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Experimental and Numerical Investigation of the Growth of an Air/SF₆ Turbulent Mixing Zone in a Shock Tube

Shock-induced mixing experiments have been conducted in a vertical shock tube of 130 mm square cross section located at ISAE. A shock wave traveling at Mach 1.2 in air hits a geometrically disturbed interface separating air and SF₆, a gas five times heavier than air, filling a chamber of length L up to the end of the shock tube. Both gases are initially separated by a 0.5 µm thick nitrocellulose membrane maintained parallel to the shock front by two wire grids: an upper one with mesh spacing equal to either \( m_l = 1.8 \text{ mm} \) or \( 12.1 \text{ mm} \), and a lower one with a mesh spacing equal to \( m_l = 1 \text{ mm} \). Weak dependence of the mixing zone growth after reshock (interaction of the mixing zone with the shock wave reflected from the top end of the test chamber) with respect to L and \( m_l \) is observed despite a clear imprint of the mesh spacing \( m_l \) in the schlieren images. Numerical simulations representative of these configurations are conducted: the simulations successfully replicate the experimentally observed weak dependence on L, but are unable to show the experimentally observed independence with respect to \( m_l \) while matching the morphological features of the schlieren pictures. [DOI: 10.1115/1.4036369]

1 Introduction

Turbulent mixing zones (TMZ) may appear at interfaces between different materials when the latter are subject to interfacial instabilities strong enough to trigger the transition to turbulence. For instance, the Richtmyer–Meshkov instability (RMI), occurring when a shock wave hits an interface, may induce the appearance of a TMZ as in the present work. The baroclinic vorticity deposit at the interface is the main driver of the RMI. The baroclinic production is due to the misalignment between the pressure gradient, carried by the shock front, and the density gradient, carried by the interface. As a result, initially small corrugations grow in a laminar manner at early time forming ordered structures. If enough kinetic energy [1] has been injected by the RMI or another interfacial instability, the latter structures become turbulent at late times, thus greatly enhancing the mixing between the two fluids. We refer to the mixture region between the pure materials as the TMZ; its extent in the direction normal to the initial mean interface is the TMZ width and the time derivative of the TMZ width (generally positive due to turbulent diffusion) is the TMZ growth.

Once the TMZ is formed, it can undergo all kinds of events that can strongly modify its behavior. Shock crossing for instance is a powerful mechanism of mixing enhancement in TMZ. Such events occur in a variety of configurations ranging from astrophysics and inertial confinement fusion to scramjet engines and have a strong impact on subsequent chemical or nuclear reactions. These fields involve complex multiphysical processes making direct numerical simulations (DNSs) unaffordable and therefore requiring cheaper models for the treatment of the turbulent mixing, such as specifically adapted Reynolds-averaged Navier–Stokes (RANS) models [2,3].

The present experiments are conducted in a shock tube that allows to study the interaction of shock waves with turbulent mixing zones and, thereby, to characterize the influence of the interaction on the subsequent TMZ evolution.

Though much work has been done concerning this subject, the problem remains challenging. Even with simple nonreactive gases, as in the shock tube used here, the application of DNS is limited to low Reynolds numbers and large eddy simulation (LES) may be questionable. Furthermore, appropriate initial conditions may be difficult to define and simulate. Ideally, the experimental conditions should ensure the shock wave/TMZ interaction

1. to be a statistically one-dimensional problem
2. to involve a fully turbulent mixing zone
3. to involve a TMZ that, prior to the shock
   — is evolving in a self-similar state (free of transient effects),
   — is free of confinement effect (due to the finite size of the shock tube section).

In this work, the TMZ is created by the RMI subsequent to the interaction of the main shock wave with an interface between gases initially at rest. In order to minimize confinement effects, we will focus on the next interaction with the shock wave reflected from the top end (first reshock) only. Since we want to study the effect of a shock wave on a turbulent mixing zone (and not a strongly deformed interface), the gas separation is chosen to promote rapid transition to turbulence of the mixing layer thanks to the RMI [4]. Rapid transition is also necessary to get a self-similarly evolving TMZ prior to reshock. These considerations lead to the use of a membrane (that produces a sharp interface) between grids imposing small-scale perturbations (that evolve rapidly). Such configurations with a grid and a membrane...
separation have previously been used in many studies, e.g., see Refs. [5] and [6].

