LA-UR- 11-00467

Approved for public release; distribution is unlimited.

Title: Planar Richtmyer-Meshkov Instabilities and Transition to Turbulence (U)

Author(s): Fernando F. Grinstein, Akshay Gowardhan, and Ray Ristorcelli

Intended for: Submitted for presentation at ETC13, Warsaw, Poland, September 12-15, 2011

Los Alamos NATIONAL LABORATORY EST. 1943

PLANAR RICHTMYER-MESHKOV INSTABILITIES AND TRANSITION TO TURBULENCE

Fernando F. Grinstein[1], Akshay A. Gowardhan[1], & J. Ray Ristorcelli [2]
[1]*X-Computational Physics Division, Los Alamos National Laboratory MS F644, Los Alamos, NM 87545*
[2]*CCS-2, Los Alamos National Laboratory, Los Alamos, NM 87545*

Summary
Extensive recent work has demonstrated that predictive under-resolved simulations of the velocity fields in turbulent flows are possible without resorting to explicit subgrid models, when using a class of physics-capturing high-resolution finite-volume numerical algorithms. This strategy is denoted implicit large eddy simulation (ILES, MILES). The performance of ILES in the substantially more difficult problem of under-resolved material mixing driven by under-resolved velocity fields and initial conditions (ICs) is a focus of the present work. Progress is presented in analyzing the effects of IC combined spectral content and thickness parametrizations.

BACKGROUND

In the large eddy simulation (LES) [1], the large energy containing structures are resolved, the smaller, presumably more isotropic, structures are filtered out, and effects of subgrid scales (SGS) are modeled. ILES [3] effectively addresses the seemingly insurmountable issues posed to LES by under-resolution, by relying on the use of SGS modeling and filtering provided implicitly by a class of physics capturing numerics; extensive verification and validation in areas of engineering, geophysics, and astrophysics has been reported [2]. In many areas of interest such as, inertial confinement fusion, understanding the collapse of the outer cores of supernovas, and supersonic combustion engines, vorticity is introduced at material interfaces by the impulsive loading of shock waves, and turbulence is generated via Richtmyer-Meshkov instabilities (RMI). Given that ILES is based on locally-adaptive, non-oscillatory, finite-volume methods it is naturally suited to emulate shock physics. The unique combination of shock and turbulence emulation capabilities supports direct use of ILES as an effective simulation *anzatz* for RMI [3]. Here, we further test this approach using a particular strategy based on a nominally-inviscid, Schmidt number ~ 1, simulation model that uses the LANL RAGE code [4,5] to investigate planar RMI. Issues of initial material interface characterization and modeling difficulties, and effects of IC resolved spectral content on transitional and late-time turbulent mixing were examined in our previous work [6]. The focus here is to carry out a systematic analysis of effects of combined IC spectral content and thickness.

RESULTS

The planar shock-tube configuration investigated involves high (SF_6) and low density (air) gases, presumed ICs at the material interface separating the gases, and eventual reshock off an end-wall (Fig. 1). The contact discontinuity between air and SF_6 is modeled as a jump in density using ideal gases with $\gamma = 1.4$ and $\gamma = 1.076$, respectively, with constant pressure across the initial interface at rest. A shocked air region is created upstream satisfying the Rankine-Hugoniot relations for a Mach 1.5 shock. The shock propagates in the (x streamwise) direction through the contact discontinuity and reflects at the end of the simulation box on the right. Periodic BCs conditions are imposed in the transverse (y,z) directions. RAGE solves the multi-material compressible conservation equations for mass density, momenta, total energy, and partial mass densities, using a 2nd-order Godunov scheme, adaptive mesh refinement, a variety of numerical options for gradient terms (limiters), and interface treatments (not used here);); the Van Leer limiter option was chosen for the present simulations.

A crucial issue when simulating turbulent flow instabilities such as considered here is that of modeling the insufficiently-characterized ICs in the laboratory experiments. The inherent difficulties with the open problem of predictability of material stirring and mixing by under-resolved numerically generated multi-scale turbulent velocity fields, are now compounded with the inherent sensitivity of turbulent flows to ICs [6,7]. The surface displacement of the material interface in the RMI experiments has been modeled combining well-defined perturbations in terms of a prescribed top-hat wavelength range of modes, $\lambda_{min} < \lambda < \lambda_{max}$, involving random amplitudes and phases and a specified standard deviation [3].

Simulations were performed for a variety of grid resolutions and perturbations. To study the effect of ICs on the evolution of RMI, the spectral content of the interface and the thickness of the interface have been varied. Figure 2 describes the material interface parametrized in terms of the relevant quantity $\eta = \kappa_o \delta$, where $\kappa_o = 2\pi/\lambda_o$, and λ_o is a representative (mean) wavelength in the particular range of wavelengths considered. The cases considered in this work are categorized into two distinct – low and high η – categories with cases having correspondingly the same spectral content but different thickness (left and right columns in Fig. 3, respectively). For cases with low η , $\lambda_o >> \delta$, single perturbation modes are well separated and it is less likely that they will interact with each other; in these regimes, the modes grow in a ballistic manner without interfering with each other. For cases with high η, say, $\lambda_o/2 < \delta$, i.e. the size of the vortices formed at the interface are of the order or less than the separation between them, and it is more likely that there will be mode coupling, and transition to non-linear regimes. The border-line case is $\lambda_o/2 \approx \delta$ or $\eta \approx \pi$.

