The 15th International Workshop on the Physics of Compressible Turbulent Mixing

Sydney 2016
Foreword

The 15th International Workshop on the Physics of Compressible Turbulent Mixing (IWPCTM) will be held at the University of Sydney, Australia from 11th - 15th July 2016.


The 15th International Workshop on the Physics of Compressible Turbulent Mixing brings together researchers from universities and research laboratories around the world to discuss the state-of-the-art in theory, modelling, experiment and simulation of compressible and variable-density turbulent mixing induced by hydrodynamic instabilities in multi-material hydrodynamic flows.

Overall, 66 oral posters and 11 posters will be presented during the Conference. In this book of abstracts they are classified by sender’s name, in alphabetical order.

Our sincere gratitude goes to the Commissariat à l’Energie Atomique (CEA, France), the Atomic Weapon Establishment (AWE, UK), the New South Wales Office of the Chief Scientist and Engineer, and the University of Sydney for their sponsorship of the 15th IWPCTM.

I wish to thank all the members of the Local Organizing Committee and Mr John Donohoe, Mrs Sarah Castellanos and Ms Bronwyn Sexton for their help in the organisation of the workshop.

Finally, I would like to wish you all an enjoyable stay in our beautiful city, and that you have many enjoyable and productive interactions during this IWPCTM.

Ben Thornber
On behalf of the Local Organising Committee, IWPCTM15
Committees

Local Organising Committee

Ben Thornber (University of Sydney)
Vince Wheatley (University of Queensland)
Oleg Schilling (LLNL)
David Youngs (University of Strathclyde)
Robin Williams (AWE)
Steven Armfield (University of Sydney)
Nicholas Williamson (University of Sydney)
Michael Kirkpatrick (University of Sydney)
Ravi Samtaney (KAUST)
Scientific Committee

M. Andrews (LANL)
J. Redondo (U. Politecnica de Catalunya, Barcelona)
S. Dalziel (Cambridge University)
V. Rozanov (Lebedev Physical Institute, Moscow)
G. Dimonte (LANL)
O. Schilling (LLNL)
D. Drikakis (Cranfield University)
J. Scott (LANL), United States
S. Gauthier (CEA)
D. Shvarts (Nuclear Research Center, Beer-Sheeva)
J. Glimm (Stony Brook)
E. Son (Joint Institute for High temperature RAS)
J. F. Haas (CEA)
D. Souffland (CEA)
L. Houas (IUSTI)
H. Takabe (U. Osaka)
J. Jacobs (U. Arizona)
R. Williams (AWE)
A. Llor (CEA)
Y. Yanilkin (VNIIIEF)
N. Nevmerzhitskii (VNIIIEF)
D. Youngs (AWE)
A. Pavlenko (VNIITF)
Conference Location

The 15th International Workshop on the Physics of Compressible Turbulent Mixing will be hosted by the University of Sydney, approximately 2.5 km from the Sydney CBD, near the junction of Parramatta and City Roads. For more information and a map guide, click here.

The workshop will be held in the Abercrombie Building in the Darlington Campus area of the University of Sydney.

The oral presentations will be in the lecture room ABS 2090, and the poster presentation in ABS 2100. These are located next to each other on the second floor, towards the rear of the building.

Registration will begin at 0730 Monday 11th July in the Abercrombie building, outside ABS 2090.

Getting there
Bus routes to the university from this stand are the 422, 423, 426, 428, L23, L28 and M30. These buses may also be boarded from the Sydney CBD. Alight from these buses at:

1. The University Gates on City Road (east-bound). Walk down Butlin Avenue past the Wentworth Building. Turn left at the University Aquatic Centre. Walk straight ahead towards the Engineering Precinct.
2. Jane Foss Russell Building (west-bound). Walk through the open arcade area and down the stairs towards the Engineering Faculty, alongside Cadigal Green. Follow the footpath through to the Sydney Uni Sports & Aquatic Centre. Turn right up Darlington road until you turn left at Codrington St. Walk straight ahead towards the University of Sydney Business School.
Technical Program
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<td>Plenary Lessons learned from numerical simulations of interfacial instabilities over the past two decades. Cook, A.W. (Lawrence Livermore National Laboratory)</td>
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<td>Mixing and Turbulence Statistics in an Inclined Interface Richtmyer-Meshkov Instability. Subramaniam, A., Lele, S.K. (Stanford University)</td>
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<td>10:25 – 10:45</td>
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<td>15:10 – 15:30</td>
<td>Linear analysis of converging Richtmyer-Meshkov instability in the presence of an azimuthal magnetic field. Bakhsh, A.; Samtaney, R. (King Abdullah University of Science and Technology)</td>
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<td>Converging double-interface Richtmyer-Meshkov instability in magnetohydrodynamics. Li, Y., Samtaney, R. (King Abdullah University of Science and Technology)</td>
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<td>Spherical Richtmyer-Meshkov in MHD with an octahedrally symmetric magnetic field. Mostert, W., Pullin, D.I., Wheatley, V., Samtaney, R. (California Institute of Technology; The University of Queensland; King Abdullah University of Science and Technology)</td>
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<td>Cylindrical shock collapse in MHD. Mostert, W., Pullin, D.I., Samtaney, R., Wheatley, V. (California Institute of Technology; King Abdullah University of Science and Technology; The University of Queensland)</td>
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17:10 – 17:40 Discussion Chairs: V. Wheatley (University of Queensland) & A. Cook (Lawrence Livermore National Laboratory)