The outline of this paper is as follows: In Sec. 2, we recall the shock tube setup and summarize the main experimental results [7,8], especially with respect to the influence of the mesh grid size \( m_l \), that we would like to interpret thanks to numerical simulation. In Sec. 3, we present our numerical methodology for pure fluid simulation of the experimental shots. We define two families of initial conditions intended to model the effect of each wire grid. The first one is a classical “egg-box” initialization while the newly proposed second one is referred to as the “wire-wake” initialization. In Sec. 4, we compare the simulation results to the experimental data and conclude that even if the wire-wake initialization is closer to experimental trends, neither of the two initializations is able to match all of them. Finally, Sec. 5 concludes by summarizing why the experimental results are still partially unexplained.

2 Summary of Experimental Results

2.1 Experimental Setup. The T130 shock tube located at ISAE is a vertical shock tube with a square cross section of size \( l_T \times l_T = 130 \times 130 \text{ mm}^2 \) [8,9]. In the present study, a shock wave traveling at a Mach number of 1.2 in air hits (from below) a periodically disturbed interface separating air and sulfur hexafluoride \( \text{SF}_6 \) (a gas five times heavier than air) filling a chamber of length \( L \) up to the top end of the shock tube. The shock wave is generated by impacting a mylar diaphragm, initially separating the driver and the driven sections of the shock tube, using a blade cutting device. The end wall is adjustable allowing to vary the test section length \( L \) over a large range, thereby modifying the time of arrival of the first reflected shock, hereafter referred to as “reshock,” on the RMI-induced TMZ. Five values of \( L \) are used in this work: \( L = 100, 150, 200, 250, \) and 300 mm. A schematic of the experimental setup and a \((X–t)\) diagram of the flow are given in Fig. 1.

Both gases are initially separated by a 0.5 \( \mu \text{m} \) thick nitrocellulose membrane. The membrane is maintained parallel to the shock front by two wire grids (see Fig. 2):

1. The lower grid with square mesh spacing \( m_l = 1 \text{ mm (ø70 \( \mu \text{m)}}\) prevents the membrane from bulging due to the weight of \( \text{SF}_6 \);
2. the upper grid with square mesh spacing \( m_s \) causes fragmentation of the membrane. Two upper (or fragmentation)

grid mesh spacings \( m_s \) have been tested in the present study: \( m_s = 1.8 \text{ mm and } m_s = 12.1 \text{ mm (ø230 \( \mu \text{m and } 610 \mu \text{m, respectively).}\)

Both grids are expected to seed small-scale initial perturbations on the gas interface for the RMI with a characteristic length given by the mesh grid sizes \( m_s \) and \( m_l \).

2.2 Mixing Zone Width From Schlieren Image Processing. During the experiments, pressure histories of the flow in the shock tube are obtained using five piezoelectric pressure transducers (PPT) and time-resolved schlieren visualizations are recorded thanks to a high-speed Phantom V12 camera. The data rate of the image recording is fixed to 27,000 images per second with a spatial resolution equal to 512 \(*\) 384 pixels\(^2\). The camera is fixed in the laboratory frame and two positions are sufficient to visualize both pre- and postreshock TMZ evolution.

The schlieren images are postprocessed in order to detect the boundaries of the mixing region between the two fluids and calculate the TMZ width. This detection is based on a frequency filtering technique that consists in first applying a two-dimensional (2D) fast Fourier transform (FFT) on the images, second high-pass filtering the previously transformed images in order to...
elaborated models [11]. The prefactor $c = 0.4$ comes from a fit obtained by Leinov et al. [12] in a series of reshock experiments. In the present experiment, values for $c$ ranging from 0.38 to 0.43 are estimated by Bouzgarrou [8] for the different chamber lengths with $m_s = 1.8$ mm. One should mention that Jacobs et al. [13] obtain a quite lower value around 0.26 for the prefactor with a completely different membraneless setup.

