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Investigation of the interface stretching within a reshocked mixing zone produced by the Richtmyer Meshkov Instability

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Abstract

The spatio-temporal evolution of a bi-dimensional (2D) and three-dimensional (3D) air/SF₆ mixing layer issued from the development of a Richtmyer-Meshkov instability (RMI) under reshock is investigated using direct numerical simulations (DNS) at moderate Mach number ($M=1.2$) and high Atwood number ($A=0.67$). This study discusses the relevance of an original criterion based on the measurement of the gaseous interface stretching in the analysis of the mixing process. The first part of the work provides an estimation of the validity of a 2D approach in time for the retained simulation cases. To this avail, a 2D simulation for one typical parameter set is compared to its 3D counterpart. As a means of comparing the development of the mixing layer in both simulations, the classical criterion relying on the evaluation of the mixing layer thickness has been chosen. This criterion is commonly used to characterize baroclinic instability as it is intuitive and easy to compute and to analyze. However, this criterion only provides the mixing zone frontiers but does not provide information about the length scale content and its evolution on the interface. In order to tackle this issue, it is proposed to adapt a still documented criterion for the determination of the interface stretching, based on the computation of the temporal evolution of the mixing interface length for the study of various cases involving different initial interface perturbations, with reshock consideration.

1 Introduction

One way of producing Richtmyer-Meshkov instability (RMI) is to impulsively accelerate an interface between two gases of different densities with a planar shock wave. RMI occurs in many physical processes such as supersonic combustion [2], astrophysics [3] and inertial confinement fusion (ICF) [4].

In a practical way, various methods can be used to decipher the mixing zone. One approach commonly used is to consider the mixing layer thickness, *i.e.* the mean (or the max) distance between the two mixing layer frontiers delimiting the mixing zone from the upstream and downstream flow. An alternative is to consider a constant mass fraction isoline and to determine its peak-to-peak (p-p) distance. However, a major drawback of the above-mentioned interface p-p criterion is that it does not necessarily discriminate the large scale shape of the interface from the maximal distance between two arbitrarily fixed values of mass fraction isolines, *e.g.*, 0.01 and 0.99 [5]. In order to improve the mixing process description, a different criterion has been proposed by Kilchyk *et al.* [1] for 2D flow configurations. In their study of the scaling interface length increase rates in Richtmyer-Meshkov instabilities, they compute the length of iso-concentration lines of the mixing zone after the interaction of the density interface with the incident shock wave, up to the early stage of the non linear phase where the interface still depicts moderately disturbed schemes. This kind of criterion is also

commonly used in the field of flame front study as an indicator of combustion quality [2], as it provides relevant information about the exchange surface between combustible and fuel. In particular, it provides information on the interface line topology, contrary to the previously mentioned thickness criteria. In this study we propose to extend the study conducted by [1] to the analysis of the reshock phenomenon on the consecutive spatio-temporal evolution of the mixing zone, a few instants after the interaction of the reshock with the mixing zone. This paper is organized as follows. The computational set-up and the definition of the criteria used for the analysis of the mixing process are first described in Sec. 2. Then, the validity of the 2D vs. 3D approach is estimated in Sec. 3. Sec. 4. presents and discusses the results obtained by applying the mixing zone analysis criterion to the data provided by the numerical simulations.

2 Numerical approach

For all the Direct Numerical Simulations (DNS) presented in this paper, we solve the multispecies compressible time-dependent Navier-Stokes equations using an Eulerian finite volume method with the StarCCM+ Siemens PLM Software. The spatial discretization is achieved using a second-order upwind scheme. The temporal integration relies on an explicit second-order time stepping method. A weighted essentially non-oscillatory (WENO) scheme is used for flux reconstruction.

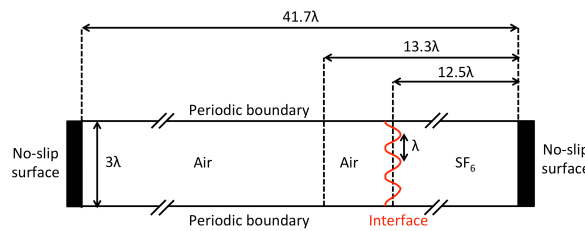


Fig. 1 Schematic of the RMI test configuration. For reshock, the shock reflects from the right no-slip surface ($\lambda = 1200\mu\text{m}$).