18:00 – 19:00 Reception FEIT Dean’s Function Room
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<td>A Comparative Analysis of RANS Model Predictions for Rayleigh Taylor and Reshocked Richtmyer-Meshkov Instability and Mixing.</td>
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<td>Nadiga, B.T., Livescu, D. (Los Alamos National Laboratory)</td>
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<td>A modified dissipation equation for Reynolds stress models dedicated to buoyancy driven turbulence.</td>
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<td>RANS simulations of Rayleigh-Taylor Instability subject to a changing body force.</td>
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<td>Yee, H.C., Kotov, D.V., Wray, A.A., Hadjadj, A., Sjögreen, B. (NASA-Ames Research Center; Bay Area Environmental Research Institute; CORIA; Lawrence Livermore National Laboratory)</td>
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<td>Filtered-velocity based LES of variable-density compressible flows.</td>
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<td>GS, S., Candler, G.V. (University of Minnesota)</td>
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<td>18:00 – 22:00</td>
<td>Banquet at the Museum of Contemporary Art, Circular Quay</td>
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| 08:30 – 09:10 | Plenary | High resolution 3-D radiation hydrodynamics modeling of inertial confinement fusion implosions on the National Ignition Facility.  
| 09:10 – 09:35 | Three- and Two-Dimensional Simulations of Re-shock Experiments at High Energy Densities at the National Ignition Facility.  
| 09:35 – 10:00 | Modeling and measuring fuel-ablator interface mixing in inertial-confinement fusion implosions.  
*Smalyuk, V.A.* (Lawrence Livermore National Laboratory) |
| 10:25 – 10:45 | Break |            |
| 10:45 – 11:10 | Detailed High-Resolution 3D ILES Simulations of OMEGA Separated Reactants ICF Experiments.  
| 11:10 – 11:35 | Study of an indirect-drive ignition capsule with the main pulse shape of decompression and recompression.  
| 11:35 – 12:00 | Energy transfer in Richtmyer-Meshkov instability induced turbulent mixing.  
*Xiao, Z.*, *Liu, H.* (Peking University) |
| 12:00 – 13:30 | Lunch |            |
*Heng Yu, Zhiwei He, Baolin Tian* (Institute of Applied Physics and Computational Mathematics, Beijing) |
| 14:20 – 14:45 | Porous materials under shock loading as a two-phase mixture.  
*Resnyansky, A.D.* (Defence Science and Technology Group, Australia) |
*Meshkov, E.E.*, *Son, E.E.*, *Son, K.E.* (Sarov Institute of Physics and Technology Research University; Russian Academy of Sciences; Moscow Institute of Physics and Technology) |
| 15:10 – 15:30 | Break |            |
| 15:30 – 15:55 | Using flyer impacting induced Richtmyer-Meshkov instability in 2A12 free surface to study yield strength at high strain-rate.  
*Peng, J.*, *Yu, Y.*, *Hu, C.*, *Li, B.*, *He, H.* (China Academy of Engineering Physics) |
| 15:55 – 16:20 | Numerical investigations of Rayleigh-Taylor instability in aluminum plate driven by explosive  
*Wang, T.*, *Cao, R.*, *Bai, J.*, *Li, P.*, *Wang, B.*, *Du, L.*, *Tao, G.* (China Academy of Engineering Physics; University of Science and Technology, China) |
*Ghaisas, N.S.*, *Subramaniam, A.*, *Lele, S.K.* (Stanford University) |
### Numerical and experimental study of the Rayleigh-Taylor instability of the Newtonian and non-Newtonian fluids.

*Doludenko, A.N., Fortova, S.V., Son, E.E.* (Russian Academy of Sciences)

**Discussion**

Chairs: D. Clarke (Lawrence Livermore National Laboratory) & P. Ramaprabhu (University of North Carolina Charlotte)

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**Time**

**Friday 15/07/2016**

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| 08:30 – 09:10 | Experiments Richtmyer–Meshkov  
Chair: R. Bonazza (University of Wisconsin – Madison) |
| 09:10 – 09:35 | Plenary  
Richtmyer-Meshkov Experiments at Los Alamos.  
Prestridge, K.  
(Los Alamos National Laboratory) |
| 09:35 – 10:00 | The effect of initial conditions on the turbulent Richtmyer-Meshkov instability.  
Jacobs, J., Sewell, E.G., Ferguson, K.I., Krivets, V.V.  
(University of Arizona) |
| 10:00 – 10:25 | Experimental Investigation of Velocity Evolution in the Richtmyer-Meshkov Instability.  
Reese, D., Oakley, J., Rothamer, D., Bonazza, R.  
(University of Wisconsin) |
| 10:25 – 10:45 | Break |
| 10:45 – 11:10 | Experiments in Richtmyer–Meshkov / Kelvin–Helmholtz  
Chair: J. Jacobs (University of Arizona) |
Flippo, K.A., Doss, F.W., DeVolder, B.G., Kline, J.L., Kot, L.B., Loomis, E.N., Merritt, E.C., Perry, T.S.  
(Los Alamos National Laboratory) |
| 11:35 – 12:00 | Effect of the initial conditions on the evolution of Richtmyer-Meshkov instability turbulent quantities.  
Tsiklashvili, V., Reilly, D., Mahaghar, M., Carter, J., Ranjan, D.  
(Georgia Institute of Technology) |
| 12:00 – 14:00 | Lunch & Scientific Committee meeting |
| 14:00 – 14:25 | Mixing in Scramjets  
Chair: R. Samtaney (King Abdullah University of Science and Technology) |
| 14:25 – 14:50 | Mixing processes in an inlet-injected scramjet.  
Gehre, R.M., Wheatley, V., Boyce, R.R.  
(University of Queensland; University of New South Wales) |
| 14:50 – 15:15 | Flow field manipulation in hypervelocity scramjets.  
Landsberg, W.O., Wheatley, V., Veeraragavan, A.  
(The University of Queensland) |
| 15:15 – 15:40 | Blast wave induced mixing in a laser ignited hypersonic flow.  
Gibbons, N., Gehre, R., Brieschenk, S., Wheatley, V.  
(University of Queensland; French-German Research Institute of Saint-Louis) |
| 15:40 – 16:05 | Turbulent Characteristics of a Hypervelocity Mixing Wake.  
Petty, D.J., Wheatley, V., Pantano, C.  
(University of Illinois; University of Queensland) |
| 16:05 – 16:15 | Closing remarks |

**Experiments Richtmyer–Meshkov**

**Plenary**

Richtmyer-Meshkov Experiments at Los Alamos.

Prestridge, K. (Los Alamos National Laboratory)

**The effect of initial conditions on the turbulent Richtmyer-Meshkov instability.**

Jacobs, J., Sewell, E.G., Ferguson, K.I., Krivets, V.V. (University of Arizona)

**Experimental Investigation of Velocity Evolution in the Richtmyer-Meshkov Instability.**

Reese, D., Oakley, J., Rothamer, D., Bonazza, R. (University of Wisconsin)

**Counterpropagating shear using laser-driven flows.**

Flippo, K.A., Doss, F.W., DeVolder, B.G., Kline, J.L., Kot, L.B., Loomis, E.N., Merritt, E.C., Perry, T.S. (Los Alamos National Laboratory)

**Effect of the initial conditions on the evolution of Richtmyer-Meshkov instability turbulent quantities.**

Tsiklashvili, V., Reilly, D., Mahaghar, M., Carter, J., Ranjan, D. (Georgia Institute of Technology)

**Quantitative study of the shock-accelerated elliptic gas cylinders.**

Zou, L., Liu, J., Liao, S. (China Academy of Engineering Physics; University of Science and Technology of China)

**Mixing in Scramjets**

**Chair: R. Samtaney (King Abdullah University of Science and Technology)**

**Mixing processes in an inlet-injected scramjet.**

Gehre, R.M., Wheatley, V., Boyce, R.R. (University of Queensland; University of New South Wales)

