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Abstracts for the 14th International Workshop on the Physics of Compressible Turbulent Mixing

Oleg Schilling

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International Workshop on the Physics of Compressible Turbulent Mixing 2014

31 August 2014 – 5 September 2014
San Francisco, California, USA

ABSTRACTS

Oleg Schilling, Chairman
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General Information

The workshop is hosted by the Lawrence Livermore National Laboratory and is held in the Grand Ballroom at the Hilton San Francisco Financial District Hotel. The Thursday session will be held across the street at City College.

The banquet will be held on Tuesday, 2 September 2014 from 19:00–21:00 at Morton's: The Steakhouse on Post Street in Union Square.

Workshop Schedule:

	9/1/2014 Monday	**9/2/2014 Tuesday**	**9/3/2014 Wednesday**	**9/4/2014 Thursday**	**9/5/2014 Friday**
8:20–8:30	Welcome	Announcements	Announcements	Announcements	Announcements
8:30–10:35	Plenary Rayleigh–Taylor experiment (3)	Plenary Rayleigh–Taylor and Kelvin–Helmholtz theory and modeling (3)	Plenary Richtmyer–Meshkov experiment (3)	Plenary Richtmyer–Meshkov simulation (3)	Strength, ejecta, particulate and EOS (5)
10:35–10:55	*Break*	*Break*	*Break*	*Break*	*Break*
10:55–12:10	Rayleigh–Taylor experiment and simulation (3)	Rayleigh–Taylor and Kelvin–Helmholtz theory and modeling (3)	Richtmyer–Meshkov experiment and simulation (3)	High energy density experiment (3)	*Discussion/ Adjourn*
12:10–13:30	*Lunch*	*Lunch*	*Lunch*	*Lunch*	
13:30–15:10	Rayleigh–Taylor simulation (4)	Rayleigh–Taylor and Richtmyer–Meshkov theory and modeling (3)	Richtmyer–Meshkov simulation (4)	High energy density simulation, theory and modeling (4)	
15:10–15:30	*Break*	*Break*	*Break*	*Break*	
15:30–17:10	Rayleigh–Taylor simulation (4)	Poster session	Richtmyer–Meshkov simulation (4)	High energy density theory and modeling (3)	
17:10–17:40	*Discussion*	*Discussion*	*Discussion*	*Discussion*	
17:40–20:00					
19:00–21:00		*Banquet*			

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PLENARY TALKS

CONTRIBUTED TALKS

POSTERS

Plenary Talk Abstracts

New results for the Asymptotic Self-Similar evolution of RT and RM instabilities at any Dimensionality and Density ratios

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Keywords: Rayleigh–Taylor instability, Richtmyer–Meshkov instability

ABSTRACT

The asymptotic self-similar evolution of the bubble front of the RT and RM instabilities for immiscible fluids is evaluated in 2D and 3D, using solutions to a new formulation of Haan's [1] and Ofer-Shvarts [2] mode-coupling models. In the RT case the model result, using the nominal values for Haan's saturation level, is α_{RT}~0.04 in 2D, consistent with 2D numerical simulations, and ~0.05 in 3D, consistent with the LEM experiments [3] but a factor of ~2 higher than the results of 3D numerical simulations [4]. In the RM case it is shown that the power law exponent is 2/5 in 2D, consistent with the Alon-Shvarts prediction and 2D numerical simulations [5], and 1/3 in 3D, higher than the value of ~0.25±0.05, obtained in the LEM experiments [3], in 3D numerical simulations [6] and proposed 3D models [7]. The reasons for that large spread in the self-similar parameters and an attempt to put them together in a unified framework will be presented. Newly proposed experiments on NIF, using very long laser pulses, in order to confirm the proposed new framework will be described.

References

[1] S.W. Haan, *Phys. of Fluids*, **B 3**, 2349, (1991).

[2] D. Ofer et al., *Physics of Plasmas*, **3**, 3073, (1996).

D. Shvarts et al., *Phys. of Plasmas*, **2**, 2465, (1995).

[3] G. Dimonte and M. Schneider, *Phys. of Fluids*, **12**, 304, (2000).

[4] G. Dimonte et al., *Phys. of Fluids*, **16**, 1668, (2004).

[5] U. Alon et al., *Phys. Rev. Lett*, **74**, 534, (1994).

[6] B. Thornber et al., *Phys. of Fluids*, **23**, 095107, (2011).

[7] D. Oron et al., *Phys. of Plasmas*, **8**, 2883, (2001); D. Kartoon et al., *LPB*, **21**, 327, (2003)

Numerical Experiments with Shock-Turbulence Interaction: Physics and Modeling

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Keywords: shock-turbulence interaction, direct numerical simulation, turbulence amplification

ABSTRACT

Many applications in engineering and physical sciences involve situations where a turbulent flow interacts with shock waves. High-speed flows around aerodynamic bodies and through propulsion systems for high-speed flight are abound with interactions of shear-driven turbulence with complex shock waves. Supernova explosions and inertial confinement fusion also involve the interaction of shockwaves with turbulence and strong density variations. Numerical simulations of such physical phenomena impose conflicting demands on the numerical algorithms. Capturing broadband spatial and temporal variations in a turbulent flow suggests the use of high-bandwidth schemes with minimal dissipation and dispersion, while capturing a flow discontinuity at a shock wave or a material surface requires numerical dissipation. This inherent conflict must be addressed in numerical simulations.

Results from a canonical shock-turbulence interaction problem, i.e. the interaction of isotropic turbulence with a (nominally) normal shock, are discussed. Highlight from DNS of this shock-turbulence interaction problem for different shock strengths and turbulence intensity [1] will be shown and results contrasted with linear theory where possible. Significant non-linear effects in the post-shock region are observed and a regime where the shock structure is substantially modified by the turbulence is explored. Recent results from the interaction of a spherical blast wave and a spherical converging shock with turbulence [2] will be contrasted with the planar problem. The turbulence behavior captured in the simulations and its modeling will be highlighted. The talk will end with recent work simulating shock-accelerated multi-material flows involving the Richtmyer-Meshkov instability in dense gas curtain [3] as an illustration of open issues for numerical- and physical-modeling.

[1] Larsson, J., Bermejo-Moreno, I. and Lele, S. K., J. Fluid Mech., 2013, vol. 717, pp. 293-321.
[2] Bhagatwala, A. and Lele, S. K., Phys. Fluids, 2012, Vol. 24, 085102.
[3] Shankar, S. K. and Lele, S. K., Shock Waves, 2014, Vol. 24, pp. 79-95.

Progress with experiments on understanding the Rayleigh-Taylor and Richtmyer-Meshkov driven flows for complex environments

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Keywords: Rayleigh–Taylor instability, Richtmyer–Meshkov instability, Kelvin–Helmholtz instability, combined instabilities, compressible mixing layers

ABSTRACT

Many studies of mixing focus on the role played by instabilities and turbulence in an incompressible medium. However, compressibility and shocks play a critical role in many practical applications. Some examples are volcanic eruptions causing environmental hazards, design of more efficient fuel pellets for inertial confinement fusion, energy-efficient scramjet engines, etc. Understanding the mixing process in such complex flows presents a set of truly fundamental and open problems of fluid mechanics. RT and RM are insidious instabilities that start with exponential growth of small scale perturbations, and end in a fully turbulent mixing process. It is this scale range and chaotic nature that challenges our experimental capabilities and physical understanding. But, the timely need to understand, predict, control, and utilize is because RT/RM mixing lies at the heart of national security priorities such as energy, threat reduction, and NNSA interests. Should the relationship between initial conditions and mixing be determined, then, in principle, the level of mixing could be controlled through the setting of specific conditions.

In this talk, I plan to review the recent experimental work in last 10 years and demonstrate how our understanding has been enhanced by these experiment. I will also describe the results from our recent laboratory experiments studying the shock-accelerated inclined interface problem and coupled shear and buoyancy-driven experiments performed in a multi-layer Gas Tunnel. Specifically, the effect of adding shear to a gravitationally unstable configuration will be discussed in detail. In these experiments, the flow visualizations are obtained using planar laser diagnostics (Mie-scattering and Planar laser-induced fluorescence). Simultaneous X-wire and cold wire anemometry in conduction with a special three-wire probe is used to obtain point-wise instantaneous velocities and density in the evolving flow field. Particle Image Velocimetry (PIV) is implemented to validate the hot wire results as well as to make field wise measurements of developing flow field. There has been a significant progress with experiments over the last 10 years, but there are a still several opportunities for the RT/RM research that will be discussed.

Hydrodynamic instability and mix experiments for ignition program on National Ignition Facility

V. A. Smalyuk

Lawrence Livermore National Laboratory

Hydrodynamic instabilities, including the Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities, are a major obstacle in quest to achieve ignition on the National Ignition Facility (NIF). A new experimental platform was developed to directly measure the instability growth as a function of convergence using in-flight x-ray radiography of pre-imposed surface modulations [1]. This work demonstrated the enhanced stabilizing effects on the ablation-front RT growth in the high-adiabat drive. Achieving ignition requires keeping the DT fuel on a lower adiabat to increase its compression. This resulted in the development a new adiabat-shaped drive that raises the adiabat at the ablation front to reduce ablation-front RT growth but leaves the adiabat of the DT fuel low to increase the DT fuel areal density. The first instability growth measurements using this new adiabat shaped drive will be presented. We will also discuss results from NIF experiments that examine instability growth from rough vs. smooth broad-band capsule surface finish, discrete 3D isolated features such as divots or bumps, and the capsule support tent. In addition, implosion performance and mix are being studied at peak compression using plastic shells filled with tritium gas and imbedding localized CD diagnostic layer in various locations in the ablator [2]. Neutron yield and ion temperature of the DT fusion reactions are used as a measure of shell-gas mix, while neutron yield of the TT fusion reaction is used as a measure of implosion performance. Experimental results and comparisons with 1D and 2D simulations, including mix models, will be presented.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

[1] V. A. Smalyuk *et al.,* Phys. Rev. Lett. **112**, 185003 (2014).

[2] V. A. Smalyuk *et al.,* Phys. Rev. Lett. **112**, 025002 (2014).

Contributed Talk Abstracts

Numerical Simulation of Explosive Dispersal of Particles in Cylindrical Geometry

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Keywords: Rayleigh–Taylor instability, Richtmyer–Meshkov instability, combined instabilities, Compressible Multiphase Turbulence, shock-particles interaction, Eulerian/Lagrangian approach.

ABSTRACT

Recent experiments have shown that when a layer of solid particles is explosively dispersed, a multiphase instability front often occurs, which leads to the formation of jet-like particle structures that are aerodynamically stable. We seek to replicate these experimental observations using highly resolved large-scale simulations, to improve our understanding of particulate fronts instabilities and the jetting phenomenon. We consider a central cylindrical core of high pressure, high density gas generated from high-energy material. Throughout the length of the cylinder, the charge is surrounded by an annular region of closely packed micron-sized, spherical and inert particles. The particles are treated as point particles, the gas is treated as a continuum, and a rigorous two-way coupled compressible multiphase formalism is used. Also, the unsteady hydrodynamic force components (i.e., added-mass, pressure-gradient and viscous-unsteady force) are included in the point-force formulation with appropriate Mach and Reynolds number correction; and, because the bed of particles surrounding the charge will initially undergo extreme compression due to the outgoing shock wave, the inter-particle collision model is carefully chosen to handle situations when the particle volume-fraction reaches the close-packing limit. The late time jets are believed to have their origins during the early phase of rapid acceleration of the bed of particles. Therefore, this work aims at capturing the early-time behavior and growth of the instabilities caused by the presence of particles. Considering the high pressures and temperatures of the gaseous products, the Jones-Wilkins-Lee equation of state is used as thermodynamic closure. Finally, the accuracy of these predictive simulations is studied by comparing the shock radius and particle front location against the data extracted from the experimental results.

This work is supported by the U.S. Department of Energy, National Nuclear Security Administration, Advanced Simulation and Computing Program, as a Cooperative Agreement under the Predictive Science Academic Alliance Program, under Contract No. DE-NA0002378.

Effect of initial conditions on late-time evolution to turbulence of Rayleigh Taylor instability under variable acceleration histories

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Keywords: Rayleigh-Taylor Instability, implicit large eddy simulation

ABSTRACT

Rayleigh Taylor Instability (RTI) occurs at the interface between a light fluid and a heavy fluid due to gravitational impact and is observed in combustion and chemical reactor processes, pollutant dispersion, internal confinement fusion (ICF), and in Type Ia supernova formation. Traditionally, RTI has been studied under a constant acceleration; however, due to the nature of these processes, it is important to understand the evolution of RTI under variable gravitational forces. This motivates the investigation of the effects of initial conditions on self-similar evolution to turbulence of RTI under variable acceleration histories [1,2]. Incompressible, three dimensional RTI is modeled using a massively parallel high resolution code, MOBILE which uses an Implicit Large Eddy Simulation (ILES) technique. In the current work, a wide range of initial conditions is investigated to understand (a) the effect of spectral index and bandwidth on RTI for an annular initial spectra, and, (b) the effect of multiple annuli (banded spectra) with different energy content in the two bands (total energy remaining the same for all cases). Our goal is to analyze the initial condition effects on late-time evolution of turbulent RTI and to identify the similarities and differences between the Rayleigh–Taylor turbulence and the more general forms of quasi-stationary turbulence. We will discuss a large number of metrics which include low order metrics like mix widths, growth constants, molecular mixing parameter, and higher order turbulence parameters like second order moments, their dissipations, and production–dissipation ratios.

References:

[1] Dimonte, G., Ramaprabhu, P., and Andrews, M.J., Rayleigh-Taylor instability with complex acceleration history. Phys. Rev. E 76, 046313 (2007).
[2] Ramaprabhu, P., Karkhanis, V., and Lawrie, A.G.W., The Rayleigh-Taylor instability driven by an accel-decel-accel profile. Phys. Fluids 25, 115104 (2013).