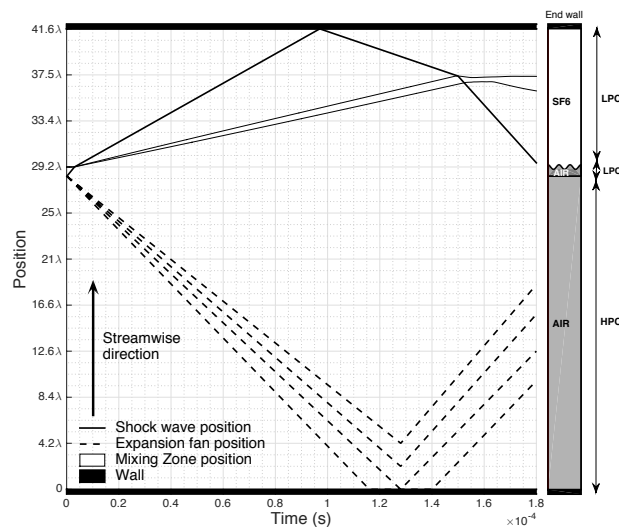


Fig.2 X-t diagram from a bi-dimensional simulation with single mode sinusoidal initial perturbation ($a_0 = 31.25\mu\text{m}$ and $\lambda = 1200\mu\text{m}$), where HPC is the High Pressure Chamber filled with air, LCP1 and LPC2 the Low Pressure Chambers filled with air and SF6 respectively

The flow configuration and the computational domain is shown in Fig. 1. The extent of the 2D computational domain equals 41.6λ in the streamwise direction and 3λ in the transverse direction (a $3\lambda \times 3\lambda$ cross section is imposed in the 3D case). At the initial instant of the computation, a pressure discontinuity is imposed 13.3λ from the end wall, and a density discontinuity obeying the analytical formulation Eq. (1) for the 2D case (Eq. (2) for the 3D case) is imposed 12.5λ from the end wall in order to materialize the initial position of the gaseous interface. The high-pressure chamber (HPC) is filled with air at a temperature of 288 K and a pressure of 0.238 MPa . Low pressure chambers LPC1 and LPC2 are filled with air and SF6, at a temperature of 230.4 K and a pressure of 0.1 MPa respectively. The resulting Mach number of the incident shock wave is 1.2. The two gases (SF6 and air) have been selected in order to impose a high-density contrast, leading to a high Atwood number of 0.67. The region of the computational domain where the RMI-induced mixing zone travels is discretized with a cell size of $3\mu\text{m}$. This cell size has been fixed thanks to an estimation of the Kolmogorov scale following Tritschler *et al.* [6]. For the present study, before the reshock phenomenon, this scale is estimated to be close to $18\mu\text{m}$ for a single mode initial perturbation with initial amplitude of $62.5\mu\text{m}$, a characteristic wavelength of $1200\mu\text{m}$ and a shock wave Mach number of 1.2. It is important to mention that, to the authors' knowledge, no information is available in the literature regarding the post-reshock evolution of the Kolmogorov scale within the mixing zone. As such the $3\mu\text{m}$ cell size has been fixed as the best compromise in terms of computational cost *vs.* spatial resolution. Outside of this region where the RMI-induced mixing zone travels, the cell size is progressively increased up to $125\mu\text{m}$ following a factor 2 arithmetic law. Periodic boundary conditions in the transverse direction are applied and the ends of the shock tube are modeled as non-slip surfaces. The initial density interface $a(y,z)$, for both 2D and 3D computations, is defined as follows :

$$(2D) : a(y) = a_0 \sin\left(\frac{2\pi y}{\lambda} + \phi\right) \quad (1)$$

$$(3D) : a(y,z) = \frac{a_0}{2} \left[\sin\left(\frac{2\pi y}{\lambda} + \phi\right) + \sin\left(\frac{2\pi z}{\lambda} + \phi\right) \right] \quad (2)$$

Here λ is the wavelength, a_0 the initial amplitude and ϕ the phase to ensure boundary periodic conditions. For these initial conditions, the time lap separating the instant of the incident shock wave interaction with the initial interface to the interaction of the reflected shock wave with the mixing zone is approximately $t = 0.14\text{ms}$.