**Flow field manipulation in hypervelocity scramjets.**

Landsberg, W.O., Wheatley, V., Veeraragavan, A. (The University of Queensland)

**Blast wave induced mixing in a laser ignited hypersonic flow.**

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**Turbulent Characteristics of a Hypervelocity Mixing Wake.**

Petty, D.J., Wheatley, V., Pantano, C. (University of Illinois; University of Queensland)

**Discussion**

Chairs: K. Prestridge (Los Alamos National Laboratory) & V. Wheatley (University of Queensland)

**Closing remarks**
Oral Abstracts
Linear analysis of converging Richtmyer-Meshkov instability in the presence of an azimuthal magnetic field

Abeer Bakhsh, Ravi Samtaney

Applied Mathematics & Computational Science, King Abdullah University of Science and Technology, Thuwal, 23955-6900, Saudi Arabia, Abeer.Bakhsh@kaust.edu.sa

Abstract

The Richtmyer-Meshkov instability (RMI) occurs when an interface between two fluids with different densities is impulsively accelerated by a shock, and is of significant importance in inertial confinement fusion (ICF). In Cartesian slab geometry, magnetohydrodynamic (MHD)-RMI has been investigated by nonlinear compressible simulations and incompressible model in the presence of transverse magnetic field (Wheatley et al., 2014). After the shock interacts with the interface, the vorticity breaks up into waves traveling parallel and anti-parallel to the magnetic field. The interference of these waves causes time oscillations of the perturbation amplitude of the interface. The analogue of the investigation by Wheatley et al. (2014) in cylindrical geometry is depicted in Figure 1 (left): a radially converging MHD shock interacts with an azimuthally perturbed interface in the presence of a magnetic field initially oriented in the azimuthal direction. We perform a linear stability analysis of this configuration via numerical simulations extending a numerical method proposed by Samtaney (2009). We investigate effects of different magnetic field strength (characterized by $\beta$) and shock strengths, as well as different perturbation wave numbers. The growth rate of the interface perturbation, shown in Figure 1 (right), depicts a behavior somewhat similar to that observed in Cartesian geometry.

Figure 1: The physical setup (Left). The time history of growth rate of the normalized perturbed interface for varying magnetic field strength; $a_0$ is the sound speed in the unshocked fluid ahead of the shock; $m = 256$ is the wave number; $R_0$ is the initial location of the interface (Right).

References

A spectral approach for stratified homogeneous turbulence with complex acceleration history

Benoît-Joseph Gréa\(^1\) & Alan Burlot\(^1\)

1. CEA, DAM, DIF, F-91297 Arpajon, France

Turbulent mixing zones driven by buoyancy are present in many engineering applications including ICF capsules. Predicting their dynamics may be hard since turbulence behaves very differently whether or not the mean density gradient \(\nabla \rho\) points in the same direction of the acceleration vector \(g\). Both the mean density gradient and the acceleration vector may depend on time. A same mixing zone can successively endure stable or unstable phases, respectively when \(\nabla \rho \cdot g < 0\) or \(> 0\).

Experiments and simulations showed that the growth rate of an unstable (or Rayleigh-Taylor) mixing zone can be drastically diminished if it was previously submitted to a stable phase [1, 2]. A natural explanation of this phenomenon is that the mixing is greatly enhanced during the stable phase, specially for large scales [3], reducing the production of vertical buoyancy flux in the mixing zone. Other factors may additionally influence the development of the mixing zone such as anisotropy [4].

We propose to investigate how behaves a turbulent mixing zone submitted to complex acceleration history through a spectral model recently proposed and validated against DNS in [5]. The model is limited to homogeneous turbulence corresponding to well developed mixing zones and to the Boussinesq approximation. However, this approach allows to reach high Reynolds numbers and to perform an extensive parametric study due to its lower computational cost compared to DNS. We will explore the influence of the acceleration strength with respect to the inertia of turbulence expressed by the Froude number. In addition, we will address the possible existence of Faraday-like instability in a mixing zone due to the time oscillation of acceleration during stable configurations.

References
RANS simulations of Rayleigh-Taylor Instability subject to a changing body force

R. L. Bertsch\(^1\), & R. A. Gore\(^2\)

1. Los Alamos National Laboratory, P. O. Box 1663, Los Alamos, NM 87545; rlb@lanl.gov
2. Los Alamos National Laboratory, P. O. Box 1663, Los Alamos, NM 87545; rag@lanl.gov

Abstract
Modeling turbulent mixing in variable density (VD) fluid flows is a key topic of interest in multi-physics applications due to the complex instability characteristics they exhibit. RANS models continue to be accurate and efficient tools to investigate the evolution of turbulence in these complex flow problems. Many RANS (Reynolds averaged Navier-Stokes) models are well validated for prototypical variable density flows such as Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM). However, most lack the ability to accurately capture mix features in VD flows with changing body forces, like those seen in rocket rig experiments that undergo phases of acceleration and deceleration. This talk will present some simulations of an improved RANS model which substitutes the molecular diffusion term in the species equation with a demix term that is dependent on the turbulent mass flux and species micro-densities. Results from these simulations will be compared with previous RANS models, DNS, and experimental data to validate the new models ability to capture the mixing physics in RT flow subject to a changing body force.

Figure 1: Evolution of the mix width subject to a changing body force.

References
Experimental investigation of the converging Richtmyer–Meshkov instability in a conventional shock tube

L. Biamino¹, G. Jourdan¹, C. Mariani¹, L. Houas¹, M. Vandenboomgaerde²

& D. Souffland²

1. Aix-Marseille Université, IUSTI, CNRS UMR 7343, 13013 Marseille, France
2. CEA/DAM/DiF, F-91297 Arpajon, France

Since a few years the IUSTI laboratory, in collaboration with CEA/DAM, investigates the Richtmyer-Meshkov instability (RMI) in cylindrical geometry while still using a conventional shock tube. This is done using a specific wedge test section, in which the incident planar shock wave is directly converted into a cylindrical one during its refraction through an elliptical interface. Subsequently, it interacts with a sinusoidal interface that is the interface of interest here. We have experimentally validated the concept using a three-fluid three-zone system (Biamino et al. 2015) where a test cell of a heavy gas (SF₆) was enclosed by a light gas (air) on either side as shown in Figure 1. To accurately shape the two interfaces, grids were made using the stereolithography technique on which a thin nitrocellulose film (1μm-thick) was attached in order to separate air from SF₆ and SF₆ from air.

It is known that nitrocellulose membrane fragments perturb the RMI. Thus, we have tested another type of membrane for the second interface: a gelatin film. We will present the results obtained with this approach and will provide a brief review of all we did on this study.

Figure 1: Schematic and view of the test section

Figure 2: Schlieren pictures: RMI induced at a SF₆/air interface using respectively a nitrocellulose membrane (left) and a gelatin film (right) to materialize the second interface.