Figure 4 collects results obtained for $L = 250$ mm when changing the position of the adjustable end wall. Letting $L$ vary from 100 to 300 mm changes the arrival time of the reshock from 0.9 ms to 2.7 ms and therefore the age of the TMZ from its transition to turbulence. As expected, all TMZ evolutions are the same before reshock in their common time range. After reshock, the TMZ growth appears independent of $L$ except for the shortest chamber that leads to a reduced growth. This behavior is most probably explained by the fact that the TMZ has not enough time to reach a self-similar evolution before reshock arrival when the chamber length $L$ is only 100 mm.

Figure 5 collects results obtained when changing the (upper) fragmentation grid: the fine one has a mesh spacing equal to $m_s = 1.8$ mm, whereas the coarse one has a mesh spacing $m_s = 12.1$ mm. Surprisingly, the TMZ width remains almost unchanged before reshock and completely unchanged after the reshock.

Just looking at the width history, one could think that the fragmentation grid has no effect on the flow. But this would not be true. Indeed, the previous results must be complemented with the visual comparison of Fig. 6. This figure compares two schlieren pictures taken just before reshock with $m_s = 1.8$ mm on the left (Fig. 6(a)) and $m_s = 12.1$ mm on the right (Fig. 6(b)). The imprint of the 12.1 mm fragmentation grid is clearly seen in Fig. 6(b) in the form of vertical white lines dividing the TMZ in cells of 12.1 mm width. Nothing comparable is seen in Fig. 6(a) with the fine grid $m_s = 1.8$ mm.

We can summarize as follows the experimental trends that we would like to understand or match with numerical simulations.

1. Provided that the TMZ is old enough, the postreshock TMZ growth is only weakly dependent on the age of the TMZ at the time of reshock.
2. The TMZ width evolution is independent of the fragmentation grid spacing, $m_s = 1.8$ mm or $m_s = 12.1$ mm, although the imprint of that grid is clearly visible in the schlieren pictures.

The main new aspect of the present article comes from the latter point. Weak dependence of the postreshock growth on the

![Fig. 3 Schlieren pictures of a shot with the fine upper grid ($m_s = 1.8$ mm). The full 130 mm cross section of the T130 shock tube is visible. (a) Before reshock: the TMZ is seen in the lower part of the figure, traveling to the top, whereas the (horizontal) shock front coming from above is just appearing in the top of the picture. (b) and (c) After reshock: the TMZ is seen in the middle part of figure, traveling to the bottom, whereas the reflected rarefaction going upward is escaping the frame on the top. The same picture is used to show the edges of the TMZ as detected by the two filters.](image)
prereshock TMZ state is widely assumed and summarized in the growth speed estimate $c A U$ where only the value of the prefactor $c$ is debated [10,12,13]. But it is the first time, to the authors’ knowledge, that such a morphological difference is experimentally observed before and after reshock, see Fig. 6, with a known origin in the initial configuration. These observations put new constraints on the numerical simulations which not only have to match the TMZ width evolution [14,15] but also have to match the TMZ morphology when starting with the relevant initial state.

3 Numerical Simulations

3.1 Numerical Methodology. We report in this section the attempts that have been performed in order to simulate the previous series of experiments with pure gas dynamics computations.
means that neither the nitrocellulosic membrane nor the wire grids are included and that only air (below the interface) and SF₆ (above the interface), treated as perfect gases with adiabatic exponents \( \gamma_{\text{air}} = 1.4 \) and \( \gamma_{\text{SF}_6} = 1.09 \), occupy the computational domain. Therefore, the real initial configuration has to be modeled in the initial condition imparted to both gases.

It is expected that the grids are the source of the dominant length scales leading to the appearance of the TMZ. As we want to simulate fine and coarse fragmentation grid experiments with the same computational domain and sufficient resolution, the size of the domain should be only a fraction \((l_0/l_T)^2\) of the real cross section of the shock tube. We choose a \( l_0 \times l_0 = 36 \times 36 \text{ mm}^2 \) numerical cross section covering \(20 \times 20\) cells of the fine upper grid \((m_l = 1.8 \text{ mm})\) or \(3 \times 3\) cells of the coarse upper grid \((m_l = 12.1 \text{ mm})\) and \(36 \times 36\) cells of the lower grid in each direction.