This work was performed under the auspices of a DOE-Stewardship Science Academic Alliance Grant (# DE-NA0001975) and a National Science Foundation Grant (1305512).

Numerical Simulations of Chemically Reacting Richtmyer-Meshkov Instability in H_2-O_2 Flames

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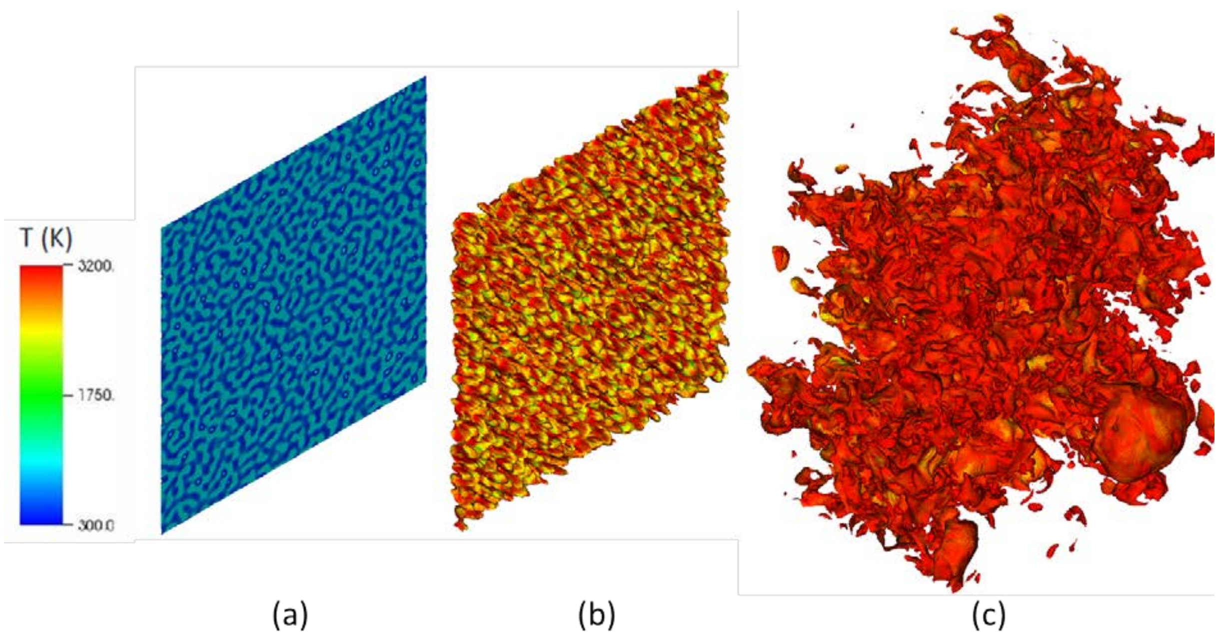
The interaction of a shock with a diffusion flame resulting in the Richtmyer-Meshkov instability, is a situation that arises in many complex combustion systems. The shock enhances mixing at a fuel-oxidizer interface through flow instabilities and improves the combustion properties of the system. We present results from numerical simulations of an H_2-O_2 diffusion flame, impacted by a Mach 1.2 shock traveling from the lighter (H_2) to the heavier (O_2) gas, with imposed single-mode and multimode perturbations. In the absence of an incident shock, the combustion generates blast waves which render the interface unstable to RMI, followed by a variable-g Rayleigh-Taylor instability. The behavior of such flames bear similarity to laser-driven target experiments, where ablation at the target surface results in the passage of a blast wave through layers of fuel and shell material. When additionally, an incident shock is present, we observe complex interactions between the shock and the blast waves, affecting the instability growth till late times. Multimode perturbed flames when subjected to a shock and a reflected reshock result in significant wrinkling of flame sheet and distributed combustion zones and a dramatic increase in combustion efficiency.



Contours of temperature superposed on the flame sheet (identified as the surface of stoichiometric mixture fraction) at (a) initial, (b) before reshock and (c) late times after reshock.

The Tilted Rocket Rig: Numerical Modelling in 2D and 3D

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Keywords: Rayleigh–Taylor instability, large-eddy simulation, Reynolds-averaged turbulence modeling, tilted rocket rig

ABSTRACT

In the ‘tilted rocket rig’ experiments [1, 2], a pair of fluids of differing density is accelerated by rocket motors, with the experimental apparatus arranged so that the initial fluid interface is tilted to the direction of the acceleration. This unique experimental geometry provides a useful test case for the validation of a numerical mixing model. In the central interface region, turbulent mixing occurs due to Rayleigh-Taylor instability. However, the bulk fluid flow is characterised by a general overturning motion, with plumes of material rising and falling at the sides of the enclosing tank, and with the motion inducing shear and strain effects within the mixing region.

In this work we consider, from ref. 1, experimental cases 110 (hexane/NaI solution, $\rho_1/\rho_2 = 2.9$, Atwood number $A = 0.5$) and 115 (pentane/SF_6, $\rho_1/\rho_2 = 19.6$, $A = 0.9$). We present simulation of these cases in 2D ALE and 3D Eulerian codes, in which the effects of turbulent mixing are modelled by an implementation of Young’s dynamic mix model [3]. Results are compared to those of 3D LES calculations, performed with the code TURMOIL.

References

[1] V. S. Smeeton and D. L. Youngs, “Experimental investigation of tubulent mixing by Rayleigh-Taylor instability, III”, *AWE Report O 35/87* 1988.

[2] D. L. Youngs, “Modelling turbulent mixing by Rayleigh-Taylor instability”, *Physica D* **37** 270–287, 1989.

[3] D. L. Youngs, “Numerical simulation of mixing by Rayleigh-Taylor and Richtmyer-Meshkov instabilities”, *Laser and Particle Beams* **12** 725, 1994.

Spectral modelling of unstably homogeneous stratified turbulence

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Keywords: Rayleigh-Taylor instability, direct numerical simulation, EDQNM

ABSTRACT

We model unconfined homogeneous turbulence with destabilizing background density gradient in the Boussinesq approximation [1]. Starting from initial isotropic turbulence state, the buoyancy force injects energy in the flow leading to a strong growth of kinetic energy, and to anisotropic structures. The corresponding dynamics is difficult to reproduce using one-point turbulent models, so that we introduce an anisotropic two-point statistical model of the eddy-damped quasi-normal markovian (EDQNM) kind [2], that includes buoyancy production. The model is compared to results of direct numerical simulations at various values of initial Froude number and kinetic to potential energy ratios. We show that the characteristic relaxation time for triple correlations in the EDQNM closure has to include an explicit correction due to stratification in order to match numerical simulation results. In that case, the anisotropy of velocity and scalar fields as well as the spectral energy distributions are also in very good agreement with DNS results.

References

[1] O. Soulard, J. Griffond, and B.-J. Gréa, "Large-scale analysis of self-similar unstably stratified homogeneous turbulence, *Phys. Fluids*, **65**, 015110, 2014.

[2] F. S. Godeferd and C. Cambon, "Detailed investigation of energy transfers in homogeneous stratified turbulence, *Phys. Fluids*, **6**, 2084–2100, 1994.

Measurements of gas/shell mix in implosions at the National Ignition Facility using the CD Symcap platform*

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Surrogate implosions play an important role at the National Ignition Facility (NIF) for isolating aspects of the complex physical processes associated with fully integrated ignition experiments. The newly developed CD Symcap platform[1] has been designed to study gas-shell mix in indirectly driven, pure T_2-gas filled CH-shell implosions equipped with 4 μm thick CD layers. This configuration provides a direct nuclear signature of mix as the DT yield (above a characterized D contamination background) is produced by D from the CD layer in the shell, mixing into the T-gas core. The CD layer can be placed at different locations within the CH shell to probe the depth and extent of mix. CD layers placed flush with the gas-shell interface and recessed to up to 8 μm have shown that most of the mix occurs at the inner-shell surface. However at 8 μm recessed, the DT yield remains above background suggesting that plastic from deeper in the shell, injected by ablation front instabilities, may also play an important role. Furthermore, time-gated x-ray images of the hotspot show large brightly-radiating objects traversing through the hotspot around bang-time, which are likely chunks of CH/CD plastic.[2] In addition, an implosion series at increased convergence has begun and the current results will be discussed.

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

[1]Smalyuk et. al., Physical Review Letters **112**, 025002 (2014).
[2]M. A. Barrios et. al., Physics of Plasmas **20**, 072706 (2013).

Measurement of Favre-Averaged Statistics in Buoyant Jets

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Keywords: variable density mixing, buoyant jets, Favre-averaged turbulence statistics

ABSTRACT

Variable density mixing of a heavy fluid jet with lower density ambient fluid in a subsonic wind tunnel was experimentally studied using Particle Image Velocimetry and Planar Laser Induced Fluorescence to simultaneously measure velocity and density fields. Results from two different Atwood numbers, 0.1 (Boussinesq limit) and 0.6 (non-Boussinesq case), reveal that buoyancy is important for most of the turbulent quantities measured. Statistical characteristics of the mixing important for modeling these flows such as the PDFs of density and density gradients, turbulent kinetic energy, Favre averaged Reynolds stress, turbulent mass flux velocity, density-specific volume correlation, and density power spectra were also examined and compared with previous direct numerical simulations. Additionally, a method for directly estimating Reynolds-averaged velocity statistics on a per-pixel basis is extended to Favre-averages, yielding improved accuracy and spatial resolution as compared to traditional post-processing of velocity and density fields.

Effects of Instabilities and Adiabat in NIF experiments

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Keywords: Rayleigh–Taylor and Richtmyer–Meshkov instabilities, inertial confinement fusion, high-energy density physics, turbulent entropy and entropy generation

ABSTRACT

Ignition is required to make thermonuclear (TN) fusion energy a viable alternative energy source. To achieve ignition in inertial confinement fusion (ICF) experiments at the National Ignition Facility (NIF) requires to compress the deuterium-tritium (DT) fuel to a high density and high temperature state and generate a self sustained TN burn on the hot DT spot. In last a few years, a series of ICF experiments have been carried out at NIF including the "low-adiabat" implosion of cryogenic layered DT capsules indirectly driven by a low-foot laser drive pulse (four shocks) and the high-adiabat implosion of cryogenic layered DT capsules indirectly driven by a high-foot laser pulse (three shocks). The capsule performance in the two series of experiments has been significantly different. The neutron yields in the hight-foot shots was enhanced by nearly a factor of 10 from the low-foot shots. Particularly, a record neutron yield ($\sim 9 \times 10^{15}$) has been produced in the high adiabat experiments. In this presentation, we will present our analytical physics model[1] for the thermonuclear ignition criterion and implosion scaling laws derived from fundamental physics principles. We will apply our model to the NIF experiments and demonstrate the essential physics underlying the performance difference between the high foot and the low foot shots. The effects of the instabilities arisen at the interfaces (between ablator and fuel, and between the cold and hot fuel) on the capsule performance and the sensitivity of the capsule performance on the fuel adiabat will be presented. Finally comparisons between our model and the NIF experiments will be given, and a good agreement is obtained.

References

[1] B. Cheng, T.J.T. Kwan, Y.M. Wang and S. Batha, "Scaling laws for ignition at the National Ignition Facility from first principles ", *Phys. Rev. E* **88**, 041101, 2013.

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Detailed 3-D simulations of high-convergence ignition implosion experiments on the National Ignition Facility

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Nearly three dozen high-convergence fusion ignition experiments were conducted on the National Ignition Facility (NIF) as part of the National Ignition Campaign (NIC); however, the NIC concluded in Sept. 2012 without achieving ignition. Moreover, experimental implosion performance was significantly lower in terms of neutron yield than detailed 2-D simulations run to model these experiments on a shot-by-shot basis. These simulations included all of the available target metrology data as well as using x-ray drives adjusted to match the measured implosion characteristics. Since the conclusion of the NIC several effects were identified that could explain the degraded capsule performance and that were absent from previous simulations, in particular larger than anticipated low-mode asymmetries in the radiation drive and possibly greater than expected ablation front instability growth. This talk describes recent 2-D and 3-D simulations of NIC implosions that include these updated effects and show improved agreement with the experimental data. The novel effects entering in fully 3-D simulations that accurately represent the experimental reality will be emphasized.

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The internal structure of stratified Rayleigh–Taylor instability

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Keywords: Rayleigh–Taylor instability, large-eddy simulation,

ABSTRACT

There have been significant advances in recent years in the understanding of the dynamics of Rayleigh–Taylor instability when it occurs at an interface between two otherwise stably stratified layers. Previous work has concentrated on the external dynamics of the flow, specifically on modelling the height of the mixing region that develops at the gravitationally unstable interface $h(t)$ and the final state $\rho(z)$, but not the internal details of the developing mixing zone. Here we explore the internal dynamics and how they differ from those of the classical problem. An implicit large eddy simulation (which uses numerical diffusion as a proxy for physical viscous diffusion) is used to model the instability and the resulting turbulent flow.

This work was funded by an EPSRC CASE studentship in conjunction with AWE.

High-Energy-Density Supersonic Counterflowing Shear Experiments on OMEGA and the NIF

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Keywords: Shear instability, compressible mixing layers, Reynolds-averaged turbulence modeling, inertial confinement fusion, high-energy density physics

ABSTRACT

A counterflowing shear experiment originally fielded at the Omega Laser Facility and currently being implemented on the National Ignition Facility (NIF) has demonstrated shear-induced mixing in a high-energy-density setting. The shear experiment launches 100+ km/s shocks into each side of a foam-filled shock tube bisected by an Al tracer plate. When the shocks cross at the tube center, a region of intense shear is created (around 150 km/s velocity difference from one side of the plate to the other). As the tracer layer becomes unstable it mixes with the surrounding foam and expands into the tube volume. Radiography recording the spreading of the mixing layer has been interpreted in simulations using the LANL hydrocode RAGE and in the context of RANS models. Analysis suggests that the experiment features qualities, such as strong thermodynamics-turbulence coupling, of special interest to the compressible and HED settings.