Numerical analysis of these results will be presented in a companion talk (see M. Vandenboomgaerde et al.).

References

Richtmyer-Meshkov instability in two-fluid plasmas

D. M. Bond, V. Wheatley, R. Samtaney & D. I. Pullin

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2. School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, Australia. v.wheatley@uq.edu.au
3. Mechanical Engineering, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia. ravi.samtaney@kaust.edu.sa
4. Graduate Aerospace Laboratories, California Institute of Technology, Pasadena, California, USA. dpullin@caltech.edu

Suppression of the Richtmyer-Meshkov instability in plasmas through the application of a seed magnetic field has been studied in the framework of ideal magnetohydrodynamics (Samtaney, 2003, Wheatley et al., 2005). These studies have shown that suppression of the instability is achieved through the transport of vorticity by magnetohydrodynamic waves away from the perturbed density interface where it was baroclinically generated during interaction with a shock wave. Here, we numerically study the suppression of the Richtmyer-Meshkov instability using the more physically accurate, fully electromagnetic, two-fluid plasma representation. By simulating ions and electrons separately, the assumptions of quasi-neutrality, small Larmor radius and small Debye length can be discarded. In this framework, we consider the case where the seed magnetic field is perpendicular to the initial density interface. We find that vorticity is still effectively transported in the two-fluid plasma system for reasonable plasma parameters, but transport is now via dispersive waves. This causes the vorticity distribution to be much more complex than in the ideal magnetohydrodynamic case. Of particular significance is that the vorticity in the vicinity of the interface oscillates in both space and time. Consequently, the behaviour of the shocked density interface is substantially altered, although its instability is still suppressed to a certain extent.

References

Simulations of the turbulent Richtmyer-Meshkov instabiltiy in a spherically convergent geometry

I. Boureima & P. Ramaprabhu

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Abstract

We investigate the development of the turbulent Richtmyer-Meshkov instability in a spherically convergent geometry. The three-dimensional simulations were performed using the astrophysical FLASH code [1], with a resolution of 1024 x 512 x 512 in the radial, azimuthal and polar directions for the multimode case. We present results from two sets of simulations, namely a spherical RM driven by a self-similar Chisnell [2] shock and an implosion problem defined by [3]. In both configurations, the shock travels from an outer fluid layer to an inner fluid that is denser. For the implosion problem, a third, fictitious layer is necessary in these Eulerian calculations to simulate an external shell that sustains the incident shock, thus mimicking an implosion. The perturbations at the interface between the outer shell of light fluid and the inner shell of heavy fluid were specified according to single-mode or multimode spherical harmonic functions. The implosion problem produces significantly greater convergence than the standard RM problem, allowing for significant enhancement of the turbulent mixing zone due to Bell-Plesset effects. The growth of the turbulent mixing layer under the effect of the reflected shock is also investigated. We report on several quantities of interest from both simulations.

Acknowledgements: This work was supported in part by the (U.S.) Department of Energy (DOE) under Contract No. DE-AC52-06NA2-5396. FLASH was developed by the DOE-sponsored ASC/Alliance Center for Astrophysical Thermonuclear Flashes at the University of Chicago.

Figure 1: Isosurfaces of mass fraction corresponding to the 50% level at (a) early, (b) intermediate and (c) late times from FLASH simulations.

References

The effect of an obstruction on the Rayleigh-Taylor instability in a confined geometry

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This talk discusses the effect of an obstruction on the evolution of the Rayleigh-Taylor instability in a confined geometry at low Atwood numbers. The introduction of an obstacle at the height of the initial interface results in dramatic changes to the dynamics of mixing, even when this obstacle is only a few percent of the domain width. Two situations are investigated using laboratory experiments and implicit large eddy simulations (ILES). In the first case, a single horizontal opening connects the upper and lower layers. A bidirectional flow exchanges fluid through the opening, establishing a circulation cell in each layer. These cells exist quasi-steadily for long periods, constantly recirculating and mixing the fluid in each layer. This acts to increase the time required for mixing compared with the classical case, but results in a more uniformly mixed final stratification.

The second case has two horizontal openings, one either side of the obstruction. This results in markedly different dynamics. The flow through each of the openings switches back and forth between being bidirectional (as with the single opening case) and unidirectional, with the direction of the unidirectional exchange reversing with a constant period. These results are consistent with the ILES we have run. Combining these data we are have identified a multistage mixing process, unique for cases with an obstruction. This mixing process can be described by an analytical model for mass flux and mean density change of each layer, we discuss this as well as the effects of an obstruction on the dynamics of mixing and the final mixing efficiency.

LIF single opening experiment at $A = 10^{-2}$ with rhodamine dye added to the upper layer. A Rayleigh-Taylor mixing zone can be seen to develop in the opening and maintaining a constant size throughout time.

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DNS of shock interactions with different surfaces

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DNS of shock interactions with different surfaces

DNS is an important tool for modelling ejecta processes, and will be used by AWE in support of a range of experimental programmes. Recently developed 3D DNS capability is shown to provide robust access to a wide range of experimental configurations.

Here, 3D DNS is used to examine the dynamics of surfaces accelerated by different drive profiles, including multiple shocks, linear acceleration ramps, and combinations thereof. We examine how different surface profiles affect these dynamics, and consider the production of jets, leading to ejecta, from surfaces with sinusoid, fly-cut and sawtooth profiles.

DNS calculations of resultant surface velocities are compared to analytical results for linear single mode shock driven surface profiles, as derived from the theory of Richtmyer [1]; this analysis highlights the extent to which nonlinearities and multimode effects can become significant.

References


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Turbulence budgets for variable density mixing in buoyant jets

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Introduction

Variable density mixing plays a role in a variety of physical systems, particularly those driven by Rayleigh-Taylor or Richtmyer-Meshkov instabilities. For low density ratios, the density can be modeled as a passive scalar or with Boussinesq approximations, but for larger ratios the density helps drive fluid transport and evolution of the turbulence. While buoyant jets and plumes have been studied for many years, theory is less developed than for single-fluid jets. Although work is ongoing to develop more detailed turbulence models for use in compressible and variable density flows, efforts have been hampered by a lack of detailed experimental data on the turbulence statistics in these conditions. This work addresses this problem through high-resolution simultaneous velocity and density measurements of buoyant turbulent jets, allowing detailed comparison of the turbulence properties, in particular estimates of the energy budgets.

Methods and Results

An open circuit wind tunnel was used to study negatively buoyant jets in coflow at initial conditions of $Re \approx 19,000$ with simultaneous PIV and acetone PLIF. Measurements were acquired at three downstream locations and two density ratios ($At = 0.1, 0.6$). 10,000 snapshots of the flow for each condition were acquired. Spatial resolution was ~280 µm, well below the Taylor microscale and within about 1 order of magnitude of the Kolmogorov length.