The three-dimensional computational grid has a 100 \( \mu \text{m} \) mesh size, corresponding to a resolution of 360 \( \times \) 360 cells for each of the 1000 cross sections of the computational domain, and a total of 130 \( \times \) 10⁶ cells. Simulations are performed with the in-house high-order code Triclade devoted to that kind of shock tube applications [16]. Here, among the different schemes of Triclade, we use the one referred to as WP5 in Ref. [16]. It is of conservative finite difference type, based on the wave propagation algorithm of Leveque [17], with high accuracy provided by the Cauchy–Kovalevsky procedure due to Daru and Tenaud [18]. Directional splitting is used and fifth order uniform time–space accuracy is reached for smooth one-dimensional problems. Euler equations are solved since physical viscosity and diffusion only become dominant at better resolutions. Indeed, an effective numerical viscosity can be estimated \textit{a posteriori} in the present simulations (from the kinetic energy budget) and its value is around twice as large as the physical one just before reshock but becomes 20 times larger than the latter after reshock. Reynolds numbers can also be evaluated using the fact that the integral scale is around one third of the TMZ width in RMI-induced mixing zones [19]. The turbulent Reynolds number based on Taylor microscale decreases to 50 before reshock but jumps to 10⁵ after reshock, whereas the turbulent Reynolds based on the integral scale jumps from 200 to 10⁶ due to baroclinic production during the interaction of the reshock with the TMZ. After reshock, the Kolmogorov scale is of the order of 10 \( \mu \text{m} \), i.e., ten times smaller than the cell size.

### 3.2 Egg-Box Versus Wire-Wake Initialization

Two kinds of initializations are described below in terms of “initial interface.” More precisely we choose a “virtual initial interface” in the following sense. Computations are performed in two steps. The first step does not involve any shock wave but is initialized with the fluctuating field resulting from the incident shock crossing, thanks to linear theories of the Richtmyer–Meshkov instability [20]. In the second step, the reflected shock wave is introduced at the time and location inferred from the 0D (unperturbed) space–time diagram of the shock tube and interacts with the TMZ obtained from the first step. The chosen initial interface is virtual in the sense that it is only used to compute the equivalent (post-shock) initial velocity field but does not directly appear in the computational domain. A similar procedure is detailed in Appendix B of Ref. [4].

The two kinds of initial perturbations used here to model both lower and upper grids are the following:

1. **Egg-box initialization**: each grid of mesh spacing \( m_l \) is accounted for by an initial deformation with the shape of an egg-box made of “sine” functions with wavelength \( \lambda \) and amplitude \( a_0 \). The egg-box initialization based on an approximation of the interface between wire grids with sine functions, Fig. 7, is the most classical one, see, e.g., Refs. [14,15], and [21]. More precisely, the building blocks of the egg-box initialization contain two sine functions in each direction \( a_0 (\cos (2\pi x/m_l) - (1/5) \cos (2\pi y/m_l) + a_0 (\cos (2\pi x/m_l) - (1/5) \cos (2\pi y/m_l) \text{ corresponding to the first harmonics of } |\cos (\pi x/m_l)| \text{ or } |\cos (\pi y/m_l)| \text{. However, such a representation may not be the most realistic } [22]. Furthermore, schlieren pictures (Fig. 6) reveal structures looking like wakes arising from the array of wires. This suggests taking each wire into account by imposing that the fluid remains roughly stationary after reshock at the wire location. We choose to deform the virtual interface as a triangular spike centered at the wire location, see Fig. 7, with a width of 400 \( \mu \text{m} \) and a height given by the previous velocity condition. In any case, the virtual initial deformation is obtained by superposition of three components: the upper grid model \((m_l = 1.8 \text{ or } 12 \text{ mm})\), the lower grid model \((m_l = 1 \text{ mm})\), and the isotropic noise. Each grid model is itself the overlap of two 2D corrugations rotated by a 90 deg angle around the shock tube axis to form a square array of the wires. The same initialization methodology is applied to both the upper and the lower grids.