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Richtmyer-Meshkov instability shock tube experiments with a quantified, three-dimensional, random, initial perturbation

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Keywords: Richtmyer-Meshkov instability, shock tube experiments

A vertical shock tube is used for experiments on the Richtmyer-Meshkov instability with a three-dimensional, random initial perturbation. A membrane-less interface is formed by opposed gas flows in which the light and heavy gases enter the shock tube from the top and from the bottom of the driven section. An air/SF_6 gas combination is used and an $M = 1.2$ incident shock wave impulsively accelerates the interface. Oscillating two loudspeakers mounted in the shock tube wall creates an initial perturbation in the form of small, random, three-dimensional surface waves on the interface. Planar Mie scattering is used to visualize the flow using a laser sheet to illuminate smoke particles seeded in the air. Image sequences are captured using two high-speed video cameras. New experiments are presented in which the full three-dimensional initial perturbation is recorded immediately prior to shock interaction. A galvanometer system redirects the laser sheet to 29 locations with one image captured per location, producing a set of images through the test section volume. The resulting volumetric image is analyzed for spectral energy content and compared with the spectra evolving from the instability resulting from this perturbation.

Turbulent Mixing at the Microscale

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With the definitive agreement between simulation and experiment for the mixing zone boundaries in idealized flows (the famous "α" problem), attention shifts to two further areas: (a) effects of complex physics on the mixing properties (as in ICF) on mix and (b) the microphysics of mixing, as is needed for prediction of reaction rates.

Our first main result is the nonuniqueness of infinite Reynolds number flows and of LES simulations, with a transparent physics and mathematics based understanding. Our second main result is a novel notion of stochastic convergence, well suited to LES, with mathematical and numerical properties including convergence of cumulative distribution functions. Relations to problems (a) and (b) are indicated.

The effect of multiple shocks on ejecta production

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Abstract

Richtmyer-Meshkov instability can result in ejecta from shocked materials. In some cases multiple shocks can interact with the surface producing ejecta. In such cases the initial surface features are deformed by the first shock. Simple theories [1] can predict ejecta production, but they rely on knowing characteristics of the surface features present. For multiple shocks the surface features have changed under the influence of previous shocks and it is not clear how to apply simple theories to estimate the ejecta production. Multiphase equations of state are used to model the surface of a material under the influence of multiple shocks. An attempt is made to characterise the relationship between shock strengths, the resulting phase of the material, and ejecta production.

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Three-Dimensional Simulation Strategy to Determine the Effects of Turbulent Mixing on Inertial-Confinement-Fusion Capsule Performance

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Keywords: inertial confinement fusion, combined instabilities, large-eddy simulation

ABSTRACT

We present and justify an effective strategy for performing 3D inertial confinement fusion (ICF) capsule simulations [1]. We have evaluated a frequently used strategy in which 2D simulations are rotated to 3D once sufficient relevant 2D flow physics has been captured and fine resolution requirements can be restricted to relatively small regions. This addresses situations typical of ICF capsules which are otherwise prohibitively intensive computationally. We tested this approach for our previously reported fully-3D simulations of laser–driven reshock experiments [2] where we can use the available 3D data as reference. Our studies indicate that simulations that begin as purely 2D lead to significant underprediction of mixing and turbulent kinetic energy production at later time when compared to the fully 3D simulations. If, however, additional suitable non-uniform perturbations are applied at the time of rotation to 3D, we show that one can obtain good agreement with the purely 3D simulation data, as measured by vorticity distributions as well as integrated mixing and turbulent kinetic energy measurements. Next, we present results of simulations of a simple OMEGA–type ICF capsule using the developed strategy. These simulations are in good agreement with available experimental data and suggest that the dominant mechanism for yield degradation in ICF implosions is hydrodynamic instability growth seeded by long-wavelength surface defects, which has the effect of displacing fuel from the hot spot (see Fig. 1). This effect is compounded by drive asymmetries and amplified by repeated shock interactions with an increasingly distorted shell, which results in further yield reduction. Our simulations are performed with and without drive asymmetries in order to compare the importance of these effects to those of surface defects; our simulations indicate that long–wavelength surface defects degrade yield by approximately 60% and short–wavelength drive asymmetry degrades yield by a further 30%.

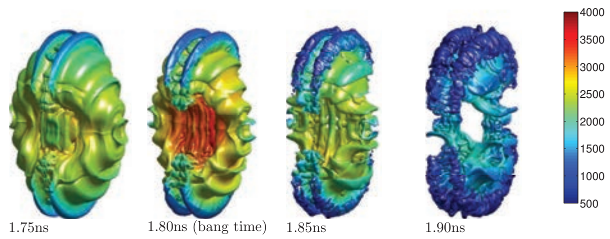

Figure 1: Fuel mass concentration $c_{fuel} = 0.1$ isosurface colored with T_{ion} (eV) [1].

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A Dynamical Systems Approach to the Alpha Problem for Rayleigh-Taylor

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June 18, 2014

The turbulent Rayleigh-Taylor layer is observed to exhibit self similar growth which scales as $h = \alpha \mathrm{At} g t^2$. This can be theoretically derived using bubble dynamics, flux balances (Cook et al., 2004), similarity theory (Ristorcelli and Clark, 2004), or simple turbulence modeling. In all these approaches, however, the value of α must be determined empirically. Furthermore, it is not clear from the theory whether α is universal. In fact, reported experimental and DNS values for α exhibit a wide variation, as documented by Dimonte et al. (2004).

The current work demonstrates a new tool for investigating the transient behavior. Starting with an moment closure model and applying an integral method is shown to result in a set of ordinary differential equations which can be viewed as a low-order model of the turbulence as it evolves towards a self-similar state. Applying the tools of dynamical systems we can examine the possible trajectories of the system in state space. Comparing these to trajectories from experiment and DNS show quite good agreement. This suggests that the observed variation in α is due to lack of similarity. It also demonstrates that the RANS models can capture the approach to self-similarity, and provides new metrics for calibrating and validating turbulence models.

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Rayleigh-Taylor instability driven by time-varying acceleration

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Abstract

We have investigated, using theory and numerical simulations the asymptotic nonlinear behavior of the Rayleigh-Taylor (RT) hydrodynamic instability driven by a variable acceleration of the form $g(t) \sim t^n$, where n is an integer. The nonlinear models of Layzer[1] and Goncharov[2] based on potential flow theory have been extended to describe temporally varying acceleration $\sim gt^n$. The model was validated by detailed 3D numerical simulations using the incompressible flow solver MOBILE[3]. For $n > -1$, we expect the analytical model and the simulations to produce nonlinear growth consistent with a RT mixing layer.In contrast for $n < -2$, the acceleration history may yield a decaying field similar to a shock driven Richtmyer-Meshkov(R-M) instability.The asymptotic growth rate and curvature of the tip of the interface are predicted by the models and tend to a finite saturation value. Such time-dependent acceleration profiles are representative of flow conditions in several applications including Inertial Confinement Fusion, type Ia supernova, and several RT/RM experiments.

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Comparison of two-equation and multi-fluid turbulence models for Rayleigh-Taylor and Richtmyer-Meshkov mixing[1]

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This paper concerns comparison engineering turbulence models for Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) mixing. We present a single-fluid based improved version of the original K-L model (Dimonte and Tipton, 2006) and compare its results with Youngs' multi-fluid model2 (Youngs, 1989) for RT and RM flows. The accuracy of the models is examined for different interface pressures and specific heat ratios, and the turbulence model results are compared with high-order Implicit Large Eddy Simulations (ILES) (Hahn at al., 2011; Youngs, 2013). It is shown that the original version of the K-L model requires modifications in order to provide comparable results to the multi-fluid model. The modifications concern the addition of an enthalpy diffusion term to the energy equation; the formulation of the source term in the turbulent kinetic energy equation; and the calculation of the local Atwood number. The proposed modifications significantly improve the results of the K-L model, which are also in good agreement with the multi-fluid model and LES with respect to the self-similar mixing width; peak turbulent kinetic energy growth rate, as well as volume fraction and turbulent kinetic energy profiles. The paper also discusses the performance of the models with respect to post reshock region and demixing.

Indicative results are presented in Figure 1 for the RT case with density ratio 20:1 (Youngs, 2013). The RT results clearly show that the proposed modifications of the K-L model give results comparable to Youngs' TF model as well as in good agreement with ILES. Figures 2 to 3 show results for the inverse chevron RM case for which ILES data have been published in (Hahn et al., 2011). The proposed modifications significantly improve the K-L model's accuracy compared to the original model, and result in good agreement with ILES.

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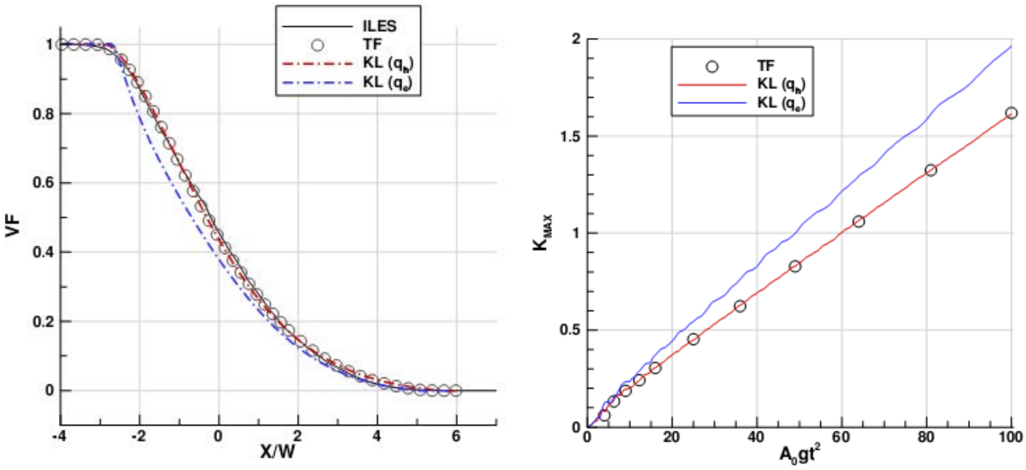

Figure 1: Volume fraction (left) and maximum turbulent kinetic energy for RT mixing with density ratio 20:1. Comparison of the two-fluid model (TF), original K-L (blue line), improved K-L (red line) and ILES data.

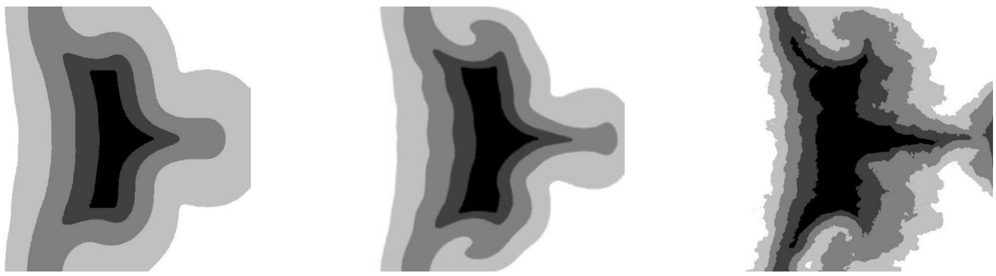

Figure 2: Volume fraction contours for the 2D inverse chevron RM case; comparison of the original K-L (left), improved K-L (middle), and ILES (right).

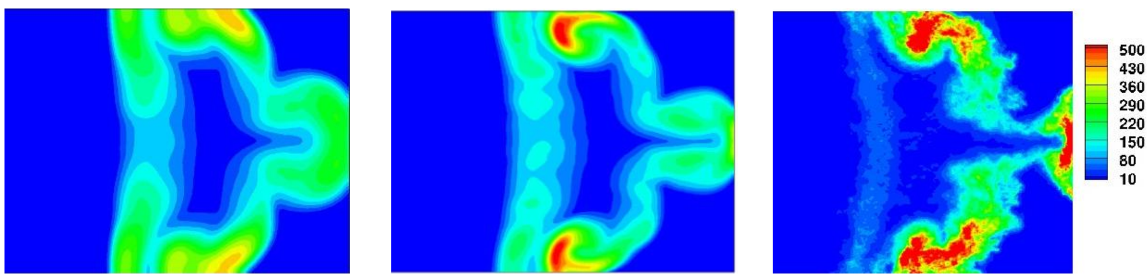

Figure 3: Maximum turbulent kinetic energy for the inverse chevron RM case; comparison of the original K-L (left), improved K-L (middle) and ILES.

Towards Adaptive Unstructured ALE methods for turbulent flows

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Keywords: Rayleigh–Taylor instability, modelling methods, direct numerical simulation, large-eddy simulation

ABSTRACT

ALE methods for multi-fluid turbulence have been in active development for 20 years, in particular for ICF applications where there are rapid mean flows with which turbulence is advected. However, even in the moving reference frame, numerical truncation error is sensitive to relative velocities between the flow and the mesh and in Rayleigh-Taylor-driven flows we rely on approximate isotropy within the mixing region to reduce the impact of such errors on our predictions. Adaptive ALE methods offer a more general framework for controlling numerical errors and the rate of associated energy dissipation. In the particular case of ILES, the filter-scale may be locally adapted in response to changes in turbulent integral scales, thus preserving the inertial scaling relationships observed in real flows. These important features broaden the applicability of ILES as well as offering flexibility for more conventional LES modelling. This paper will present ideas first mooted by [1] and developed for applications in Rayleigh-Taylor instability by [2], as well covering some more recent extensions and validation.

