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STUDIES OF TURBULENT MIXING IN SHOCK-DRIVEN RICHTMYER-MESHKOV INSTABILITY

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Abstract We study the turbulent mixing that occurs when a perturbed planar density gradient separating two gases is impacted by a planar shock wave of moderate strength and then subsequently re-shocked when the original shock is reflected from an end-wall back into the mixing layer. We perform a systematic study of the influence of the relative molecular weights of the gases. In particular, we examine the gas combinations air-CO_2, air-SF_6, and H_2-air. A large eddy simulation method (LES) is applied based on the stretched sub-grid-vortex model of Pullin. We also examine the evolution towards isotropy of the generated turbulence. Our simulations suggest that for sufficiently high shock Mach numbers, the initial mixing layer evolves at late time to a fully developed turbulent flow with a Kolmogorov-type inertial range energy spectrum following a canonical $-5/3$ power law. However, only partial evolution to isotropy of the flow is observed.

INTRODUCTION

When a perturbed density interface separating two fluids is impacted by a shock wave, vorticity is deposited at the interface by means of baroclinic torque as a result of the misalignment of the pressure gradient ∇p across the shock and the local density gradient $\nabla\rho$ at the interface. Perturbations grow and eventually develop complex structure, forming a mixing zone of interpenetrating light and heavy fluids. This class of instabilities, known as the Richtmyer-Meshkov instability (RMI), is often thought of as an impulsive or shock-induced version of the continuously driven Rayleigh-Taylor instability (RTI), which occurs at accelerated density-stratified interfaces. The configuration for the initial condition is shown in Figure 1 below.

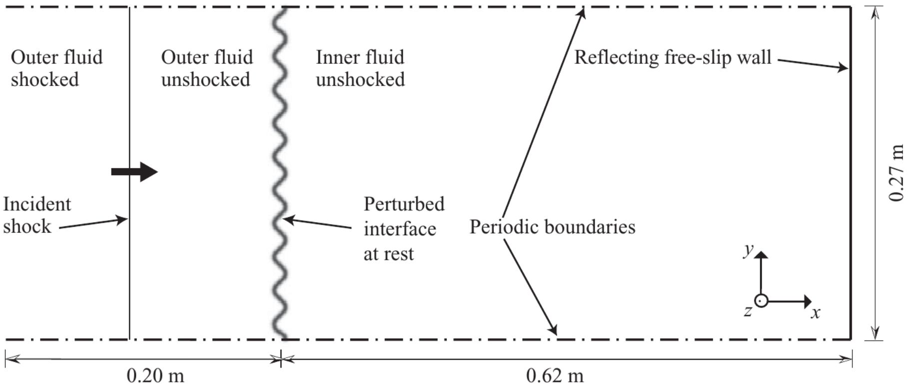

Figure 1. Geometry of the simulation domain before an incident shock impacts a single-mode perturbed density interface, separating two quiescent fluids of different densities. Note that the domain is squared in the (y, z)-cross-section.

The RMI derives its name from the numerical and analytical predictions of Richtmyer [5], subsequently confirmed by the shock tube experimental results of Meshkov [3]. In the RTI case, the interface becomes unstable if the density gradient is opposite in its direction to the acceleration, i.e. $\nabla p \cdot \nabla\rho < 0$ (e.g. heavy fluid lying on top of a lighter fluid in a gravitational field). However, in the RMI case, perturbation growth will result whether the incident shock wave propagates from a light to a heavy gas or from a heavy to a light gas in which case phase reversal precedes the growth), and such shock-interface interactions need to be distinguished. In shock tube experiments with an end-wall the initial shock-contact interaction and the re-shock will be of alternating density gradients (i.e. light to heavy or heavy to light) as the shock reverses its direction of propagation when it reflects off the end-wall.

The physics of re-shock environments involving the RMI is of interest as a result of its relevance to applications such as supernovae dynamics and inertial confinement fusion (ICF). The majority of simulations of such phenomena are still performed in one and two dimensions, as the computational resources required to fully resolve the range of spatial and temporal scales in three-dimensional turbulent flows are still beyond the reach of available computing facilities. To reduce the computational costs, we describe in this work the simulation of such RMI flows using adaptive mesh refinement to capture the strong waves coupled with a vortex-based sub-grid scale turbulence model to effect a LES of the ensuing turbulent flow.

EVOLUTION OF THE TURBULENCE

We perform LES using the stretched vortex sub-grid-scale model as put forth in Misra and Pullin [4]. The sub-grid dynamics are roughly modeled by a distribution of stretched vortices that are approximate solutions of the Navier-Stokes equations and that are consistent with the Kolmogorov energy spectrum. A key feature of this model is that it provides an estimate of the sub-grid scale energy and other sub-grid quantities. In previous work the model has been extended to compressible flows and in this work we have extended it further to include multi-component mixtures.

A variety of simulations have been carried out to observe the level of mixing, the growth of the mixing layer and the distribution or turbulent kinetic energy. The key parameters varied are the Atwood ratio given by

$$A = \frac{\rho_o - \rho_i}{\rho_o + \rho_i}$$

and the shock Mach number M associated with the rightward moving shock initiated in the outer fluid.

As an example of the characterization of the ensuing turbulence we show in Figure 2 below the evolution of the volume averaged turbulent kinetic energy (TKE) and dissipation ϵ as well as estimates from the model of the sub-grid contributions to these quantities. [1]

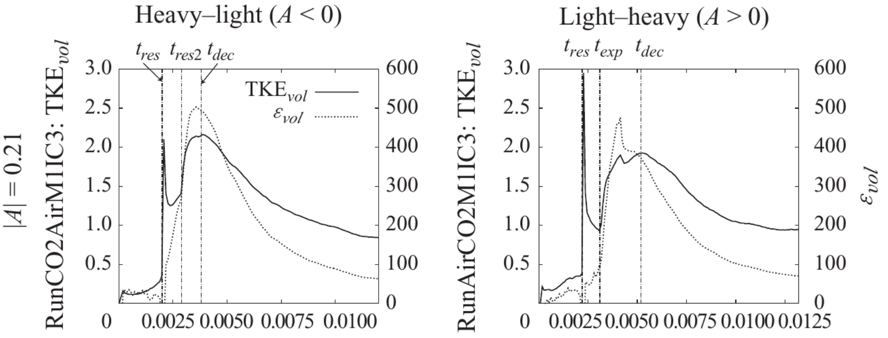

Figure 2. Volume-averaged resolved and sub-grid TKE and turbulent dissipation ϵ versus t.

EVOLUTION OF THE ENERGY SPECTRA

Using the LES approach, we also examine the evolution of the energy spectra as well as the isotropization of the RMI turbulence. For sufficiently high Mach numbers, the mixing layer ultimately evolves to a late-time fully-developed turbulent flow with a Kolmogorov-like inertial range following a -5/3 power law. The degree of isotropy observed varies, but at late times the flow is not seen to be fully isotropic. For all Mach numbers considered the late time flow resembles homogeneous decaying turbulence of Batchelor type with a kinetic decay energy exponent ≈ 1.4 and a large scale energy spectrum $\approx k^4$. [2]

References

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