2. **Wire-wake initialization**: each grid of mesh spacing \( m_l \) is accounted for by an initial deformation with the shape of a square array of wire-wakes with spacing \( m_l \).

In both cases, a small amount of (gaussian) random noise is added to break periodicity. The noise has a spectrum \((k/k_p)^4 e^{-2(k/k_p)^2}\) with \( k_p = 2\pi/2 \text{ mm}^{-1} \) and an rms value of 0.04 mm.

The egg-box initialization is a two-dimensional representation of the TMZ. After reshock, the Kolmogorov scale is of the order of 10 \( \mu \text{m} \), i.e., ten times smaller than the cell size.

**Fig. 6** Schlieren pictures taken just before reshock with the two fragmentation grids: (a) fine upper grid and (b) coarse upper grid

**Fig. 7** Two-dimensional schemes of the perturbation building blocks for two interwire cells: bottom—egg-box and top—wire-wake
parameters and hope to get a correct agreement anew. However, with the egg-box initialization, a question arises about how to change \( a_0 \) when \( m_s \) goes from 1.8 mm to 12 mm. Two “natural” possibilities come to mind. Either we keep the perturbation aspect ratio \( a_0/m_s \) constant, or we keep the perturbation size \( a_0 \) constant. Keeping the same aspect ratio immediately leads to a much too large TMZ, whereas keeping the same amplitude (like here) maintains reasonable TMZ width before reshock but leads to a too large growth after reshock.

On the other side, an advantage of the wire-wake initialization is that no additional arbitrary choice is needed to switch from the grid with \( m_s = 1.8 \text{ mm} \) to the grid with \( m_s = 12 \text{ mm} \).

The initial choices retained for comparisons with experiments are made visible in Figs. 8 and 9. These figures show the initial virtual interface and the interface 0.05 ms after initialization with egg-box and wire-wake, respectively for fine and coarse fragmentation grids. In contrast with the egg-box initialization, small parcels of fluid corresponding to the location of the wires can be seen, in the lower part of Fig. 9, detaching under the mean interface (as in experiment) when wire-wake initialization is used.

In order to make the initial condition clearer, Fig. 10 shows the longitudinal velocity spectrum in the plane of the interface around the initial time for the configuration with \( m_s = 12 \text{ mm} \) and \( m_s = 1 \text{ mm} \). The horizontal wavenumber \( k = \sqrt{k_x^2 + k_z^2} \) is made dimensionless by using the transverse size of the computational domain \( L_p \). It means that the spectrum is plotted with respect to \( k/k_0 \) where \( k_0 = 2\pi/L_p = 2\pi/36 \text{ mm}^{-1} \).  Wavelengths of 12 mm (corresponding to the spacing of the upper grid) are therefore located at \( k/k_0 = 3 \), whereas wavelengths of 1 mm (corresponding to the spacing of the lower grid) are located at \( k/k_0 = 36 \). The two kinds of initialization are compared in Fig. 10. Due to the periodicity, the wire-wake interface sketched in Fig. 7 is a kind a Dirac comb. Its Fourier transform is also a Dirac comb, thus explaining the presence of harmonics having a large initial value. The symmetry breaking gaussian noise is the same in the two initializations.

### 4 Comparison Between Simulations and Experiments

Figure 11 compares the TMZ width obtained by simulations and experiments for \( m_s = 1.8 \text{ mm} \) and two chamber lengths \( L = 150 \text{ mm} \) and 250 mm. As explained earlier, both kinds of initialization are chosen to roughly fit the measured TMZ before reshock. In the simulations, the TMZ thickness is obtained from an integral mixing width \( W = 6 \int_0^\infty \bar{Y}_w(z) \bar{Y}_{SF6}(z) \, dz \) (where \( \bar{Y}(z) \) is the Favre spanwise planar averaged mass fraction at altitude \( z \)). This numerical TMZ width is compared to the one given by filter 1 in the experiments as it provides better agreement than the one computed with filter 2.