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A Difference Scheme for Lagrangian Hydrodynamics in Two-Dimensional Cylindrical Geometry

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Abstract: For a staggered grid, Lagrangian, hydrodynamics scheme in which pressure, density, and specific internal energy are centered in the zones and coordinate position and velocity are defined on the points, the control volume scheme [1] is widely used. For the usual control volume scheme, Caramana et al. [2] give a description that spherical symmetry in cylindrical geometry is not preserved with the control volume scheme because the areas along the angular direction are not equal even when the angles between the radial lines are equal.

We reexamine the usual difference method with the control volume scheme [1] and find that the problem comes from the assumption of pressure on a control volume element which leads to a wrong result of the net force on a node volume. Furthermore, we propose a new difference form for difference calculations of the equations of motion. The method basically considers integrating pressure over the surfaces of those masses to conserve momentum transfer between vertices. The new method is proved to preserve spherical symmetry, and some numerical examples are presented.

Keywords: Lagrangian hydrodynamics, symmetry, two dimensional, cylindrical geometry, difference scheme.

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Generalized Cahn-Hilliard Navier-Stokes equations for numerical simulations of flows with immiscible fluids

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Abstract: By using a multi-component generalization of Landau's near-equilibrium approach and the second-law of thermodynamics, we have developed a set of physically consistent multi-component generalized compressible Cahn-Hilliard Navier-Stokes equations (CHNSE), with arbitrary thermodynamic properties, which can describe not only flows with pure miscible and pure immiscible materials but also complex flows in which both miscible and immiscible effects may coexist. The formulation naturally handles topological changes at the interface. For pure miscible fluids, under certain simplifying assumptions, the classical form of the equations, such as the well-known Stefan-Maxwell relation, can be recovered. Furthermore, for the first time, the incompressible limit of the newly developed CHNSE is rigorously derived (with full consistency between species and energy equations) and applied to the immiscible Rayleigh-Taylor instability problem. The results compare well with linear stability theory and available experimental data.

DNS and LIA analysis of the shock-turbulence interaction

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Keywords: direct numerical simulation, shock waves, compressible turbulence.

ABSTRACT

The interaction between isotropic turbulence and a normal shock wave is studied using Direct Numerical Simulations (DNS), with all flow scales (including the shock width) accurately solved, and the Linear Interaction Analysis (LIA). The turbulence quantities from DNS converge to the LIA solutions as the turbulent Mach number, M_t, becomes small, even at low upstream Reynolds numbers. As the flow approaches the LIA limit, the Reynolds stress amplification retains a separate shock Mach number, M_s, dependency and does not collapse onto a single parameter as proposed in recent studies. This reconciles a long time open question about the role of LIA and establishes it as a reliable prediction tool for low M_t turbulence-shock interaction problems. LIA is extended to investigate detailed turbulence physics. The interaction is first studied using DNS data with $M_s = 1.1 \div 2.2$. Then the extended LIA relations are used to show consistency with the DNS results and study the interaction at high M_s, where the resolution requirements make DNS studies unfeasible, even on the largest supercomputers.

3D numerical analysis of the evolution of Richtmyer-Meshkov instability under re-shock conditions

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Keywords: Richtmyer–Meshkov instability, direct numerical simulations, shock tube laboratory experiments, re-shock experiments

ABSTRACT

The Leinov et al. [1] re-shock experiments, in which the re-shock arrival time was changed by varying the end wall distance and the shock Mach number was changed by varying the incident shock wave Mach number, were analyzed by 3D direct numerical simulations. Varying the initial 3D conditions in the simulations, it was found that a good agreement with the experimental results was achieved only when a specific broadband initial spectra was used. Assuming this "best fit" initial condition, the TMZ evolution was shown to approach a self-similar behavior of the bubble front. The TMZ power law at the first and second (re-shock) shock was deducted from the experimental and numerical data and compared with the results of the bubble competition model [2].

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Effect of Transverse Magnetic field on bubble growth induced by Rayleigh-Taylor Instability in viscous fluids

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Keywords: Rayleigh-Taylor instability, viscosity, magnetic field

ABSTRACT

The present paper is addressed to the problem of the time development of the nonlinear interfacial structure induced by Rayleigh-Taylor Instability (RTI) in the presence of transverse magnetic field parallel to the surface of separation of two viscous fluids. Here, we derive a set of nonlinear equations to describe the bubble growth using Layzer's potential flow model. In this model, the wave vector is assumed to lie in the same plane and perpendicular to the magnetic field. With such a geometry, there is no effect of the magnetic field in the classical [1] linear approximation. However, in nonlinear case, RTI can stabilize/destabilize or can show nonlinear oscillation in presence of magnetic field depending on the action of hydrodynamic and magnetic pressure [2]. Again, the effect of viscosity on RTI shows a significant importance for increasing wave number k as μk^2, where μ is the kinematic coefficient of viscosity. However, in presence of transverse magnetic field in viscous fluids, the bubble growth rate will be suppressed. The dissipative effect due to viscosity also increases with increasing k and shows a damped oscillation of the interface. The oscillation of the interface can be controlled by the viscosity of fluids and magnetic pressure inside the conducting fluids. Moreover, frequency of damped oscillation increases with increasing of Alfven velocity in both fluids. Again, the bubble growth will be saturated if we increase the viscosity of the fluids keeping unchanged Alfven velocity.

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Effects of Initial Conditions on the Evolution of Richtmyer-Meshkov Instabilities

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Keywords: Richtmyer–Meshkov instability, Turbulence.

ABSTRACT

Given the necessary Reynolds number and evolution time, a Richtmyer-Meshkov instability (RMI) might experience a mixing transition [1]. Some studies over broadband initial conditions suggest that the emergence of a classical Kolmogorov $\kappa^{-5/3}$ inertial range, in an RMI that has experienced a mixing transition, is independent on the initial conditions. Since observations of this kind have not been replicated for single- or multi-mode perturbed interfaces, it is still premature to consider that the emergence of a Kolmogorov inertial range in RMI after the mixing transition is universal. To shed light on this subject, we conducted high-resolution simultaneous PIV/PLIF measurements on a multi-mode perturbed interface between air and SF_6. Since our data are also intended for code validation, we used statistically stationary initial conditions, measuring the velocity and density fields both instantaneously and in an averaged sense. Based on our experimental data, we estimated a number of relevant turbulence statistics for different stages of the evolution of the shocked interface.

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LLNL-JRNL-636376

Solution to Rayleigh-Taylor instabilities: bubbles, spikes, and their scalings

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When a fluid pushes on and accelerates a heavier fluid small perturbations at their interface grow with time and lead to turbulent mixing. The same instability, known as the Rayleigh-Taylor instability, operates when a heavy fluid is supported by a lighter fluid in a gravitational field. It has a particularly deleterious effect on initial-confinement-fusion implosions and is known to operate over 18 orders of magnitude in dimension. We propose analytic expressions for the bubble and spike amplitudes and mixing widths in the linear, nonlinear, and turbulent regimes. They cover arbitrary density ratios and accelerations that are constant or changing relatively slowly with time. We discuss their scalings and compare them with simulations and experiments.

Miscible and immiscible experiments on the Rayleigh-Taylor instability using planar laser induced fluorescence visualization

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Keywords: Rayleigh–Taylor instability

ABSTRACT

Incompressible Rayleigh-Taylor instability experiments are presented in which two stratified liquids having Atwood number of 0.2 are accelerated in a vertical linear induction motor driven drop tower. A test sled having only vertical freedom of motion contains the experimental tank and visualization equipment. The sled is positioned at the top of the tower within the linear induction motors and accelerated downward causing the initially stable interface to be unstable and allowing the Rayleigh-Taylor instability to develop. Forced and unforced experiments are conducted using both immiscible and miscible liquid combinations. The interface is visualized using a 445nm laser light source that illuminates a fluorescent dye mixed in one of the fluids. The laser beam is synchronously swept across the fluorescent fluid, at the frame rate of the camera, exposing a single plane of the interface and allowing for the measurement of spike and bubble growth. Comparisons between miscible and immiscible mixing layer growth rates are made from the resulting interface concentration profiles.

Multicomponent Reynolds-Averaged Navier–Stokes Simulations of Reshocked Richtmyer–Meshkov Instability and Turbulent Mixing: Mach Number and Atwood Number Effects

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Keywords: Richtmyer–Meshkov instability, reshock, Reynolds-averaged Navier–Stokes modeling, multicomponent flow

ABSTRACT

Reshocked Richtmyer–Meshkov turbulent mixing of gases with various large shock Mach numbers from experiments previously performed in the horizontal double diaphragm shock tube at the University of Provence is simulated using a third-order weighted essentially nonoscillatory implementation of a new K–ϵ multicomponent Reynolds-averaged Navier–Stokes model. The following gas combinations are considered, as summarized in Valerio et al. [*Physics of Fluids* **11**, 214 (1999)]: CO_2/He, CO_2/Ar, and CO_2/Kr (with $At = -0.73$, -0.05, and 0.3, respectively) and incident shock Mach numbers $Ma = 2.4$, 3.1, and 4.5 for each gas pair. The evolution of the mixing layer widths is shown to be in good agreement with the experimental data. Budgets of the turbulent transport equations are used to elucidate the mechanisms contributing to turbulent mixing in large Mach number reshocked Richtmyer–Meshkov instability. These results are contrasted with those from previous modeling of smaller Mach number experiments by Morán-López and Schilling [*High Energy Density Physics* **9**, 112 (2013); *Shock Waves* **24**, 325 (2014)] to identify the physical effects which require accurate modeling, including mean and turbulent enthalpy diffusion, pressure–dilatation, and dilatation dissipation.

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Large-Eddy and Unsteady RANS Simulations of a Shock-Accelerated Heavy Gas Cylinder

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Keywords: Richtmyer–Meshkov instability, large-eddy simulation, Reynolds-averaged turbulence modeling, turbulent mixing

ABSTRACT

Two-dimensional numerical simulations of the so-called "shock-jet" test problem for Richtmyer-Meshkov instability (RMI) are conducted using both large-eddy simulation (LES) and unsteady Reynolds-averaged Navier-Stokes (URANS) approaches in an arbitrary Lagrangian/Eulerian (ALE) hydrodynamics code. Turbulence statistics are extracted from LES by running an ensemble of simulations with multi-mode perturbations to the initial conditions. Detailed grid convergence studies are conducted, and LES results are found to agree well with both experiment and high-order simulations conducted by Shankar, Kawai, and Lele [1]. URANS results using a k-L approach are found to be highly sensitive to the initialization of L and to the time at which L becomes resolved on the computational mesh. It is observed that a gradient diffusion closure for turbulent species flux is a poor approximation at early time, and a new closure based on the mass-flux velocity is proposed for low-Reynolds-number mixing.

Figure 1: Contours of heavy gas mass fraction obtained with LES. Time increasing from left to right.

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Experiments on the expansion wave driven Rayleigh-Taylor instability

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Keywords: Rayleigh–Taylor instability, Richtmyer–Meshkov instability

ABSTRACT

Experiments are presented in which a diffuse interface between two gases is accelerated to become Rayleigh-Taylor unstable. The initially flat interface is generated by the opposing flow of two test gases at matched volumetric flow rates exiting through small holes in the test section. This interface is then accelerated by an expansion wave which is generated by the rupturing of a diaphragm separating the heavy gas from a vacuum tank evacuated to 0.01atm. The expansion wave generates a large (of order 1000 g), but non-constant, acceleration acting on the interface causing the Rayleigh-Taylor instability to develop.

Planar Mie scattering is employed using a planar laser sheet generated at the top of the apparatus, which illuminates smoke particles seeded in the heavy gas. The scattered light is then imaged using a CMOS cameras operating at 12kHz. Experiments are presented in which perturbations are introduced either by vertically or horizontally oscillating the fluid interface to generate perturbations. Instability amplitude and growth rates are extracted and will be presented and compared with models and simulations.

On the role of a pre-existing turbulent field in the development of a mixing region in the presence of an acceleration field

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The Rayleigh-Taylor (RT) instability may occur in high-energy-density environments, where interfaces are accelerated by shocks or blast waves. Initial perturbations at a RT unstable interface grow due to the instability, and may evolve to a turbulent mixing region. The mixing region growth is of particular interest in inertial confinement fusion as penetration of the cold outer-layer of the fuel to the hot spot region at the center of the capsule due to hydrodynamic instabilities is one of the main engineering challenges in achieving an efficient fusion. In this work, we are interested in investigating the role of a pre-existing turbulent field in the development of a mixing region between two fluids of different densities, subject to an acceleration field. We consider three different configurations: RT stable, RT unstable configurations and zero acceleration. A high-order accurate minimally dissipative kinetic-energy preserving is used to perform current direct numerical simulations. Our results show that initially the acceleration field has negligible effect on the growth, which is governed by turbulent diffusion. After this initial period, the growth is arrested in the RT stable set-up due to buoyancy. In the absence of an acceleration field, the mixing region becomes self-similar, and the growth rate decreases as turbulence decays. Different arguments are proposed to describe the observed growth. In the RT unstable set-up, baroclinic vorticity is generated, which provides energy for the initially decaying field. The largest growth is achieved for the RT unstable case as expected, but a quadratic growth, expected for the classical RT set-up, is not achieved. In addition to the mixing region growth analysis, we studied flow isotropy at different scales and small-scale intermittency. Our results confirm that an acceleration field leads to anisotropy at the Taylor microscale. In the absence of such an acceleration field, a high density ratio is required to observe anisotropy at the Taylor microscale in the mixing region. It is shown that an acceleration field results in higher small-scale intermittency particularly in the direction of the acceleration. The mass fraction field is found more intermittent than the velocity field.

