locally deformed by the interaction. The diffusion zone has been compressed by the reflected shock and the discontinuous interface has been turbulized. Later, the wall bubble seems to become turbulent even in the case of the continuous interface. The interferometer photo shown on Figure 4c was recorded after passage of the second reflected shock on the continuous interface (time 4). The shock appears locally deformed by the wall structures of the mixing zone. It is in fact more disturbed in the discontinuous case (not shown) because the mixing zone is turbulent. Below this second reflected shock, the turbulent wall layer due to the first reflected shock can be seen. The continuous mixing zone is still laminar but the colored layers tend to be erased by the signature of the small scales on the wall. The measurement of the density profile becomes difficult at this stage.

3 Density profiles

Because the random optical signature of the small scales of turbulent mixing on the walls complicates the data-reduction process, the differential-interferometry method can be used only to obtain concentration and partial density profiles for the continuous mixing zone until time 3 (just before the interaction with the second reflected shock). An additional difficulty in the case of discontinuous interfaces is the perturbing signature of the membrane at early time or its fragments at late time.

Figure 5 shows the partial density profiles of SF_6 in the SF_6-air mixing zone at times 1, 2, and 3. The profiles are typical of the molecular diffusion process for which

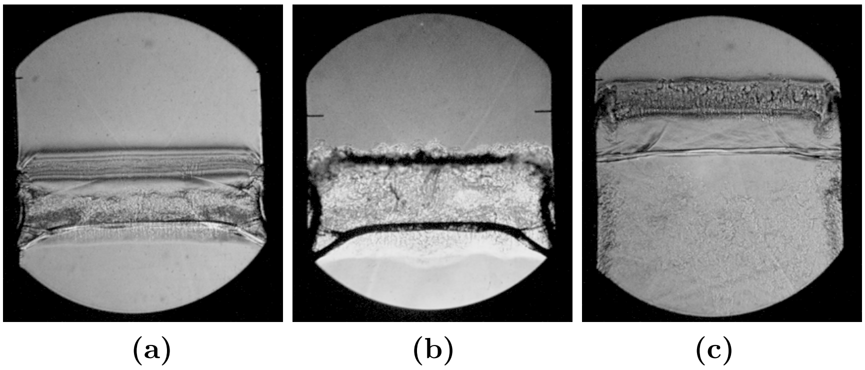


Figure 4: SF_6-air interface: (a) continuous time 2; (b) discontinuous time 2; (c) continuous time 4.

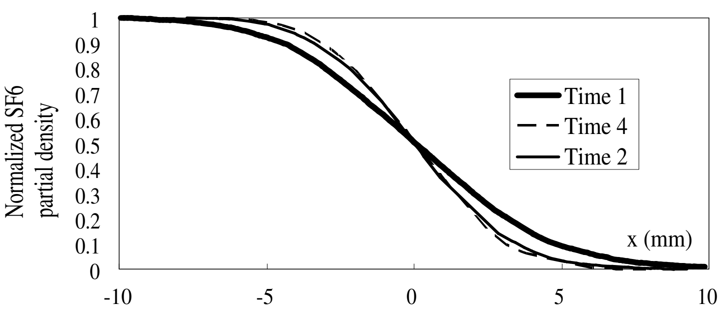


Figure 5: Density profiles for SF_6-air continuous interface.

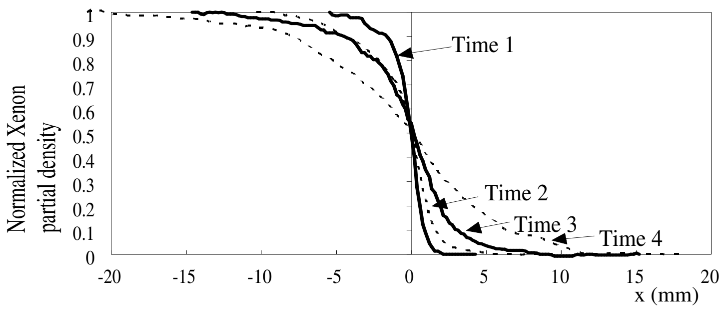


Figure 6: Density profiles for Xe-air discontinuous interface.

the concentrations follow the error function law. Between times 1 and 2, the profiles are steepened due to the hydrodynamic compression by the first reflected shock. There is no widening, however, between times 2 and 3 indicating that no rapid diffusion has happened in this time interval. This is consistent with the absence of turbulent scales in the core of the mixing zone. A comparison of the two diagnostics is possible for the continuous Xe-air mixing zone. The partial densities of Xe (not shown) at times 2 and 3 (between the passage of the first and second reflected shock wave) are similar for the two methods. The X-ray method could be used for the discontinuous Xe-air interfaces, because the membrane (made of low atomic-number elements) is transparent to the X-ray photons and because the absorption process integrates the random scales along the optical axis to yield an optical density on the radiographic film. Figure 6 shows the partial Xe density profiles at times 1, 2, 3, and 4. The profiles widen between times 2 and 3, in accordance with a process of turbulent diffusion.

4 Conclusions

With differential interferometry, high-quality visualization of the mixing zones subjected to shock interaction can be obtained, as with conventional schlieren techniques. Our method has provided density measurements for mixing zones which remain essentially controlled by molecular diffusion and as long as turbulent scales on the walls do not perturb the optical signature, i.e. for continuous interfaces until the arrival of the second reflected shock. The results are similar to the radiography and applicable to any gas pairs. The partial density profiles can be used to determine a mixing-zone thickness based on quantitative criteria. In the present experimental conditions with a slow blade retraction for the continuous interface, the mixing zone never becomes turbulent and its thickness does not increase. The mixing zones created by the shock interaction with a discontinuous interface thicken due to turbulent diffusion and become wider than the continuous interface after the second reshock. There is no significant shape difference between the twice-averaged density profiles of planar diffusive or turbulent mixing zones.

References

[1] Cavailler C, Croso H, Haas JF, Rodriguez G (1992): A new vertical shock tube for Rayleigh-Taylor instability studies. In: Proceedings of the 3rd International Workshop on the Physics of Compressible Turbulent Mixing, Royaumont, Wilke editor, CEA/DAM, p 27.

[2] Desse JM, Pegneaux JC (1993): Direct measurement of the density field using high speed differential interferometry. Exp. in Fluids, 15: 452.

[3] Rodriguez G, Galametz I, Croso H, Haas JF (1994): Richtmyer-Meshkov instability in a vertical shock tube. In: Proceedings of the 4th International Workshop on the Physics of Compressible Turbulent Mixing, Edited by Linden PF, Youngs DL & Dalziel SB, Cambridge University Press, Cambridge, England, p 260.

[4] Rodriguez G, Galametz I, Croso H, Haas JF (1995): Richtmyer-Meshkov instability in a vertical shock tube. In: Shock Waves @ Marseille IV, Brun R and Dumitrescu L eds., Proceedings of the 19th International Symposium on Shock Waves, Springer Verlag, Heidelberg, p 275.