After reshock, the agreement remains satisfactory for both test section lengths and for both initializations. Note that for the shortest chamber (150 mm), a reflected rarefaction reaches the TMZ before 2 ms. That event is not computed so that the later points should not be included in the comparison. Although the numerical simulations seem to predict a slight increase of the postreshock growth when the chamber length is varied from \( L = 150 \text{ mm} \) to \( L = 250 \text{ mm} \), the first experimental trend indicating weak dependence with respect to \( L \) is roughly met by the simulations. The latter statement can be quantified by looking at the relative difference between the slopes after reshock in Fig. 11. We measure the slopes for the three couples of experimental and numerical TMZ width by fitting a linear function in the time ranges 1.5–1.8 ms and 2.5–2.8 ms for the \( L = 150 \text{ mm} \) and \( L = 250 \text{ mm} \), respectively. The slopes are denoted \( (\bar{W}/L)_L \) since they are the temporal mean, over the given time range, of the TMZ growth

![Fig. 8 “Egg-box” initialization with (left) fine \( m_s = 1.8 \text{ mm} \) and (right) coarse \( m_s = 12 \text{ mm} \) fragmentation grid: (top) pseudo-color of the virtual interface deformation used for initialization, (bottom) interface at 0.05 ms after initialization](image-url)
velocity \( \dot{W} \). For each couple, we then compute the relative difference
\[
2 \left( \frac{\langle \dot{W} \rangle_L \middle|_{L=250} - \langle \dot{W} \rangle_L \middle|_{L=150}}{\langle \dot{W} \rangle_L \middle|_{L=250} + \langle \dot{W} \rangle_L \middle|_{L=150}} \right)
\]
between the TMZ post-reshock growth velocity for the two chamber length. An increase of 34% is obtained for the experiment, 2% for the simulation with wire-wake initialization and 5% for the simulation with egg-box initialization. Notice that the scaling \( \langle \dot{W} \rangle_{\text{reshock}} \propto \Delta \dot{U} \) proposed by Mikaelian [10] predicts a complete independence of \( \langle \dot{W} \rangle_{\text{reshock}} \) with respect to \( L \).

In contrast, the simulations fail to match the second trend showing an independence of the post-reshock growth rate with respect to the grid mesh spacing \( m_s \). Figure 12 compares the TMZ width obtained by simulations and experiments for \( L = 250 \text{ mm} \) and two fragmentation grids \( m_s = 1.8 \text{ mm} \) and \( m_s = 12.1 \text{ mm} \). For both initializations, the simulations predict an increase in post-reshock growth when \( m_s \) goes from 1.8 mm to 12.1 mm. The wire-wake initialization appears to be more coherent with experiment than the egg-box one in the sense that the difference between \( m_s = 1.8 \text{ mm} \) and \( m_s = 12.1 \text{ mm} \) is slightly reduced. As previously, we can quantify the latter statement by looking at the relative difference between the slopes after reshock in Fig. 12. The time range 2.5–2.8 ms is chosen for fitting and the relative difference between \( m_s = 1.8 \text{ mm} \) and \( m_s = 12.1 \text{ mm} \) is computed as
\[
2 \left( \frac{\langle \dot{W} \rangle_L \middle|_{L=250} - \langle \dot{W} \rangle_L \middle|_{L=150}}{\langle \dot{W} \rangle_L \middle|_{L=250} + \langle \dot{W} \rangle_L \middle|_{L=150}} \right).
\]
Experimental slopes differ by around 8%, whereas the numerical slope increase is larger: 50% for the wire-wake initialization and 96% for the egg-box one.

The width history is, however, not sufficient to draw any conclusions on the relevance of the simulations as we have seen that schlieren images reveal a clear imprint of the mesh spacing without any effect on the estimated width. That is why we show in Figs. 13–16 simulated schlieren images [23] obtained in the computations for both grids just before reshock (Figs. 13 and 14) and after reshock (Figs. 15 and 16).