Modifying Shock-Driven Turbulent Mixing Through the Spectral Content of Initial Interface Perturbations

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Keywords: Richtmyer–Meshkov instability, compressible mixing layers, large-eddy simulation

ABSTRACT

The mixing of materials due to the Richtmeyer-Meshkov instability and the ensuing turbulent behavior is of intense interest in a variety of physical systems including inertial confinement fusion, combustion, and the final stages of stellar evolution. Extensive numerical and laboratory studies of shock-driven mixing have demonstrated the rich behavior associated with the onset of turbulence due to the shocks. Here we report on progress in understanding shock-driven mixing at interfaces between fluids of differing densities through 3D numerical simulations using the RAGE code[1]. Our simulations employ an ILES framework in which only numerical diffusion is considered through highly-stable numerical operators [2]. We consider a shock tube configuration with a band of high density gas (SF_6) embedded in low density gas (air). Shocks with Mach numbers of 1.26 and 1.5 are passed through SF_6 bands of varying thickness, resulting in transitional turbulence due to the Richtmyer-Meshkov instability. The system is followed as a rarefaction wave and a reflected secondary shock from the back wall passes through the SF_6 band. We apply a variety of initial perturbations to the initial interfaces between the two fluids in which the physical standard deviation and the spectral slope of the perturbations are held constant, but the number of modes initially present is varied. By thus decreasing the density of initial spectral modes of the interface, we find that we can achieve substantially longer ballistic growth of the interface perturbations and as much as 50% less total mixing at late times. This has direct implications for the treatment of interfaces in both 3D and reduced dimensionality models.

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Large Eddy Simulation Requirements for the Richtmyer-Meshkov Instability

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Keywords: Richtmyer–Meshkov instability, compressible mixing layers, large-eddy simulation

ABSTRACT

The shock induced mixing of two gases separated by a perturbed interface is investigated through Large Eddy Simulation and Direct Numerical Simulation. At coarse resolutions, the effects of numerical dissipation outweigh those of physical dissipation on the entrainment and mixing process of the Richtmyer-Meshkov Instability. Decreasing the Reynolds of the flow while increasing the grid resolution largely mitigates the relative numerical dissipation but is often unachievable for realistic flows. A model for an effective viscosity is proposed which allows for an a posteriori analysis of the simulation data that is agnostic to the LES model, numerics and the physical Reynolds number of the simulation. An analogous approximation for an effective species diffusivity is also presented. This framework can then be used to estimate the effective Reynolds number and Schmidt number of future simulations and elucidate the impact of numerical dissipation on the mixing process for an arbitrary numerical method.

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Experimental acceleration histories in a shocked multiphase flow.

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Keywords: shocked multiphase flow, unsteady forces, unsteady drag, acceleration history

ABSTRACT

The horizontal shock tube at Los Alamos, used for over 20 years to study shock-driven mixing between different density gases, has been retrofitted with a new particle seeding system, test section, and diaphragmless driver to investigate the unsteady forces on particles dispersed in air as they are accelerated by a shock wave. A Particle Image Velocimetry/Accelerometry (PIVA) system has been implemented at the facility using eight laser pulses and an eight-frame high speed camera, while a shadowgraphy system is used simultaneously to optically measure shock position. Presented are the acceleration histories of individual solid particles when impacted by a Mach 1.3 shock wave. In these experiments, a parameter space is explored with particle diameter ranging between 2 and 90 μm and particle density between 15 and 2600 kg/m^3. Measurements at this facility will be used to develop and validate empirical models implemented in numerical codes.

Validating Richtmyer–Meshkov and Rayleigh–Taylor Growth in National Ignition Facility Implosions

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Keywords: Rayleigh–Taylor instability, Richtmyer–Meshkov instability, inertial confinement fusion, simulation validation

ABSTRACT

The hydrodynamic growth of capsule imperfections can threaten the success of inertial confinement fusion implosions. Therefore, it is important to design implosions that are robust to hydrodynamic instabilities. However, the numerical simulation of interacting Rayleigh–Taylor and Richtmyer–Meshkov growth in these implosions is sensitive to modeling uncertainties such as radiation drive and material equations of state, the effects of which are especially apparent at high mode number (small perturbation wavelength) and high convergence ratio (small capsule radius). A series of validation experiments were conducted at the National Ignition Facility to explore the acceleration phase of spherically converging ignition–relevant implosions. These experiments on the Hydro–Growth Radiography platform [1] measured the growth of pre–imposed imperfections up to Legendre mode 160 and a convergence ratio of greater than four using two different laser drives: a "low–foot" drive used during the National Ignition Campaign [2] and a higher adiabat "high–foot" drive [3]. We will discuss these experiments, how their results compare to numerical simulations and analytic theories of hydrodynamic growth, and their implications for the modeling of future designs.

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LLNL-ABS-655219

Simulations of CD Mix Capsule Experiments

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Keywords: Combined instabilities, compressible mixing layers, large-eddy simulation, Reynolds-averaged turbulence modeling, ICF, high-energy density physics, experiment

ABSTRACT

The CD Mix campaign is a recent series of experiments to measure atomic ablator-gas mix in capsule implosions on the National Ignition Facility [1]. Plastic capsules containing deuterated plastic (CD) layers were filled with Tritium gas. As the reactants are initially separated, the DT fusion yield provides a direct measure of atomic mix in the outer part of the core. By varying the depth of the CD layer, a measure of mix penetration length can be made. We will describe the 2D ARES Arbitrary Lagrangian-Eulerian Radiation Hydrodynamics simulations of these experiments. Imposed surface roughness perturbations are adjusted to match the TT neutron yield from the core of the implosion. To match the DT neutron yield and temperature, two different dynamic mix models are applied: the K-L Reynolds Averaged Navier-Stokes model [2], and a multicomponent Navier-Stokes model. We compare these models and assess their ability to capture the dependence of DT yield on the recession depth of the CD layer. We will discuss the modeling methodologies as well as future experiments to further constrain the mix models.

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LLNL-ABS-654297

Simulation of High Atwood Reshocked Richtmyer–Meshkov

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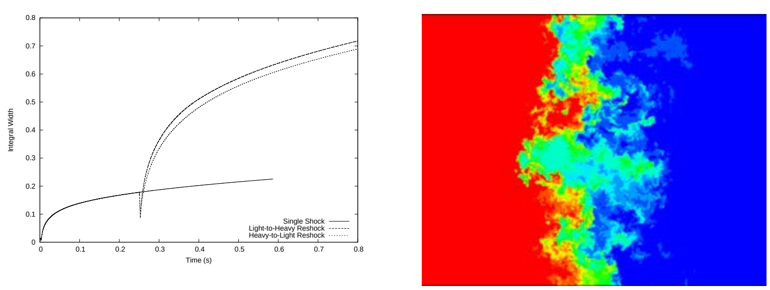
ABSTRACT

We present ILES simulations of high Atwood ($At \geq 0.9$) reshocked Richtmyer–Meshkov instability at high resolution (512 x 512 x 860) with a multimode initial perturbation.

Differences in flow physics as a function of shock direction and Atwood number are investigated. Two initial conditions are used, first shocks from light-to-heavy and heavy-to-light. Once self-similarity is achieved, each case is independently reshocked from light-to-heavy and heavy-to-light, giving four reshock simulations.

Results are compared with empirical solutions for reshock (e.g. [2]), previous high Atwood RMI simulations (e.g. [1]) and benchmark simulations at $At = 0.5$.

Sample results for the integral width showing the effect of reshock direction are shown in Fig. 1a whilst a typical density profile is shown in Fig. 1b.



(a) Integral Width

(b) Density Profile

Figure 1: Sample Results

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The Rayleigh-Taylor Instability driven by an accel-decel-accel profile

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We describe simulations of the Rayleigh-Taylor (RT) instability driven by a complex acceleration history, g(t), with initially destabilizing acceleration, $g > 0$, an intermediate stage of stabilizing deceleration, $g < 0$, and subsequent destabilizing acceleration, $g > 0$. Initial perturbations with both single mode and multimode waveforms were considered. In the single-mode case, we observe a phase inversion during the acceleration reversal from $g > 0$ to $g < 0$. If the zero-crossing of g(t) occurs once the instability growth has reached nonlinear saturation, then rising bubbles and falling spikes reverse direction and collide, causing small-scale structures to emerge and enhancing molecular mixing. For multi-mode perturbations, bubbles and spikes collide during phase inversion, though in this case the interfacial region is turbulent, and undergoes a period of enhanced structural breakdown. This is accompanied by a rapid increase in the rate of molecular mixing, and increasing isotropy within the region. During the final stage of $g > 0$ acceleration, self-similar RT mixing re-emerges, together with a return to anisotropy. We track several turbulent statistical quantities through this complex evolution, which we present as a resource for the validation and refinement of turbulent mix models.

Figure: Volume fraction contours in the horizontal plane at early, intermediate (deceleration) and late-times (reacceleration).

Simultaneous Concentration and Velocity Field Measurements in a Shock-accelerated Mixing Layer

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A novel technique to obtain simultaneous velocity and concentration measurements is applied to the Richtmyer-Meshkov instability. After acceleration by a Mach 2.2 shock wave, the interface between the two gases develops into a turbulent mixing layer. A time-separated pair of acetone planar laser-induced fluorescence images are processed to yield concentration (Fig. 1a,b) and, through application of the Advection-Corrected Correlation Image Velocimetry (ACCIV) technique, velocity fields (Fig. 1c,d). This is the first application of this technique to shock-accelerated flows. We show that, when applied to numerical simulations, this technique reproduces the velocity field to a similar quality as particle image velocimetry. When applied to the turbulent mixing layer of the experiments, information about the Reynolds number and anisotropy of the flow is obtained.

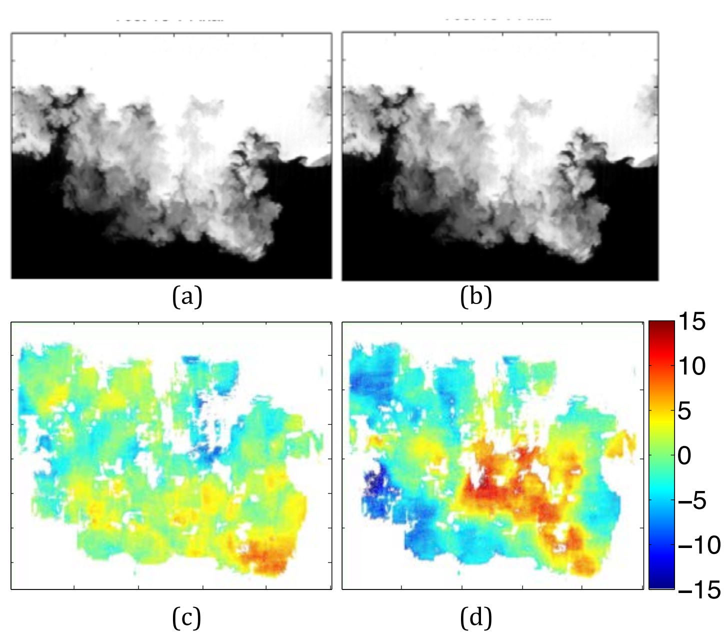

Figure 1: (a,b) Experimental image pair, with inter-frame time Δt=30 μs, corrected to show relative acetone concentration. It is this images pair that is used as input to the ACCIV algorithm. (c,d) ACCIV velocity field results, in m/s, for the (c) transverse (d) streamwise directions.

Shock-Driven Variable-Density Turbulence: New Insights

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Keywords: Richtmyer–Meshkov instability, Kelvin–Helmholtz instability, combined instabilities, reshock, Planar Laser-Induced Fluorescence, Particle Image Velocimetry

ABSTRACT

Results are presented from a newly-constructed inclined shock tube facility which was used to study the coupled Richtmyer-Meshkov instability and Kelvin-Helmholtz instability before and after reshock. This study focuses on the effect of multiple initial conditions, which include two Attwood numbers (0.23 and 0.67), two Mach numbers (1.55 and 2.01), and two inclination angles (60° and 80°). Mie scattering images of the interface development were acquired to track mixing width (see Fig. 1). Particle image velocimetry measurements were ensemble averaged over ten instantaneous realizations, which were used to determine circulation deposition as well as turbulent stresses and the cross correlation ($\overline{u'v'}$) across the mixing width. Furthermore, energy spectra were obtained for three stages of development before and after reshock. The most developed case exhibited the beginning of an inertial subrange after reshock, which may indicate a turbulent state has been reached. High-resolution planar laser-induced fluorescence was employed to obtain full-field density statistics. The density field was quantified with the density p.d.f. across the mixing width.

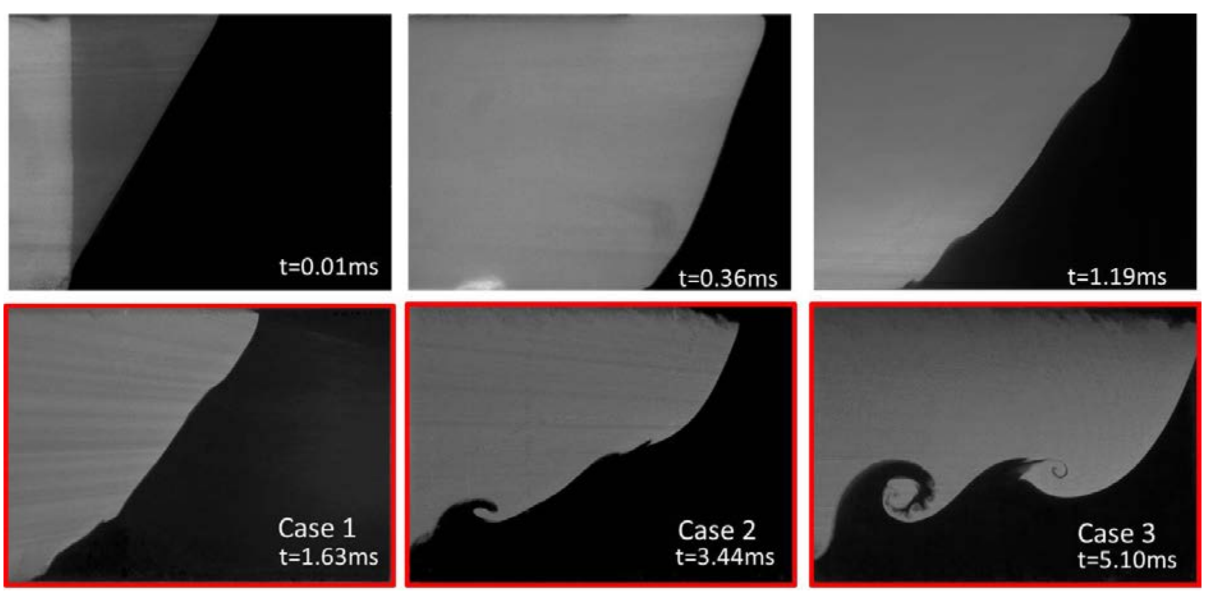

Figure 1: Initial shock development of inclined interface RMI for Mach 1.55, Atwood 0.23, and Angle of inclination 60°.