Results have revealed differences in production of turbulent kinetic energy, dissipation rates, and variations in the turbulent length scales between low and high density ratio cases, and can be used for validation of computer simulations and new variable density turbulence models.

Figure 1: a) Schematic of test section. b) Relative size and position of interrogation regions. c) Instantaneous velocity and density field for $At=0.6$ (vectors downsampled for clarity).

Figure 2: Comparison of a) turbulent kinetic energy, b) dissipation rates, and c) length scales.
High resolution 3-D radiation hydrodynamics modeling of inertial confinement fusion implosions on the National Ignition Facility


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Considerable progress has recently been made in improving the performance of inertial confinement fusion implosions on the National Ignition Facility (NIF). In particular, recent “high foot” implosions that use a stronger radiation drive during the early phase of the implosion (the “foot”) have reached neutron yields an order of magnitude higher than previous “low foot” implosions. Nevertheless, the measured yields of many of these implosions, particularly at high laser energies and using the thinnest ablator shells, are significantly below the predictions of 2-D radiation hydrodynamics modeling that resolves only the longest wavelength perturbations. To address this discrepancy, this talk describes detailed 3-D simulations of four high foot implosions with sufficient resolution to capture all of the relevant perturbations believed to impact these implosions. These simulations represent the state-of-the-art in 3-D multi-physics modeling of NIF implosions and can resolve ablation front instability growth at wavelengths as small as 50 µm over the full sphere. To do so, they require roughly 500 million computational zones, 5 million CPU-hrs to complete, and generate ~ 100 TB of data per simulation. Nonetheless, when all of the relevant scales are included, the simulations show reasonable agreement in neutron yield with the experimental data, and roughly a factor of two greater yield degradation is found when comparing comparable 3-D to 2-D simulations. Additionally, a factor of several greater yield degradation is found comparing fully resolved 3-D simulations to simulations that resolve only the longest wavelength perturbations. The results of these simulations suggest a growing level of understanding of the high foot implosion platform and emphasize the need for fully resolved simulations to model accurately the complex physics of high convergence implosions on NIF.

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Prefer Oral presentation.

References

Numerical Simulations of KH, RM and RT Instabilities

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Rayleigh-Taylor (RT), Richtmyer-Meshkov (RM) and Kelvin-Helmholtz (KH) instabilities serve as efficient mixing mechanisms in a wide variety of flows, from supernovae to jet engines. In computing these instabilities, the primary challenges are to: (1) capture all relevant physics, (2) conserve mass, momentum and energy, (3) resolve an adequate range of scales, (4) minimize numerical errors and (5) bring the results into agreement with experiments. Carefully crafted numerical simulations, like experiments, can sometimes lead to the discovery of previously unknown flow phenomena. Over the past decade, we have used the Miranda code to temporally integrate the multi-component Navier-Stokes equations at spatial resolutions up to $3072^3$ grid points. The code employs 10th-order compact schemes for spatial derivatives, combined with 4th-order Runge-Kutta time advancement. Some of our major findings are as follows: The rate of growth of a mixing layer is equivalent to the net mass flux through the equilibrium plane. RT growth rates can be significantly reduced by adding shear. RT instability can produce shock waves. The growth rate of RM instability can be predicted from known interfacial perturbations. Thermal fluctuations can seed instabilities along KH braids. And finally, enthalpy diffusion is essential in preserving the second law of thermodynamics.

Figure 1: Miranda simulation of RM instability exhibiting vortex projectiles.

References

Turbulent mixing by buoyancy-driven flows in long tubes

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Abstract

We explore the buoyancy-driven turbulent flow that develops due to a change of orientation for a long tube initially filled with a statically stable stratification. For simple orientation histories, the flow may be characterised by the low mixing of a gravity current, the modest mixing of Kelvin-Helmholtz instability, or the much greater mixing of Rayleigh-Taylor instability. However, precise details of the orientation history can prove to be important. We present experimental results, along with some simple numerical simulations, for a range of orientation histories, exploring both the temporal development of the flow and the level of mixing achieved.

Figure 1: Evolution of Rayleigh-Taylor unstable density stratification a tall tube where the angle to vertical is oscillated by ± 5°.

\textbf{Type C}, \( A = 0.01471, \theta = 5.0 \)

\textbf{Filtered} \( \bar{C} = 0.0182 \)

\textbf{Filter} \( \bar{h}/W = \beta/\sqrt{T_i} \); Fit: \( \beta = 2.316 \)
Non-Linear Modeling and Simulation of Richtmyer–Meshkov Instabilities

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Hydrodynamic instabilities that result from the interaction of a shock-wave with a perturbed interface are known as Richtmyer–Meshkov instabilities (RMI). RMI is important in a wide variety of applications including Inertial Confinement Fusion. Recent work at Los Alamos National Laboratory has focused on extending non-linear interface stability models to RMI with a goal of computing initial conditions for turbulence models (Rollin & Andrews 2013). Ongoing experiments at Los Alamos National Laboratory (LANL) are focusing on careful measurement of initial conditions and repeated statistical measurements of the instability growth and transition to turbulence. This talk will discuss current efforts to model these experiments using non-linear theoretical models and scale resolving two and three-dimensional simulations.

Analysis of the experimental data supplies the initial condition for the theoretical model and the numerical simulation. The effect of different initial conditions and mesh resolutions will be examined to build confidence in the simulations and study the role of non-linear mode coupling in early-time RMI. Comparison of the different models to experimental data will be presented. All calculations are performed in the arbitrary Lagrangian/Eulerian (ALE) code FLAG, developed at LANL.

Figure 1: Material Interface from a 3D FLAG calculation of the LANL Vertical Shock Tube Experiment

References
Numerical and experimental study of the Rayleigh-Taylor instability of the Newtonian and non-Newtonian fluids

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Submission of abstracts

The present work is devoted to the DNS simulation of the Rayleigh-Taylor instability of non-Newtonian fluids. The main aim of this work was to carry out the numerical simulations of intermixing of two media with different rheology and different Atwood numbers and getting the width of the mixing layer and the kinetic energy spectra, depending on the basic properties of the shear thinning liquids and the Atwood numbers. Theoretical study is carried out on the basis of the system of the Navier-Stokes equations for weakly compressible media.

![Figure 1: The topology of the contact boundary of fluids at different times.](image)

During the numerical experiments of the Rayleigh-Taylor instability with the multimode perturbation of the contact boundary (Figure 1) it was found that the stirring of the dilatant fluid is similar to the mixing regime of the Newtonian fluid. Thus, the corresponding coefficients of turbulent mixing $\alpha$ have similar values. Increase in the width of mixing layers for visco-plastic and pseudoplastic liquids are significantly different from that for the Newtonian fluid.