Numerical and experimental schlieren images are shown here with the same scale. The full experimental cross section is visible. Numerical pictures are doubled, thanks to spanwise periodicity to
present a 72 mm width field. Just before reshock, two numerical spurious lines appear due to the “start-up error” [17] coming from the shock insertion at the beginning of the second step of the computation. They have negligible amplitude even if the sensitive schlieren diagnostic makes them visible. The spurious entropy wave remains discernible even after reshock. The wave denoted “RTRSW” comes from the partial reflection on the grids of the transmitted reshock in air. The arrows indicate directions of propagation in the laboratory frame. In postreshock Figs. 15 and 16, the dark region in the upper part of the SF6 is the rarefaction wave reflected by the interaction of the reshock with the TMZ. Note that the acoustic waves radiated in the (more compressible) SF6 by the bubble development can be seen above the TMZ in Fig. 16.

Before reshock, the TMZ with \( m_s = 1.8 \) mm, Fig. 13, does neither show any peculiar structure, nor do the numerical schlieren. On the opposite, with \( m_s = 12.1 \) mm, Fig. 14, the experimental TMZ is clearly divided into 12.1 mm wide cells. A similar morphology is obtained with the wire-wake initialization though less sharply divided. The egg-box initialization retains the sine structure and looks more like an undulation with more pronounced bubbles on the top front. The constraint of making the \( m_s = 12.1 \) mm grid imprint visible before reshock imposes, in the

![Fig. 11 TMZ width with respect to time for the fragmentation grid \( m_s = 1.8 \) mm for two chamber lengths \( L = 150 \) mm and \( L = 250 \) mm. Experiments: symbols, simulations: lines.](image1)

![Fig. 12 TMZ width with respect to time for the chamber length \( L = 250 \) mm and for the two fragmentation grids \( m_s = 1.8 \) mm and \( m_s = 12.1 \) mm. Experiments: filled symbols, simulations \( m_s = 1.8 \) mm: lines, simulations \( m_s = 12 \) mm: open symbols.](image2)
egg-box initialization process, the choice of a large enough amplitude for the corresponding modes (i.e., the modes with 12.1 mm wavelength), which in turn leads to over-estimated postreshock growth.

After reshock, with $m_s = 1.8\,\text{mm}$, Fig. 15, both initializations show a similar morphology with a top front looking more finely structured than the experimental front showing larger bubbles. Also, with $m_s = 12.1\,\text{mm}$, Fig. 16, both initializations appear to be similar (with the egg-box growing quicker than the wire-wake). They show a morphology dominated by the imprint of the fragmentation grid and close to the experimental one.

5 Paradoxical Results

Our pure fluid simulations of the complex experimental setup with grids and membrane are so far unsuccessful in matching all measured trends even with our improved wire-wake initialization.
pictures, Fig. 6. The TMZ width being of the order of 10 mm at a given length scale especially as its imprint is obvious in schlieren images. It is unchanged when the chamber length L varies from 150 to 300 mm, the TMZ is expected to evolve under self-similar conditions at the time of reshock. Then, all length scales should be related to the TMZ width, and prior to that time, to the relevant length scales in the initial conditions. The upper fragmentation grid mesh spacing m_s seems the best candidate to provide a relevant length scale especially as its imprint is obvious in schlieren pictures, Fig. 6. The TMZ width being of the order of 10 mm at the time of reshock, perturbations of similar or larger wavelength should not have reached saturation, thereby invalidating the self-similar hypothesis for the grid with large mesh spacing (m_s = 12.1 mm). Once triggered by RMI, the modes are indeed expected to evolve quasi-linearly until their amplitude is of the order of their wavelength [24]. The lack of self-similarity is confirmed by Fig. 17 showing the spectra at t = 3 ms, the end of the simulations. For the grid with the largest mesh spacing m_s, the spectra are clearly dominated by the wavelength 12 mm. On the other hand, for the grid with the shortest mesh spacing m_s = 1.8 mm, no wavelength stands out from the spectrum. This seems to hint that the latter spectrum has been equilibrated by nonlinear interactions as expected for self-similar turbulent mixing, whereas the former one has not yet reached self-similarity and the wavelength 12 mm still evolves in its way.