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Some exact statistical results for binary mixing and reaction in variable density turbulence

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Abstract

We report a number of exact statistical results on binary active scalar mixing and reaction in variable density turbulence. The results are relevant to isobaric isothermal material mixing, isobaric thermal mixing and turbulent combustion for which a progress variable is used. We derive expressions relating various second order moments of the mass fraction, specific volume and density fields. We highlight the central role of the density specific volume covariance $\langle \rho v \rangle$ as a measure of the difference between Favre and Reynolds means and as a key quantity with considerable dynamical significance linking several second order statistics. For laboratory experiments we have developed exact relations between the Reynolds scalar variance $\langle c^2 \rangle$ its Favre analog $\langle \rho^* c''^2 \rangle$, and various second moments including $\langle \rho v \rangle$. We assume a binary one step reaction to assess the mixing state. The mean reaction rate in variable density turbulent mixing can be expressed, in closed form, using the first order Favre mean variables and the Reynolds averaged density variance, $\langle \rho^2 \rangle$. The normalized density variance, $\langle \rho^2 \rangle$ is the mix metric analogous to the normalized mass faction variance $\langle y_1^2 \rangle$ in constant density turbulence. The use of the normalized Favre variance of the mass fraction, $\langle \rho^* c''^2 \rangle$, as a mix metric is not theoretically justified. We document a novel derivation of an expression for $\langle \rho^2 \rangle$ in terms of a rational function of $\langle \rho v \rangle$ that avoids recourse to Taylor series that are slow to converge for large density ratios. We have derived exact results relating several other second and third order moments and see many relations between odd and even order moments demonstrating a natural and inherent skewness in the mixing process of an active scalar in variable density turbulence.

Viscous Rayleigh Taylor instability experiments using elastic-plastic materials

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Keywords: Rayleigh-Taylor Instability, Mechanical Strength

ABSTRACT

A rotating wheel RT experiment using centrifugal forces to accelerate a two-material interface was used to study the effect of amplitude and wavelength on RT instability in elastic-plastic materials. The experiment consists of a container filled with air and mayonnaise, a non-Newtonian emulsion, with a predetermined initial perturbation between the two materials (Atwood number ~ 0.997). Using sinusoidal cutting guides to define the mayonnaise's surface, single mode perturbations of various amplitudes and wavelengths were analyzed and results found the instability required for acceleration increased for both decreasing initial amplitude and wavelength. A better understanding of the role material properties play in RT-strength would lead to controlling and suppressing RT instability [1, 2]. To study the effect of initial amplitude and wavelength on RT instability, different sinusoidal perturbations were formed on an elastic-plastic material (mayonnaise) and accelerated rotationally in a test section with air as the light fluid. Results for both 2D and 3D perturbations were compared to study the acceleration required for instability and the exponential growth after the interface yielded.

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Impact of Bulk Vorticity Generated by a Rippled Shock Wave on the Evolution of Richtmyer-Meshkov Instability

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Keywords: Richtmyer–Meshkov instability, compressible mixing layers, direct numerical simulation, inertial confinement fusion, astrophysics

ABSTRACT

Richtmyer-Meshkov instability (RMI) plays a crucial role in various plasma phenomena such as astrophysical supernova explosions and inertial fusion implosions. One of the urgent and curious questions related to the RMI is the interaction with a magnetic field. It is known that there are two important effects brought by the inclusion of an external field, which are the amplification of the ambient field [1] and the suppression of the unstable growth [2].

In this work, we will discuss about the dependence of the growth velocity of RMI on the equation of state (EOS). The linear growth velocity is determined by not only the size of the circulation generated at the interface but also the effects of the bulk vorticity left behind the rippled shock waves traveling away from the interface. It is found that mitigation of the RMI due to the bulk vorticity cannot be negligible when the fluid is highly compressible and the incident shock is strong. This feature can be demonstrated consistently by the analytic solutions for the linear growth velocity and by direct numerical simulations of RMI.

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Progress on Multicomponent Reynolds-Averaged Navier–Stokes Model Development and Validation for Rayleigh–Taylor and Reshocked Richtmyer–Meshkov Turbulent Mixing

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Keywords: Rayleigh–Taylor mixing, Richtmyer–Meshkov mixing, reshock, RANS modeling

ABSTRACT

Recent progress on the development and validation of a new K–ϵ multicomponent Reynolds-averaged Navier–Stokes model is discussed. The model includes mixture molecular dissipation and diffusion terms, molecular and turbulent enthalpy diffusion terms, as well as models for pressure–dilatation and dilatation dissipation. The model has previously been shown to be consistent with self-similar evolution, observed asymmetries between bubble and spike front mixing, and DNS predictions for canonical (constant acceleration) Rayleigh–Taylor mixing [1]. The model has also successfully been applied to a set of ten reshocked Richtmyer–Meshkov mixing experiments [2], and more recently to experiments with larger Mach numbers and various positive and negative initial Atwood numbers [3]. An extension of the model to include a modeled density variance transport equation is described. The three-equation model is applied to a set of diverse Rayleigh–Taylor mixing cases, including several cases with complex acceleration histories similar to those considered using numerical simulations. The evolution of various turbulence statistics (e.g., mixing layer widths, turbulent kinetic energy, dissipation rate and density variance, turbulent Reynolds numbers, production-to-dissipation ratios), spatial profiles of fields across the mixing layers, and turbulent transport equation budgets are compared among these cases to elucidate differences in the turbulence production, dissipation and diffusion mechanisms. It is also shown that the mechanical turbulence timescale is, in general, poorly correlated with the molecular mixing timescale determined by the time-evolution of the molecular mixing parameter (proportional to the density variance) for both Rayleigh–Taylor and reshocked Richtmyer–Meshkov mixing.

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The Equation of State for n components

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Abstract: A calculation model has been presented for n-component mixture, assuming that n components of mixture are in Local Thermodynamic Equilibrium state, which means they are isothermal and isobaric, and that the sub-volume of each component is additive and the EOS of each component is known. The EOS of W-Mo-Fe-Ni alloy is calculated, which shows good consistence with experimental results.

Keywords: mixture, EOS, isothermal-isobaric Assumption

Towards a Statistical model for KH Instability in the Compressible Regime: Numerical calculations and Experiments

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Keywords: Kelvin–Helmholtz instability, compressible mixing layers, direct numerical simulations, HEDP laboratory experiments

ABSTRACT

The Kelvin-Helmholtz (KH) instability evolves between two fluid regions subjected to a velocity jump at the interface. Small initial perturbations located on the shear layer grow in the form of vortices, forming a mixing zone. Motivating by the statistical model for the incompressible case [1], we would like to construct model for the general compressible case by separating the problem to two building elements: the evolution of a single vortex and the merger rate of two vortices. We study numerically and theoretically the compressibility effects on these two elements and the resultant multi mode mixing zone width, known experimentally to have inhibited growth rate [2]. Design of an experiment with a single mode in the compressible regime [3] and preliminary results indicating a growth rate reduction, will be shown and discussed.

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Large-scale analysis of self-similar Rayleigh–Taylor turbulence in the mode coupling regime

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Keywords: Rayleigh–Taylor turbulence, permanence of large eddies

ABSTRACT

The permanence of large eddies is the central principle upon which relies the description of the self-similar properties of decaying homogeneous isotropic turbulence [1, 2]. Its applicability to Rayleigh-Taylor turbulence was first conjectured in [3] and led to predictions of the value of the mixing width constant α in good agreement with simulations done in the mode–coupling regime. This conjecture also led to the unconventional idea that mode–coupling is not universal but depends on a large scale invariant, the value of which is set by initial conditions and/or the early stages of the flow evolution.

In this talk, we would like to review the conjecture made in [3] at the light of an eddy-damped quasi-normal markovianized (EDQNM) model. Within the bounds of this model, we assess the effects of non-linear terms at large scales and check whether or not they modify the quasi-linear evolution of large scales assumed in [3]. Besides, we also present predictions on the scaling of large scales and their anisotropy. Finally, we discuss the implications of these predictions on the self-similarity of the flow.

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A Numerical Study of the Two and Three Dimensional Richtmyer Meshkov Instability

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Keywords: Richtmyer–Meshkov instability, large-eddy-simulation

ABSTRACT

The Richtmyer-Meshkov instability occurs as shock waves pass through a perturbed material interface. This paper presents a series of large-eddy-simulations of the two dimensional turbulent RM instability and compares the results to the fully three dimensional simulations conducted by Thornber et al. [1]. There are two aims to this paper, the first is to explore the number of independent realisations which are required to give a statistically converged solution for a two dimensional flow field, in a similar vein to that undertaken by Clark [2]. The second aim is to elucidate the key differences in flow physics between the two dimensional and three dimensional Richtmyer-Meshkov instabilities, particularly their asymptotic self-similar regime. Earlier publications on the Rayleigh Taylor instability imply that lower mixing, larger structures, and more rapid late time growth are expected [3]. This paper examines the statistical convergence of the 2D simulations as a function of ensemble number and grid resolution, and the ensemble averaged growth rates, mixing parameters, turbulent kinetic energy and spectra.

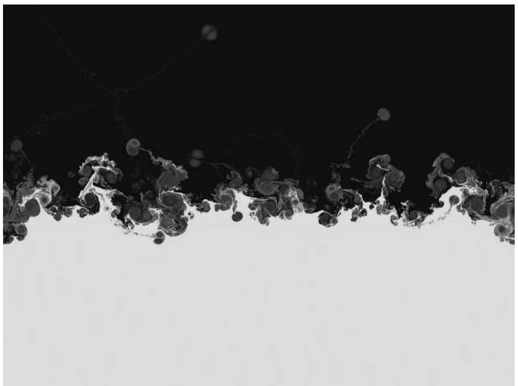

Figure 1: Contour flood of volume fraction for an $At^+ = 0.5$ simulation of the two-dimensional Richtmyer-Meshkov instability at a grid resolution of 4096×4096.

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Direct Numerical Simulations of Turbulent Mixing by Compressible Rayleigh-Taylor Instability

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Abstract: Turbulent mixing by compressible Rayleigh-Taylor instability (RTI) is simulated and analyzed by using direct numerical simulations (DNS). The conservative mass, momentum and energy equations, non-conservative species-transfer equation, and ideal gas equation of state are solved with high-order finite-difference method. Convection and viscous terms are discretized with 7th-order WENO and 8th-order central difference schemes, respectively, and unsteady terms are advanced explicitly with 3rd-order Runge–Kutta method. The initialization schemes are discussed and documented. The evolution of RTI has a great dependence on the initial parameters of dimensionless density ratio (Atwood number) and disturbance mode, and on the control parameters of dimensionless acceleration (i.e. compressibility parameter Fr). A series of (2D/3D) DNS cases are performed to study their effects on RTI evolution by investigating quantities frequently-used in instability and turbulence, including mixing width, concentration distribution and budgets of turbulence equation. A preliminary results show: (1) large Fr would stabilize RTI flow, and turbulent mixing would not happen; (2) Compared with single-mode disturbance, the mixing width decrease rapidly in multimode and random- mode disturbance; (3) Under some parameters, the mixing width is not a quadratic function of time, against with the scaling law of incompressible RTI; (4) the tip-velocity of bubble/spike depends on the local Atwood number.

Keywords: Direct Numerical Simulation, Turbulent Mixing, Rayleigh-Taylor Instability

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Influence of Plasma Transport in R-T and K-H Instabilities

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Keywords: Rayleigh–Taylor instability, Kelvin–Helmholtz instability, combined instabilities, compressible mixing layers, direct numerical simulation, inertial confinement fusion, astrophysics, high-energy density physics, plasma transport

ABSTRACT

Rayleigh-Taylor and Kelvin-Helmholtz instabilities are examined in 2D computations with plasma diffusive transport over a large range of scales to determine where plasma diffusivity becomes an important transport mechanism. The plasma transport includes diffusivity of mass (species diffusion), momentum (viscosity), and energy (conductivity dominated by electrons). Test problems include ionized gases with a large atomic mass difference, and fuel-capsule conditions typical of ICF (Inertial Confinement Fusion) experiments at the Omega facility. The test problems are run in varying domain sizes, starting at 1 cm, and then decreasing the domain size for each run by one order of magnitude, down to 1 micron, while scaling the time and applied acceleration (RT) or velocity (KH) appropriately, so that with no plasma transport, the Euler equations are solved to give identical instability growth at each scale. Each size domain is then run with plasma transport. We find no significant plasma transport effects in the 1 cm box, while the plasma transport plays an increasingly significant role as the box size decreases. In the 10 and 100 micron boxes the plasma transport is significant and it becomes dominant in the 1 or 10 micron size box depending upon the specific figure of merit. Additional analysis of the KH instability compares the KH roll-up in different size boxes at the same scaled time, and shows the plasma transport appears to significantly attenuate the vortex roll-up and to eliminate the instability at the smallest scales. Following the simulations to later times shows that a similar vortex roll-up does occur in the presence of plasma viscosity, but the time to transition is significantly delayed. The results support the hypothesis that classical plasma transport properties are important at the small scales expected for instability growth in ICF and possibly in other small scale HEDP (High Energy Density Physics) experiments.