The impact of this IC parametrization on material mixing has been investigated in detail; representative examples of our results are exemplified below. Analysis of the simulation data is based on using an ensemble (cross-stream) averaging operation, denoted by $< f >= A^{-1} \int f(y,z)\,\mathrm{d}y\mathrm{d}z$, where $A = \int \mathrm{d}y\mathrm{d}z$. Relevant quantities used are, $\psi(x) =< Y_{SF_6} >$,

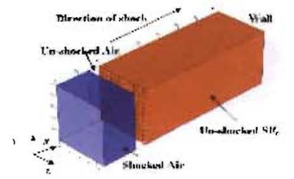

Figure 1. Schematic of the planar shocktube domain.

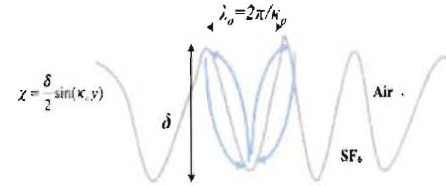

Figure 2. Characteristics of the initial material interface perturbation.

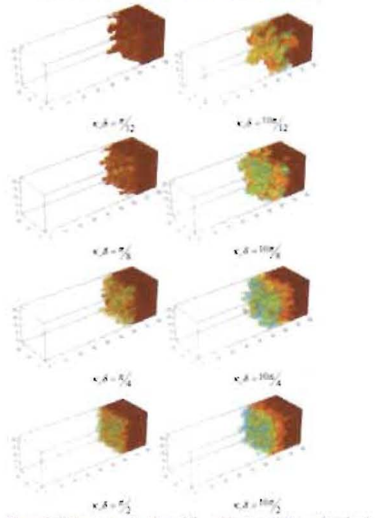

Figure 3. Volume visualization of Y_{SF_6} at time t = 3000 μs after shock.

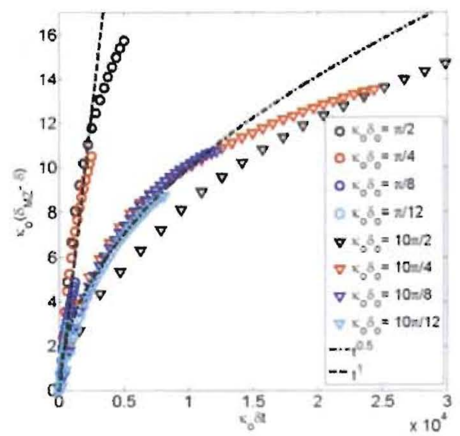

Figure 4. Mixedness shifted and normalized with IC parameters.

$M(x) = 4\psi(x)(1 - \psi(x))$, where ρ is the mass density, ρ_{SF_6} is the SF_6 mass-density, and $Y_{SF_6} = \rho_{SF_6}/\rho$ is the SF_6 mass fraction; the integrated mixedness is defined by $\delta_{MZ} = \int M(x)\,\mathrm{d}x$ [6]. The instantaneous volume visualizations of the local mass fraction Y_{SF_6} at the selected time = 3000 μs shown in Fig. 3, suggest smaller-scale content and mixing increasing with η. Agreement with Richtmyer's theory [8] (early time growth proportional to η) is found for a very short time after the material interface is shocked. Soon thereafter, the growth is found to be actually inversely proportional to η. The above analysis suggests that relevant RMI integral mixing may scale with suitable IC parametrizations. We have addressed this possibility by plotting appropriately shifted and normalized mixedness measures *vs.* $\eta\times$time (Fig. 4). Except for the highest η considered (η=5π), low η and high η results tend to correspondingly collapse into distinctly different correlation groups, collapsing well with temporal behaviors $\sim t^1$ and $\sim t^{0.5}$, respectively, suggesting transition to non linearity above the threshold value $\eta \sim \pi$. Efforts made to scale other relevant flow quantities will be reported in the presentation and final version of the paper. Turbulent flow characteristics and dynamics of the problem, and metrics for transition to turbulence will be investigated in detail for cases with and without reshock; appropriate grid resolution issues will be addressed in this context.

This work was made possible by funding from the LAND LDRD-DR Program 20090058DR. Los Alamos National Laboratory is operated by LANS, LLC for the U.S. DOE NNSA under Contract No. DE-AC52-06NA25396.

References

[1] Sagaut P., *Large Eddy Simulation for Incompressible Flows*, 3rd Ed., Springer, NY, 2006.

[2] F.F. Grinstein, L.G. Margolin, and W.J. Rider, Eds., *Implicit Large Eddy Simulation: Computing Turbulent Flow Dynamics*, Cambridge University Press, New York, 2007.

[3] D. Drikakis, F.F. Grinstein, and D.Youngs, "On the computation of instabilities and symmetry-breaking in fluid mechanics", *Progress in Aerospace Sciences*, **41**, 8, pp. 609-641, 2005.

[4] Baltrusaitis, R. M., Gittings, M. L., Weaver, R. P., Benjamin, R. F. Budzinski, J. M., "Simulation of shock-generated instabilities". *Phys. Fluids* **8**, 2471–2483, 1996.

[5] Gittings. M., Weaver, R. , Clover, M. , Betlach, T. , Byrne, N. , Coker, R. , Dendy, E., Hueckstaedt, R. , New, K. , Oakes, W. R. , Ranta, D. , Stefan, R. , "The RAGE Radiation-Hydrodynamic Code", *Comput. Science Discovery* **1** 015005, 2008.

[6] F.F. Grinstein, A.A. Gowardhan, and A.J. Wachtor, "Simulations of Richtmyer-Meshkov Instabilities in Planar Shock-Tube Experiments", *Phys. Fluids*, 2011, to appear.

[7] George, W.K., "Recent Advancements Toward the Understanding of Turbulent Boundary Layers," *AIAA Journal*, **44**, no.11, pp.2435–49, 2006.

[8] Richtmyer, R. D., "Taylor instability in shock acceleration of compressible fluids". *Commun. Pure Appl. Maths.* **13**, 297–319, 1960.