Numerical simulations react as expected to the growth of m_s: compared to the saturated 1.8 mm small wavelength, the contribution of the (quasi-linearly evolving) 12 mm large wavelength yields an increment of TMZ growth after reshock in the simulations, in contrast with the experiments. That effect is clear with the egg-box initialization: increasing the amplitude a_0 (for the mode with 12 mm wavelength) increases the amplitude at the time of reshock and leads to larger postreshock growth while decreasing the amplitude a_0 lets the grid imprint, with 12 mm periodicity, disappear from simulated schlieren images, in opposition to experimental ones. The wire-wake initialization improves the comparisons with respect to the egg-box one by reducing the growth increment (while reducing the arbitrariness in the choice of initial conditions when changing the grid). But none of the two initializations succeed in obtaining the independence observed in experiments for the postreshock growth rate with respect to the fragmentation grid while showing its imprint in the schlieren visualizations.

We remind that the two clear trends drawn from the shock tube experiments are:

1) weak dependence of the postreshock TMZ growth with respect to the age of the TMZ at the time of reshock provided that the TMZ is old enough;
2) independence of the TMZ width evolution with respect to the fragmentation grid spacing, m_s = 1.8 mm or m_s = 12.1 mm, despite the fact that the imprint of that grid is clearly visible on the schlieren pictures.

The first statement is roughly retrieved by computations, but this is not the case for the second one.

The experimental results remain difficult to understand for the following reason. Since the TMZ growth after reshock is almost unchanged when the chamber length L varies from 150 to 300 mm, the TMZ is expected to evolve under self-similar conditions at the time of reshock. Then, all length scales should be related to the TMZ width, and prior to that time, to the relevant length scales in the initial conditions. The upper fragmentation grid mesh spacing m_s seems the best candidate to provide a relevant length scale especially as its imprint is obvious in schlieren pictures, Fig. 6. The TMZ width being of the order of 10 mm at the time of reshock, perturbations of similar or larger wavelength should not have reached saturation, thereby invalidating the self-similar hypothesis for the grid with large mesh spacing (m_s = 12.1 mm). Once triggered by RMI, the modes are indeed expected to evolve quasi-linearly until their amplitude is of the order of their wavelength [24]. The lack of self-similarity is confirmed by Fig. 17 showing the spectra at t = 3 ms, the end of the simulations. For the grid with the largest mesh spacing m_s, the spectra are clearly dominated by the wavelength 12 mm. On the other hand, for the grid with the shortest mesh spacing m_s = 1.8 mm, no wavelength stands out from the spectrum. This seems to hint that the latter spectrum has been equilibrated by nonlinear interactions as expected for self-similar turbulent mixing, whereas the former one has not yet reached self-similarity and the wavelength 12 mm still evolves in its way.

Numerical simulations react as expected to the growth of m_s: compared to the saturated 1.8 mm small wavelength, the contribution of the (quasi-linearly evolving) 12 mm large wavelength yields an increment of TMZ growth after reshock in the simulations, in contrast with the experiments. That effect is clear with the egg-box initialization: increasing the amplitude a_0 (for the mode with 12 mm wavelength) increases the amplitude at the time of reshock and leads to larger postreshock growth while decreasing the amplitude a_0 lets the grid imprint, with 12 mm periodicity, disappear from simulated schlieren images, in opposition to experimental ones. The wire-wake initialization improves the comparisons with respect to the egg-box one by reducing the growth increment (while reducing the arbitrariness in the choice of initial conditions when changing the grid). But none of the two initializations succeed in obtaining the independence observed in experiments for the postreshock growth rate with respect to the fragmentation grid while showing its imprint in the schlieren visualizations.

Fig. 16 Schlieren pictures of the TMZ with the coarse fragmentation grid m_s = 12.1 mm after postreshock growth (t = 2.85 ms). Experiment in the center and simulation with wire-wake and egg-box initializations on either sides.

Fig. 17 Longitudinal velocity spectrum in the plane of the interface at time 3 ms for L = 250 mm. The configurations with the two upper grids m_s = 12.1 mm and m_s = 1.8 mm are shown for the two kinds of initialization.

References