This work was performed under the auspices of the National Nuclear Security Administration, US Dept. of Energy.

Modeling Ablation Front Instabilities and Mixing in ICF

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Keywords: Rayleigh–Taylor instability, Richtmyer–Meshkov instability, inertial confinement fusion

ABSTRACT

Hydrodynamic instabilities at the ablation front of inertial confinement fusion (ICF) implosions have been found responsible for mixing ablator material into the hot spot in some experiments during the National Ignition Campaign [1]. Here we present detailed modeling of this mixing process using the arbitrary Lagrange Eulerian (ALE) code HYDRA and the high-order Eulerian code Miranda. Ablation front perturbations can penetrate deep into the ablator and fuel, yet can be kept from entering the hot spot by their interaction with the stagnation shock. This interaction resembles the canonical shock-bubble interaction and results in a vortex ring that pushes the ablator material outward. If the perturbation grows large enough, it will inject a jet of ablator material into the hot spot. We show that this size threshold can be modeled based on linear growth. In three dimensions, this jet of material quickly breaks apart and mixes in the hot spot. The breakup of this jet depends on the turbulent state of the hot spot, which is significantly influenced by the dissipative effects of viscosity [2].

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This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

Statistics of turbulent mixing

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This talk will investigate the statistics of turbulent mixing processes, based on calculations of 2- and 3-layer Rayleigh-Taylor mixing and shocked cylinder problems using the MILES code TURMOIL. Distributions of mixing materials, turbulence kinetic energy and turbulence lengthscale will be compared to results from the AWE multiphase mix model. The calculations suggest ways in which the kinematically-distinct phases which the model treats might be identified. The shocked cylinder case generates anisotropic organized structures in the turbulence kinetic energy field, which are not directly treated by the model; however these will not be immediately important in driving mixing.

Effects of Shock Strength on the Single-Interface Richtmyer-Meshkov Instability

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Keywords: Richtmyer–Meshkov instability, turbulent mixing

ABSTRACT

The multimode Richtmyer-Meshkov instability (RMI) is characterized by turbulent mixing over a spectrum of scales. In order to understand the effects of incident shock Mach number on the Richtmyer-Meshkov instability, we must measure both the scalar and dynamic mixing of the flow. We have implemented simultaneous density (Q-PLIF) and velocity (PIV) field measurements at the Los Alamos Shock Tube facility to better understand turbulent RM mixing.

We investigate the evolution of a shocked, multimodal air-SF_6 interface ($A = 0.58$) for two Mach numbers (Ma$=$ 1.21, and 1.29). Measurements are acquired at multiple downstream locations and used to statistically characterize late-time mixing and evolution of correlated and uncorrelated density-velocity mixing quantities. We compare mixing of both large (*e.g.* mixing width) and small (*e.g.* density self-correlation, Favre-averaged stresses, mass flux, and vorticity) scale quantities for each incident Mach number and to previous studies.

Some recent studies of hydrodynamic instability relative to implosion of Inertial Confinement Fusion

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Abstract: Trade-off between DT material compression and controlling hydrodynamic instability is critical for ignition of Inertial Confinement Fusion (ICF). For recent National Ignition Facility (NIF) indirect-drive (ID) implosion experiments of the CH ignition target, large ablator mix into the central hotspot and non-uniformity of shell density for the low-foot (LF) implosion result in very low neutron yield, and reducing mix of the high-foot (HF) implosion raises neutron yield one order higher than the LF implosion, but it is still difficult to realize ignition due to its low pressure and density of the hotspot. We propose a new ignition scheme of high abadiat acceleration and re-compression (HAARC) of the main laser pulse for controlling hydrodynamic instability and reducing requirement of ignition driven laser energy, which has considerably low growth of hydrodynamic instability and high fusion energy gain. Some 1D and 2D simulation results of the LARED-S radiation hydrodynamic code are given. The issues of hydrodynamic instability relative to the ID ignition implosion are discussed and compared for the HF and HAARC implosions. In this report, experimental results of ablative Rayleigh-Taylor instability (ARTI) by the ID and the direct-drive (DD) is presented, and 2D LARED-S simulations have good agreement with the experimental results. Finally, work of weakly nonlinear theory for convergent coast of implosion is introduced which shows the lower saturation amplitude and enhanced nonlinear interaction strongly depending on the convergent ratio.

Keywords: Hydrodynamic instability in implosion, Ablative Rayleigh-Taylor instability, Ignition target design, Inertial confinement fusion

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Direct Numerical Simulation and Implicit Large Eddy Simulation of Rayleigh-Taylor mixing.

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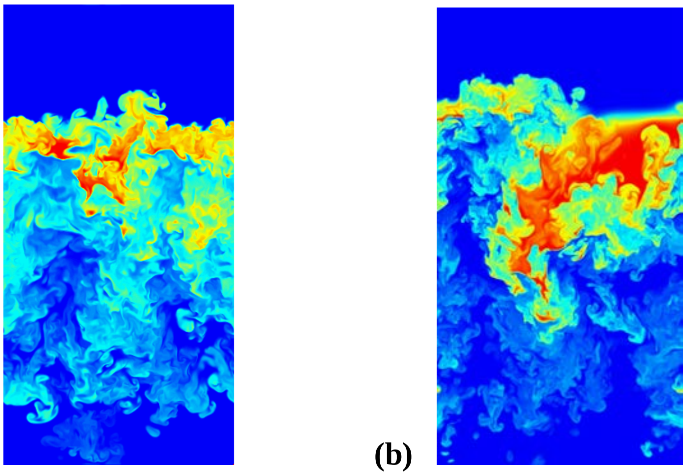
In earlier work (Youngs 2009, 2013), the 3D ILES code TURMOIL has been used for simulation of Rayleigh-Taylor (RT) mixing, while making the assumption that the Reynolds number is high enough to have little effect on the main quantities required for engineering applications. Viscosity and diffusivity have now been included in TURMOIL so that DNS may be performed, at least at moderate Reynolds number. This has been done for two purposes (a) to quantify the effects of finite Reynolds number and Schmidt number on RT mixing and (b) to use DNS results for the highest achievable Reynolds numbers to test the validity of the ILES. TURMOIL is a compressible code and the recently implemented DNS model may be used for incompressible flows (by performing calculations at low Mach number) or for fully compressible flows with shock waves. However, DNS is limited to relatively simple situations and it is argued that ILES remains essential for more complex applications.

The paper gives a brief description of the DNS model and its numerical implementation, and shows results for simple benchmark problems. Results will then be presented for a range of recent applications including RT mixing at a plane boundary and the break-up of a dense fluid layer due to RT mixing. Figure 1 shows sample results for the break up of a dense fluid layer at density ratio 3:1. The overall amount of mixing is similar for the DNS and ILES, but the degree of molecular mixing is less for the DNS.



(a) (b)

Figure 1: Break of a dense fluid layer due to RT instability. (a) ILES (256x256x512 meshes). (b) DNS, Re~3000, Sc=1 (1024x1024x2048 meshes).

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Poster Abstracts

Exploring Analogies between Driven 2D Euler Flow and Driven Vlasov-Poisson System: Nonlinear, Non-Stationary, Self-Organized Asymptotic States from HED Plasmas to Fluid Turbulence

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Keywords:Vlasov-Poisson System, 2D Euler Turbulence, phase space self-organized structures, multi-fractality, conformal invariance, wave-particle interactions, high-energy density physics

ABSTRACT

Results will be shown of extensive simulations of the coupled nonlinear integro-differential equations known as the Vlasov-Poisson system. These equations are isomorphic to 2D Euler (as long as there are two species of oppositely charged and same mass particles). We will show that nonlinear states of self-organization exist which form coherent multimode structures in phase space over particle orbits that are chaotic. We will delve into comprehensively diagnosed output such as phase space partitioning, Wigner distribution characterization of the time-frequency evolution of the spatial harmonics of the density field, low mode reconstruction of the self-organized, non-stationary nonlinear, kinetic structures, and test particle dynamics ad their statistical properties in the self-consistent fields. The paradigm of Kinetic Electrostatic Electron Nonlinear (KEEN) waves, to take but one example, is that trapping-untrapping and retrapping oscillations occur which keep the fields afloat, non-stationary and yet largely coherent while the particle dynamics in wide regions around the separatrices are chaotic. Such interplay of chaos and coherence is of great interest in turbulence studies. We will show how advances in 2D Euler turbulence such as the multifractal nature of the zero vorticity line and its universality (belonging to the Percolation class) translate to insights in the world of HED and the Vlasov-Poisson system.

In addition, we will show new phenomena when two KEEN waves merge, retaining full memory of the order in which they were created prior to merging. We will also show how KEEN waves interacts with an electron plasma wave (EPW) resonantly and non resonantly. The 2:1 resonant case itself is quite novel since it involves two or more harmonics of the KEEN wave, such that the fundamental has half the frequency of an EPW but the same wavenumber while the second harmonic has the same frequency as the EPW but twice the wavenumber. Such triad interactions between linearly resonant modes, such as EPW, and nonlinear self-organized states, with multiple phase-locked harmonics, such as KEEN waves, allow the destruction of the former by the nonlocal-in-phase-space action of the latter.

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This work was performed under the auspices of the department of energy's joint program in high energy density physics.

Experimental investigation of the Richtmyer-Meshkov instability in a cylindrical geometry using a gas lens approach

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Keywords: Richtmyer–Meshkov instability, shock tube experiments, converging shock wave

ABSTRACT

Since two decades, the IUSTI laboratory investigates in collaboration with CEA/DAM/DIF the Richtmyer-Meshkov instability (RMI). Up to now, most of the experiments concerning the RMI were performed in a conventional shock tube, generating a planar shock wave. However, the RMI often occurs in spherical case where the convergence effects must be taken into account. During the 13th IWPCTM [1], we have successfully demonstrated the possibility of using a conventional shock tube to convert a planar shock wave into a cylindrical one through a perfect gas lens [2]. This can be done when a planar shock wave passes through a shaped interface between two gases. By coupling the shape with the impedance mismatch at the interface it was possible to generate a circular transmitted shock wave. The next step is now to study the Richtmyer-Meshkov instability in this converging geometry by inserting a second perturbed interface that will be destabilized by the shock wave during its convergence phase. We have implemented on our T80 shock tube a new convergent test section, including two stereolithographed grids and nitrocellulose membranes to materialize the gas lens interface (air/SF_6) and the second perturbed interface (SF_6/air). Figure 1 gives a sketch of the new convergent test section. We plan to present during the workshop the first experimental results obtained with this new apparatus including pressure measurements and shadowgraph visualizations.

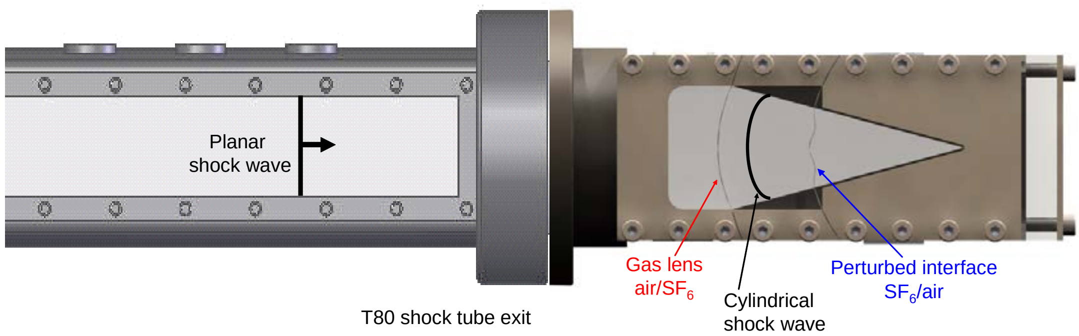

Figure 1: Sketch of the new convergent test section implemented on T80 shock tube exit.

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Design of a Supernova-relevant Rayleigh-Taylor Experiment on the National Ignition Facility. I. Planar Target Design and Diagnostics.

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Keywords: hydrodynamics, hydrodynamic instabilities, laboratory astrophysics, Rayleigh-Taylor, HEDP laboratory experiments, National Ignition Facility

ABSTRACT

We present a feasability study for a laser-driven shock experiment on the National Ignition Facility (NIF), studying the nonlinear evolution of the Rayleigh-Taylor instability. The experiment is relevant to the problem of material mixing in core-collapse supernovae and is intended to serve as a stepping stone for more realistic Rayleigh-Taylor experiments using spherical geometry.

We use the CRASH code to perform radiation hydrodynamics simulations of the experiment including the actual NIF laser drive. It is shown that the simulations are converged with respect to numerical resolution effects. Small-scale imperfections, such as they might be introduced during the process of target fabrication, are found to have negligible impact, provided that their size is smaller than μm. The simulation results are in excellent agreement with a a buoyancy-drag model, and the mix layer width is found to increase at higher drive energies.

IWPCTM14 Abstract (Poster)
Kathryn Garside

Title: Effects of Detonation Failure in the AWE Convergent Shock Tube on Mixing at Material Interfaces

Abstract: The AWE Convergent Shock Tube (CST) was designed to validate models of shock driven mixing in a convergent geometry. In the current experimental configuration 34 miniature spark plugs are mounted in a region of detonable gas at the top of the main body. Detonations lit by these spark plugs drive a shock towards the apex of the CST, where the development of Richtmyer-Meshkov instability at the surfaces of a dense gas region are imaged using a high speed shadowgraph technique. As such, there is a requirement that the detonation of the multiple spark plugs produces a uniform cylindrical shock wave to drive the mixing process. LES calculations have been conducted using a new programmed burn routine to study the effect of the discrete lighting points, and detonation failure from individual sparkplugs, on mixing at the material interfaces.