Present work provides proof of the combined influence of fluid rheology and the Atwood number on the development of the Rayleigh-Taylor instability. For example, growth rate of the mixing layer width for the pseudoplastic fluid significantly depends on the Atwood number.

Besides that, the Rayleigh-Taylor instability in the inviscid and viscous cases is investigated, based on numerical simulations of the Euler and the Navier-Stokes equations. Our study demonstrates that emerging flows and their characteristics are identical for both models.

In addition, the results of experimental studies of the Rayleigh-Taylor instability in a system of non-Newtonian fluid and air (i.e. the Atwood number equals to $\sim 1$) are presented.
Richtmyer-Meshkov Induced Turbulent Mixing in Dense Implosing Shells

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We present simulations of turbulent mixing in implosions of dense spherical and cylindrical shells, where we compare five different numerical codes: FLASH (Fryxell et al. 2000), TURMOIL (Youngs & Williams 2008), HYDRA (Marinak et al. 1996), MIRANDA (Cook et al. 2004) and FLAMENCO (Garcia-Uceda et al. 2014, Thornber & Zhou 2015). The numerical setup is based on the test case described in Joggerst et al. 2014. Overall, there is good agreement between the different codes with respect to the growth of the mix layer, but there are differences in the small-scale mixing.

We consider 2D single-mode calculations as well as a 3D narrowband and a 3D broadband case. The 2D results compare well with the predictions from an analytically solvable Bell-Plesset model. When including the effect of the compression of the mix layer due to the convergence of the flow, the narrowband case can be fitted by a model which assumes a self-similar growth law for a single shock with a power-law index $q = 0.25$. Finally, we use the analytical results from the Bell-Plesset model to construct a just-saturated-mode model that can be used to describe the mix layer growth in the 3D broadband case.

References
Shear instabilities in high-energy-density (>100 GJ/m³) physics are important for understanding how compressible turbulence affects late-time quenching of inertial fusion capsules. A counterflowing shear experiment initially designed for the Omega Laser studies shear instability in isolation by launching 110 km/s shocks along opposite sides of an Al tracer plate in a foam-filled shock tube (Doss, 2013a). When the shocks cross, a region of intense pressure balanced shear is created. As the shear instability develops, the tracer layer mixes with the surrounding foam, expanding. Radiography is compared to hydrocode simulations. Using the larger National Ignition Facility we have redesigned the experiment for indirect drive to drive larger volumes more steadily, shown in Figure 1 (Flippo, 2014; Doss, 2015). We have observed shear-induced hydrodynamic features surviving to late time (> 34 ns) suggesting that we have created a relatively long-lived volume of pure shear evolution. We have shown the ability, by controlling the broadband roughness, to completely change the evolution of the instability (Flippo, 2016; Doss, 2013b) and, using single-mode foils, to understand Kelvin-Helmholtz dynamics in the geometry of the experiment (Merritt, 2015). The design and techniques developed for these experiments are of general interest for designing indirectly-driven NIF shock tube experiments.

Figure 1: Target geometry (left) and experimental data (right) from the counterpropagating shear experiment on the 192 beam NIF Facility. Dark area is the tracer layer, and shocks are red/purple.

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Flippo, K. A., et al., 2016 Late-time mixing sensitivity to initial broadband surface roughness in high-energy-density shear layers, Phys. Rev. Lett (submitted)
Mixing processes in an inlet-injected scramjet

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The performance of scramjet engines is often limited by the extent of fuel-air mixing. One technique for increasing mixing efficiency is to inject fuel upstream of the combustor, within the inlet of the scramjet. Here, we investigate the mixing processes in a planar, inlet-injected Mach 8 scramjet flow-path via wall-modelled large-eddy simulation. The flow-path is fuelled with hydrogen through four sonic porthole injectors located on its intake ramp. At the combustor entrance, the turbulent fuel plumes interact with an oblique shock wave generated by the engine cowl, and an expansion fan generated by the intersection of the intake ramp and the combustor. These interactions have a dominant role in the mixing process, with the baroclinically generated vorticity causing the fuel plumes to roll-up in the opposite sense to the counter rotating vortex pair generated by the injection process. This reverse roll-up enhances both entrainment of air into the fuel plume and the mixing rate. The evolution of the fuel plumes is also found to be substantially affected by their confinement, either by the adjacent fuel plumes or the combustor walls. The interaction of the fuel plumes with the separated flow at the combustor entrance and the combustor corner vorticies is examined. These are responsible for rapidly mixing and transporting a small fraction of the fuel that plays a key role in the ignition process. Overall, it is determined that inlet-injection has a transformational effect on the mixing process with scramjets and thus has the potential to substantially increase their performance.

Figure 1: Visualization of the instananeous vortex cores within half of an inlet injected scramjet. The isosurface is colored with product mass fraction contours. Pressure contours are shown on the walls.

Preference: Oral
Progress in Eulerian Simulations of Multi-Material Elastic-Plastic Flow

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The aim is to develop a simulation capability for capturing multi-material mixing involving elastic-plastic solids undergoing large deformations that are of interest in disciplines such as inertial confinement fusion, cavitation and metal welding. Eulerian, as opposed to Lagrangian or Arbitrary Lagrangian-Eulerian, methods are more suitable for the current problems of interest. We use the framework for elastic-plastic flow developed by Plohr and Sharp (1992), and the diffuse-interface approach for multiple materials by Ndanou et al. (2015). A tenth-order compact finite-difference scheme with artificial fluid properties to capture shocks, previously applied to multi-fluid turbulent mixing (Cook, 2007), is used for the problems of interest here.

As an example of a 2D calculation of rotational plastic flow, we consider two plates with matching sinusoidal edges that impact each other obliquely with velocities \( (u, v) = (\pm 300, \pm 300) \) m/s. As shown in Figure 1, the vorticity initialized at the interface remains predominantly in the interface region, and drives stirring processes. This is in contrast to purely elastic solids, where vorticity is transported out by shear waves, and no mixing occurs. The velocity vectors indicate pockets of circulation not very dissimilar to Kelvin-Helmholtz instability. Demonstration of this method for other elastic-plastic problems, such as the multi-material Wilkins’ flying plate and capsule-implosion problem, will be presented at the conference.

![Figure 1: Vorticity contours in red and blue overlaid with velocity vectors in black and green demonstrating plastic flow in an oblique collision between plates with matching sinusoidal edges at two time instants.](image)

This work was supported by Grant B612155 from the Lawrence Livermore National Laboratory, US Department of Energy.