The calculation of the mixing width relies on isolines or surfaces corresponding to a fixed mass fraction value of air equal to 0.5. The mixing thickness M is then defined as:

$$M = \max(Y_{air}(0.5)) - \min(Y_{air}(0.5)) \quad (3)$$

Where Y_{air} corresponds to the air mass fraction. The mixing length can also be reduced to a dimensionless quantity using the initial interface amplitude as follows:

$$M^* = \frac{M}{2a_0} \quad (4)$$

The interface length (criterion introduced by Kilchyk *et al.* [1]) is computed by summing each segment that connects consecutive points along interface (Fig. 3)

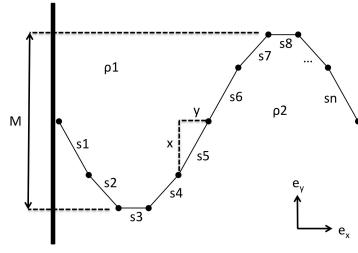


Fig.3 Schematic of isoline corresponding to a fixed mass fraction of air (Y_{air}). Black dots represent computational values. Black segments (s_1 to s_n) are used to compute interface length and M is the mixing thickness Eq. (5).

Two-dimensional geometries satisfying analytical solutions for their length have been tested. Analytical formulation for each function f on an interval l is defined as:

$$L = \int_l \sqrt{1 + f'^2} dl \quad (5)$$

Validation step with analytical function have shown good accordance between the results obtained from the algorithm (Fig. 3) and the analytical results. Error is estimated to be under 0.7%. The interface length L is normalized by its initial length L_0 following Eq. (6):

$$L^* = \frac{L}{L_0} \quad (6)$$

It is important to mention that, for late instants of the spatio-temporal evolution of the mixing zone, numerous gas pockets may separate from the main interface line. These isolated gas pockets will not be taken into account in the computation of L^* .

3 Validity estimation of the 2D vs. 3D approach

Fig. 4 compares the temporal evolution of the mixing layer thickness for both 2D and 3D simulation cases. The analysis aims at estimating the relevance of the 2D vs. 3D approach. Here the density interface initial perturbations are defined by equations Eq. (1) and Eq. (2), where the perturbation wavelength λ is fixed to $1200\mu m$ and its amplitude $a_0 = 31.25\mu m$.

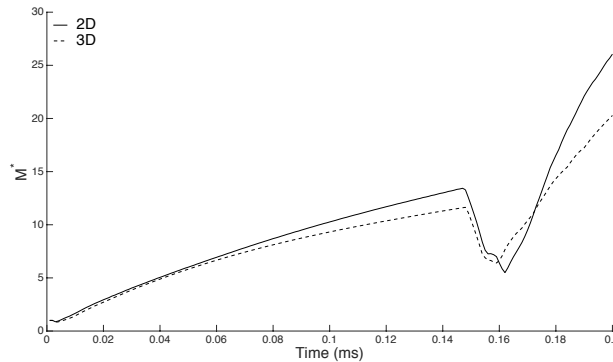


Fig. 4 Temporal evolution of the normalized mixing length M^* for both dimensional approaches. Initial perturbation parameters are $\lambda = 1200\mu m$ and $a_0 = 62.5\mu m$

Fig. 4 shows a good agreement of the temporal evolution of the mixing layer thickness between both cases during linear and non-linear phases. Reshock occurs at the same instant ($t \sim 0.148ms$) and the growth rates of the mixing layer during the compression stage consecutive to the reshock experience similar strong decreases. The time limit where the relevance of the 2D approach can confidently be assessed to approximately $t_{2D,eq.3D} = 0.175ms$. Consequently, the analysis of the 2D simulations will be conducted up $t_{2D,eq.3D}$.