The effects of variable viscosity on the decay of homogeneous isotropic turbulence

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Keywords: variable viscosity flow, EDQNM

ABSTRACT

In this work [1], we investigate the decay of incompressible homogeneous isotropic turbulence in a variable viscosity fluid. The viscosity coefficient is assumed to depend linearly on a scalar, representing either a temperature or a concentration, and obeying a simple advection-diffusion equation. At high Reynolds numbers, Direct Numerical Simulations (DNS) allow us to confirm the validity of Taylor's postulate that the dissipation is independent from the viscosity and its fluctuations. At low Reynolds numbers, we report the presence of extra energy at small scales due to these variable viscosity effects. This implies that the turbulent kinetic energy decreases less rapidly as a function of time in variable viscosity fluids. In order to explain this phenomenon and quantify its importance on the turbulent ow, we propose a statistical approach based on an eddy-damped quasi-normal markovian (EDQNM) spectral closure which takes into account the non linearity introduced by variable viscosity. It is shown that this latter additional term is of constant sign in the energy spectrum equation and reduces the dissipation of the ow as observed. Also, by assuming the dominance of distant interactions between wave numbers, we can propose a simple formula expressing that variable viscosity effects lead to an effective reduction of the mean viscosity proportional to the variance of viscosity fluctuations.

References

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Shock-acceleration of a pair of gas inhomogeneities

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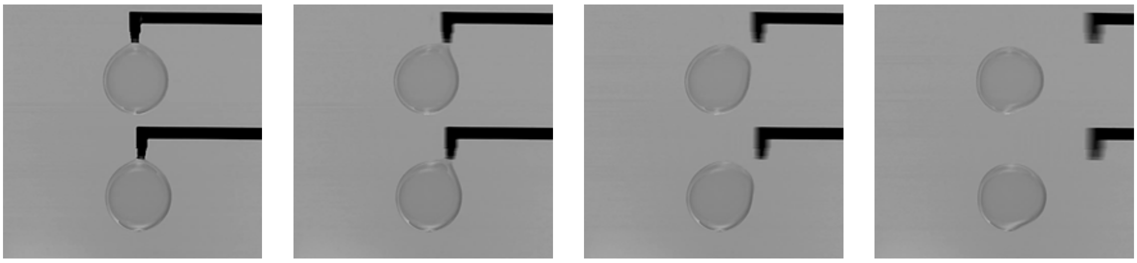
In a newly designed experiment, two soap film bubbles filled with argon or xenon are released in free fall as shown in Fig. 1, one behind the other one, inside a vertical shock tube filled with nitrogen. A downward traveling planar shock wave accelerates the two bubbles, atomizing the soap film. An initial condition image of both bubbles is recorded immediately prior to shock acceleration of the upper bubble. A vertical cross section of the shocked bubbles is visualized via planar Mie scattering performed by illuminating the flow with a vertically directed laser sheet (532 nm) whose light is scattered by the soap droplets towards two CCD cameras. Two post-shock images are collected during each experiment. An example of flow morphology is shown in Fig. 2 which is a simulation of a pair of shocked Xe bubbles.



(a) (b) (c) (d)

Figure 1: Initial condition setup. (a) Initial retractor position. Time after initiating retraction: (b) 36 ms, (c) 48 ms and (d) 64 ms.

(a) (b) (c) (d)

Figure 2: Simulation of shocked bubble pair for M=1.37 in N_2 with Xe bubble gas. Non-dimensional “cloud-crushing time” is $t^* = \frac{Wt}{D}$, where W is shock speed, t is time and D is bubble diameter. (a) Initial bubble position, $t^* = 0$, (b) $t^* = 4$, $t^* = 8$ and $t^* = 12$.

Extreme Fluids Team Validation Experiments

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Keywords: validation experiments

ABSTRACT

The Extreme Fluids Team is performing experiments in three physics areas: Richtmyer-Meshkov mixing, variable density mixing, and multiphase flows. This poster describes the experimental facilities in detail, the present and future measurement capabilities, and the experimental data that are available for numerical validation. The Vertical Shock Tube was developed to understand and quantify turbulent mixing using simultaneous density and velocity field measurements with well-characterized initial conditions. The Turbulent Mixing Tunnel studies variable-density turbulent mixing using simultaneous velocity and density field measurements. Using large data sets of $n > 3000$, we have measured Reynolds stress, turbulent kinetic energy, turbulent mass flux velocity, and other turbulence quantities. The Horizontal Shock Tube studies the unsteady dynamics of shock-accelerated particles in a gas carrier phase. The team welcomes interactions with groups who are interested in using our experimental results for validation efforts.

Turbulent Mixing of the Multi-channel Discharge Plasma and Electrolyte at Atmospheric and Lower Pressures

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The structure and forms of the multi-channel and anomalous glowing discharge in the process of turbulent mixing in electrolyte. It is observed that a gas-vapor bubble of cylindrical shape is formed while there occurs a turbulent mixing of the discharge and electrolyte. The turbulent mixing occurs in inhomogeneous and channeled parts of the discharge on the electrolyte surface.

Turbulent Mixing of Spatial Discharge Plasma with Electrolyte Jet

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The goal of this work is to study the development of spatial discharges along and beyond the jet electrolyte electrode in the process of turbulent mixing at atmospheric pressure. The discharge development process was filmed by the high-speed video camera Fastec HiSpec. The shooting rate of the camera is 7529 frames per second. The filming reveals that together with the spatial discharge along the jet there are local discharges with smaller volume. The discharge is affected by the air convection and moves in a horizontal direction. The discharge volume diminishes with time and it comes off the electrolyte surface. Transversal waves are generated on the surface of the electrolyte. Convection and waves create a turbulent mixing area on the electrolyte electrode. The spatial discharge is formed at specific conditions near the electrolyte surface.

High Current High Frequency Capacitance Discharge in the Process of Turbulent Mixing

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The results of experimental investigations of the high current HF capacitance discharge (HFCD) between a jet electrolyte electrode and flowing electrolyte cell in the pressure range $2 \cdot 10^3 \div 10^5$ Pa. It is established that pressure significantly influences the voltage of transition to the high current turbulent mixing regime. It is found that “streamer discharges” facilitate the transition from low current discharge to high current HFCD with turbulent mixing. At voltages $U \geq 3500$ V the high current HFCD transforms to a torch discharge with turbulent mixing.

Unstably stratified homogeneous turbulence: large-scale properties and self-similarity

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Keywords: unstably stratified homogeneous turbulence

ABSTRACT

The large-scale properties of self-similar unstably stratified homogeneous (USH) turbulence are investigated using an eddy-damped quasi-normal markovianized (EDQNM) approximation of the non-linear term. This analysis shows that a special role is played by the wave vectors contained in the equatorial plane, i.e. the plane perpendicular to gravity. It is indeed in this plane that turbulent spectra reach their maxima and evolve linearly from their initial condition when their initial infrared exponent is smaller than 4. At other angles, this property is not satisfied and turbulent spectra eventually undergo an evolution dominated by non-linear backscattering processes.

The self-similar evolution of USH turbulence is also shown to be related to the properties of large scales. In particular, the asymptotic growth rate of the mixing length depends on the initial infrared exponent in the equatorial plane. Besides, the self-similar asymptotic values of the concentration and velocity correlations also depend on the properties of large scales. This allows to derive relations between the correlations and the growth rate parameter.

Dependency of the Richtmyer-Meshkov instability on the initial conditions in shock tube experiments

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Keywords: Richtmyer–Meshkov instability, shock tube experiments

ABSTRACT

Recent results of Richtmyer-Meshkov instability experiments on the IUSTI T200 shock tube highlight the dependency of the perturbation growths on initial conditions [1].

In this shock tube the two gases are separated by a thin nitrocellulose film attached to a stereolithographed grid specifying the initial single-mode target perturbation. An important issue with this technique is the potentially deleterious effects of the membrane remnants after the shock-interface interaction. The good agreement between our last experimental results and simulation or model predictions shows that the increase of the incident shock wave Mach number up to 1.45 in air drastically reduces the influence of the membrane remnants.

Experimental evidences of differences in the remnants behavior between light/heavy cases (air/SF_6, $A \approx 0.7$) and heavy/light cases (air/He, $A \approx -0.76$) have been produced in a previous work [2]. They will be illustrated and investigated via simplified numerical simulations.

Finally, the specificity of Richtmyer-Meshkov instability experiments with sharp interfaces, as those achieved here, and their sensitivity to the presence of short wavelength perturbations superimposed on the single-mode target perturbation will be demonstrated through numerical simulations using the TRICLADE code.

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Progress with Buoyancy Driven Mixing by Volumetric Energy Deposition

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A two fluid experiment is presented which transitions from a Rayleigh-Taylor (RT) stable to RT unstable configuration via volumetric energy deposition by microwave radiation. The Atwood number (*At*) varies from negative to positive in this experiment, which is initiated with a light, non-polar fluid at rest above a heavier, higher polarity fluid. The initial alignment of the density gradient with gravity makes the system stable. Exposure to microwave energy causes rotation of the polar molecules in the heavier fluid, causing the bottom fluid to heat and its density to drop due to thermal expansion. As preferential heating of the bottom fluid continues, the system passes through the neutral stability point, $At = 0$, and thereafter buoyancy driven mixing ensues. Challenges and limitations on experimental facility design, data collection, and fluid selection are discussed. Experimental and numerical predictions of the neutral stability point, and onset of buoyancy driven mixing, are compared, and differences with classical, constant *At* RT driven turbulence are discussed. Preliminary data collected using Laser Doppler Velocimetry and plans for future experiments will also be presented.

2D and 3D Simulations of Linear-Nonlinear RM Instability Growth with RAGE Code

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Hydrodynamic instabilities, turbulence, and mixing constitute some of the most important unsolved problems in physics today. Our goal is to examine the regime of highly nonlinear instability growth for Richtmyer-Meshkov (RM) instabilities. This regime is characterized by the development of intense vorticity, complex and distorted flow patterns, and persistent features of the initial state.

We use the Los Alamos RAGE code to simulate several experimental applications to study the simulation of RM instabilities into the nonlinear/fully turbulent phase. In this paper we will show detailed results for 2D and 3D RM hydrodynamic instabilities for both weak shocks (Ms = 1.2) and stronger shocks (Ms = 3 - 5). Comparisons will be made to the nonlinear theory of Zhang and Son[1] for both 2D and 3D amplitudes and growth rates, as well as the growth rates for the bubble and spikes individually.

We present here the methods used for these simulations, the results of the simulations, and our future directions for the code work.

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Simulation analysis of deceleration phase Rayleigh-Taylor instability in asymmetric implosion appeared in GekkoXII laser irradiation

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Keywords: Rayleigh–Taylor instability, inertial confinement fusion, three-dimensional simulation

ABSTRACT

In fast ignition (FI) scheme of inertial confinement fusion (ICF) [1, 2], a fuel capsule is imploded by high-intense lasers with Au hollow cone attached. Then, at the maximum compression time, ultra-high-intense laser is irradiated into the cone to raise the core temperature. Due to the presence of the cone, the orientation of the implosion laser is limited not to irradiate the cone. In Fast Ignition Realization Experiment at Osaka University, GekkoXII laser facility is used, which has twelve lasers set to irradiate a target with dodecahedron orientation. To avoid the irradiation to the cone, the nine beams are only used in the experiments (Fig. 1). In such an irradiation geometry, the target is imploded highly asymmetrically. Thus, we estimated the dynamics of the imploding target with GekkoXII nine-beam irradiation by three-dimensional pure hydro simulation. The result shows that strong asymmetric flow toward the cone side occurs and the compression efficiency is quite degraded compared with the result of twelve-beam irradiation (symmetric implosion). On the other hand, it is found that the fuel-shell interface (inner surface) in the case of the nine-beam is more smooth than that of the twelve-beam case at the maximum compression time. Fig. 2(a) and Fig. 2(b) show the inner surface near the maximum compression time in the case of the nine-beam and the twelve-beam, respectively. The nine-beam case has more smooth surface except a protruding object in front of the tip of the cone. The non-uniformity of the inner surface is thought to be amplified by Rayleigh-Taylor instability (RTI) in deceleration phase of implosion. Therefore, we estimated the RTI growth rate on the inner surface of both cases from the trajectory, and which shows that the RTI growth rate in the case of the nine-beam is smaller. We will discuss the detail in our presentation.

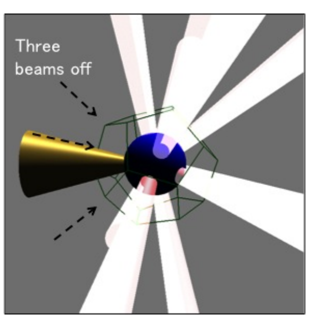

Figure 1: GekkoXII nine-beam irradiation.

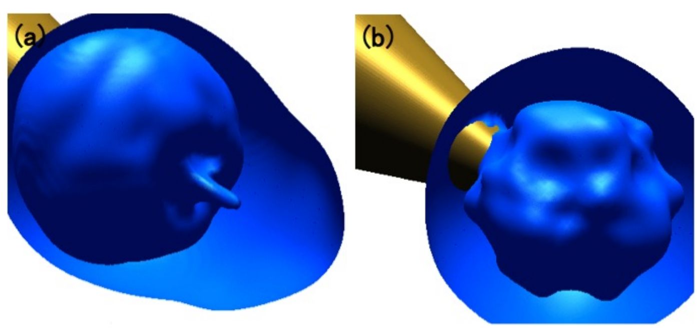

Figure 2: Density iso-surface corresponding to fuel-shell interface. (a) nine-beam (b) twelve-beam

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