References
Blast wave induced mixing in a laser ignited hypersonic flow

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In the experiments of Brieschenk et al. [1], hypersonic flow over a ramp with a hydrogen injector was ignited using a laser pulse. The experiments determined that ignition could be achieved in the cold conditions favourable for a low compression scramjet, by using an external source of energy to ignite the flow. In a previous paper, Gibbons et al. [2], we investigated the mechanics of this ignition process using Wall-Modelled Large Eddy Simulations to study how the laser induced spark expands and drives a blast wave out into the fuel plume (see Figure 1). The primary ignition mechanism was determined to be the shock heating of gas in front of the jet, but the blast wave also deposits vorticity on the fuel plume and increases the mixing rate. In this work we will use the simulation results to determine whether the mixing enhancement is a significant factor in the ignition process.

Figure 1: Simulation of hypersonic crossflow at Mach 9, 250 ns after laser pulse. Background shows density gradients, overlayed by stoichiometric ratio ($\phi$) and atomic hydrogen mass fraction ($Y_H$).

References


A modified dissipation equation for Reynolds stress models dedicated to buoyancy driven turbulence

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The turbulence induced by buoyancy, occurring for instance in Rayleigh-Taylor mixing, remains challenging to model even with Reynolds stress models (RSM). Unsteady stratified homogeneous turbulence (USHT) is an idealized configuration providing a useful framework to study this type of buoyancy induced turbulence (Griffond et al. 2014). A spectral turbulent model, based on an EDQNM closure, has been developed and validated against DNS for USHT (Burlot et al. 2015). Then, it has been used to provide reference results for one-point statistics evolutions allowing to assess one-point turbulence models (Gréa et al. 2016).

In Ref. (Gréa et al. 2016), a $k-\varepsilon$ model, a two-fluids two-structures one called “2SFK” (Llor & Bailly 2003) and an augmented RSM called “GSG\(^+\)” (Souffland et al. 2014) have been tested against the reference results. Poor comparisons are obtained not only for the $k-\varepsilon$ model but also, unexpectedly, for the more sophisticated models. For GSG\(^+\), this is surprising for the following reasons. First, the model is compatible with the rapid distorsion theory, so that it should capture the initial dynamics. Second, the coefficients are chosen to also give the correct long-time asymptotic evolution. Consequently, both ends being correct, GSG\(^+\) was expected to give correct predictions for the whole times.

In the current work, we try to identify the origin of this issue and propose a way to improve it for the RSM. After close examination, the flaw of GSG\(^+\) can be traced back to the dissipation equation that is classically derived from an analogy with the turbulent kinetic energy equation. A hint of the trouble is found by comparing it to the 2SFK-equation for dissipation that is based on the sole so-called “non-directed” kinetic energy instead of the total turbulent kinetic energy. Introducing conditional averaging in the stochastic model from which GSG is derived allows us to decompose the kinetic energy into two parts: one conditioned on the concentration field and the remainder. Deriving the dissipation equation for GSG\(^+\) from the latter leads to an improvement of the results.

References


COARSE GRAINED SIMULATIONS OF TURBULENT MATERIAL MIXING

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The mixing of initially separate materials in a turbulent flow by the small scales of turbulent motion is a critical and often poorly understood element of many research programs, such as inertial confinement fusion, supernova implosions and explosions, combustion, as well as many other applications in engineering, geophysics, and astrophysics. In typical contexts of interest, we are interested in detailed understanding of the consequences of material interpenetration, hydrodynamical instabilities, and mixing arising from perturbations at the material interfaces. Under-resolved computer simulations are often unavoidable in the turbulent flow applications exhibiting extreme geometrical complexity and a broad range of length and time scales. In such applications coarse grained simulation (CGS) is the practical simulation approach. In CGS, large energy containing structures are resolved, smaller structures are spatially filtered out, and effects of unresolved subgrid scales (SGS) are modeled. CGS includes classical LES [1] using explicit SGS models, implicit LES (ILES) [2] relying on SGS modeling implicitly provided by physics capturing numerics, and more general LES combining explicit / implicit SGS modeling. CGS predictability for under-resolved material mixing driven by under-resolved velocity fields and under-resolved initial conditions (IC) in simulations of shock-driven turbulent material mixing is our focus.

Robust CGS for dissipative turbulent phenomena exhibiting enslavement of small-scale dynamics is achievable with suitable SGS modeling, enough scale separation, and well-resolved IC. However, late-time predictability assessments for high-Re phenomena can not be robust when inherent CGS grid resolution (or explicit spatial filtering) sensitivities are present: simulations and analysis are constrained by the characterization and modeling of (intertwined) SGS and IC specifics – while nature controls the flow physics independently. Because of chaotic variability associated with unavoidable small perturbations (uncertainties) of presumed IC, it may be impossible even within a mathematically well-posed dissipative flow simulation framework to provide realistic late-time solutions good enough to address specific questions of interest. The impossibility of very-long-range predictions for weather forecasting [3] comes appropriately to mind here; we find similar challenging issues when attempting late-time measurements of shock driven turbulent material mixing very sensitive to initial material interface conditions [4].

Ensemble averaged CGS over a suitably complete set of realizations covering the relevant IC variability to address the chaotic sensitivity issues is a strategy of choice – but is also computationally expensive. Transition to turbulence involves unsteady large-scale 3D vortex dynamics, which can be captured by CGS but not by single-point closures typically used in RANS [5]. State-of-the-art industrial aerospace/ automotive simulations rely on 3D RANS and 3D hybrid RANS/LES as main strategies to drastically reduce computational costs in full scale configurations – with the recognition that 3D unsteady RANS should be used to capture the 3D flow physics even when 2D geometries are involved [6,7]. We explore the 3D unsteady RANS realm for engineering emulations [6], where computed and modeled dissipation can be blended, 3D IC can be prescribed, and improved non-equilibrium statistical predictions of interest become possible by having just enough 3D-ness and grid resolution. We report the use of 3D RANS in simulations of canonical shock-tube experiments of interest. A vision is presented for extending the hybrid RANS/CGS strategies for variable density turbulent flows.