4 Interface stretching

Fig.5 illustrates the 2D parametric study of the influence of the initial density interface amplitude a_0 on the interface stretching criterion, defined by Eq. (6). Four different initial amplitude values, referenced on Fig.5, were computed while fixing the initial wavelength λ to $720\mu m$.

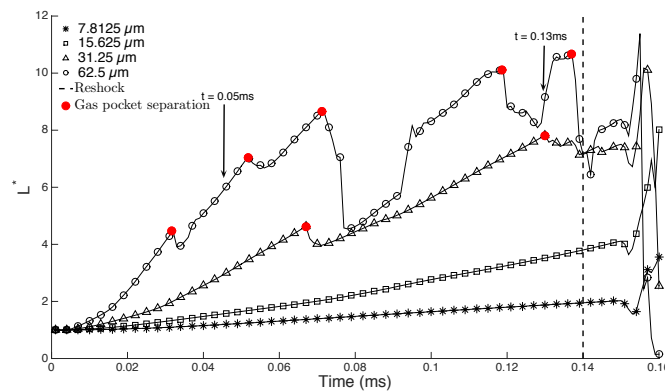


Fig. 5 Temporal evolution of the normalized interface stretching criterion L^* as a function of the initial density interface amplitude a_0 . Black dotted line marks the instant of the reflected shock wave/mixing zone interaction. Red dots correspond to the instant when gas pockets separate from the main interface (see Fig. 6).

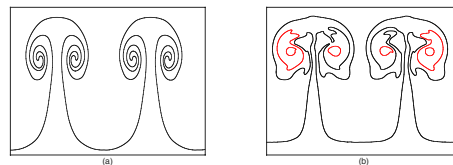


Fig. 6 Instantaneous isolines of molar fraction of air equal to 0.5. (a) $t = 0.05ms$, (b) $t = 0.13ms$. Red lines depict gas pockets.

Fig. 5 shows that the growth rate of the interface stretching length is first undergoing a non-linear increasing phase, up to the interaction of the reflected shock wave with the mixing zone at $t \sim 0.148ms$. At this instant, the mixing zone is compressed and the interface transiently flattens. The latter promotes the slight decrease of the interface stretching length L^* . This compression is also visible on Fig.4 where the normalized mixing length M^* experiences a dramatic decrease. Note that the linear phase, that normally occurs prior to the nonlinear phase, is only hardly visible on the curves, due to the large scaling factor imposed by the range of the initial amplitudes a_0 . The duration of the nonlinear phase depends on the initial interface amplitude. Interestingly enough, it is important to note that for the larger initial

amplitudes a_0 , the nonlinear evolution of the L^* criterion is repeatedly truncated, as marked by red dots, under the influence of gas pocket separations. Fig.6 provides an illustration of this gas pocket separation process. In this particular case, it is likely that the two contra-rotating vortices on both side of each spikes cause this gas pocket separation. Finally, Fig. 5 also reveals a time lag in the re compression of the reshocked mixing zone for small initial amplitudes a_0 of the density interface ($a_0=7.8\mu m$ and $a_0=15.6\mu m$). For the cases where the amplitude a_0 of the density interface is larger ($a_0=31.2\mu m$ and $a_0=62.5\mu m$), the separation of gas pockets prior to the reshock phenomenon drastically modifies the behavior of the time history of L^* after reshock, which depicts a much more disturbed trend.

5 Conclusion

In this paper, the spatio-temporal evolution of a reshocked air/SF6 mixing zone induced by the Richtmyer-Meshkov instability has been numerically studied by means of Direct Numerical Simulations for various initial density interface amplitudes. Validity estimation of 2D vs. 3D approaches has been performed on the basis of a mixing width criterion. A 2D parametric study has been conducted to investigate the influence of the gaseous interface initial perturbation amplitude on the resulting interface stretching. The analysis of the stretching length criterion has shown that the early development of the mixing zone depicts a brief linear, then non-linear growth rate phase. In the case of high initial amplitudes, where the RMI-promoted baroclinic torque deposit on the interface is enhanced due to the stronger pressure-density gradients misalignments, gas pocket separations are observed. This may translate the influence of the initial interface perturbation amplitude on the characteristics of the vortex population incepted within the mixing zone during the shock/reshock process.

Acknowledgments

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