Filtered-velocity based LES of variable-density compressible flows

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Understanding mixing processes in high-speed reacting flows is essential to development of scramjet engines for hypersonic propulsion. Scramjet flows exhibit strong spatio-temporal density variations that arise due to heat release, compressibility and differences in composition. Strong density gradients, associated with baroclinic and dilatational sources of vorticity, influence the local flow dynamics. The present work aims to study these physical effects at small scales and develop subgrid-scale models for this class of flows. We work with the formulation that employs filtered velocity ($\bar{u}_i$) as the resolved-scale velocity variable. This is because the conventional formulation with density-filtered velocity ($\tilde{u}_i$) masks the contribution of subgrid-scale variable-density and compressibility effects. One such effect is the subgrid-scale acceleration arising from the non-linear interactions of pressure gradient and density. The proposed LES formulation explicitly incorporates these effects. The subgrid-scale terms are analysed on simulations of decaying turbulence initialized with unmixed variable-density fluids. Two different turbulent Mach numbers are considered.
Detailed High-Resolution 3D ILES Simulations of OMEGA Separated Reactants ICF Experiments

Brian M. Haines¹, G. Grim², J. Fincke¹, R. Shah¹, C. Forrest³, K. Silverstein³, F. Marshall³, M. Boswell¹, M. Fowler¹, R. Gore¹, A. Hayes-Sterbenz¹, G. Jungman¹, A. Klein¹, R. Rundberg, M. Steinkamp¹, & J. Wilhelmy¹

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We present high-resolution 3D simulations of implosions of separated reactants ICF capsules performed at the OMEGA laser facility. The capsules, called “CD Mixcaps,” consist of a polystyrene (CH) shell with a deuterated (CD) layer with varied burial depths and are filled with tritium gas. In these implosions, DT fusion reactions occur only in the presence of mix between gas and shell material. Simulations feature accurate models for all known experimental drive and target asymmetries. Importantly, no adjustable parameters are used to improve agreement with experimental data. Simulations are performed with the RAGE radiation-hydrodynamics code using an Implicit Large Eddy Simulation (ILES) strategy for the hydrodynamics. We obtain good agreement with experimental data (see Fig. 1), including the DT/TT neutron yield ratios used to diagnose mix, for all capsules. Simulated capsule performance and mix metrics also demonstrate good agreement with converged simulations employing explicit models for plasma diffusion and viscosity.

In our simulations, mixing is driven by short-wavelength asymmetries and transported towards the center of the hot spot by longer-wavelength features. Without long-wavelength asymmetries, the DT/TT neutron yield ratio is underestimated by 50% and TT neutron yield is overestimated by 75% (see Fig. 1). Consistent with our previous results, mix does not play a significant role in TT neutron yield degradation; instead, this is dominated by the displacement of fuel from the center of the implosion due to long-wavelength asymmetries. Through these processes, the long-wavelength asymmetries degrade TT yield more than the DT yield and thus bring DT/TT neutron yield ratios into agreement with experiment.

In order to assess the importance of 3D flow effects, we perform comparisons of 2D and 3D simulations with all asymmetries. At bang time, 3D flows cause a 20% increase in the mixing layer width, a 7% enhancement to an integrated mixing metric, and a 25% increase in the separation between the fuel and internal energy due to long-wavelength asymmetries. Together, these lead to an increase of 15% in the DT/TT neutron yield ratio in 3D.

Figure 1: Comparison of simulation and experimental results.
The effect of initial conditions on the turbulent Richtmyer-Meshkov instability

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A vertical shock tube is used for experiments on the Richtmyer-Meshkov instability (RMI) in which an interface is formed by opposed gas flows where the light and heavy gases enter the shock tube from the top and from the bottom of the driven section. An air/SF₆ gas combination is used and an $M = 1.2$ incident shock wave impulsively accelerates the interface. Initial perturbations are generated by harmonically oscillating the gases vertically, using two loudspeakers mounted in the shock tube walls, to produce Faraday resonance resulting in a random short wavelength perturbation. Planar Mie scattering is used to visualize the flow using a laser sheet to illuminate smoke particles seeded in one of the two gases. Experiments are presented quantifying the growth of the integral mixing layer width in addition to the spectra of the initial perturbation. These results are then compared with with the model of Youngs (2004) in which the turbulent RMI initiated from a broadband initial perturbation with a spectrum of the form $P(k) = C k^s$ results in the width of the developing mixing layer having power law growth with a growth exponent $\theta = 2/(s + 5)$. New analysis of results from our shock tube experiments appear to show agreement with Youngs’ model indicating that our experiments are strongly dependent upon the initial conditions.

References


An oral presentation preferred.
Numerical simulations and experiments of ejecta production from second shock

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Abstract

We consider hydrodynamic continuum simulations to mimic ejecta generation in recent two-shockwave target experiments at Los Alamos National Laboratory [1], where a metallic surface was loaded by two successive shock waves. The numerical simulations were performed with the astrophysical FLASH code, developed at the University of Chicago. The time of second shock arrival in the simulations was varied to generate interfaces of different amplitudes for the second shock impact. The negative Atwood number ($A \rightarrow -1$) of ejecta simulations leads to two successive phase inversions of the interface corresponding to the passage of the shocks from heavy to light media in each instance[2]. In experiments[3], the precise composition of the metallic phase of ejecta (solid/liquid) can depend on the shock-loading pressure, and we find that hydrodynamic simulations quantify the liquid phase ejecta physics with a fair degree of accuracy, where RM instability is not suppressed by the strength effect. In particular, we find that our results for the free-surface velocity, maximum ejecta velocity, and maximum ejecta areal density following second shock are well explained by a recently proposed model [4] that accounts for the shape of the groove immediately before the shock impact. We also comment on the parametric space for hydrodynamic simulations in which they can be used to compare with the target experiments.

Acknowledgments: This work was supported by the (U.S.) Department of Energy (DOE) under Contract No. DE-AC52-06NA2-5396. FLASH was developed by the DOE-sponsored ASC/Alliance Center for Astrophysical Thermonuclear Flashes at the University of Chicago.

Figure: Ejecta visualized through density contours from a continuum hydrodynamic simulation.

References
Flow field manipulation in hypervelocity scramjets

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As scramjets progress from proof-of-concept engines to operable three-dimensional (3D) systems, fuel injection techniques must adapt. With 3D engines utilising the vehicle forebody as a compression plane, thick boundary layers develop over this body side surface, while the opposing (cowl) side is subjected to rapid shock compression at the engine closure point. Flow property variations across the engine’s height leads to non-uniform, density stratified flow entering the combustor, with the majority of captured air passing through a high dynamic pressure, cowl side core flow. This has been observed in 3D computational fluid dynamic simulations of the Mach 12 Rectangular-to-Elliptical Shape-Transitioning (M12REST) scramjet, where combustor-based hydrogen fuelling techniques, successful in lower speed engines (Chan et al., 2014), display low penetration, failing to access centreline oxygen (Landsberg et al., 2014). Aiming to increase jet penetration, three cowl side injectors were converted to a single, larger jet, placed upstream of the combustor entrance. This ‘manipulator jet’ is placed such that it injects directly into the cowl side core flow, in addition to injectors placed on the combustor entrance side walls. Chemically reacting solutions to the Reynolds-Averaged Navier-Stokes equations were developed, with equations closed through the SST-Menter turbulence model. The combustor-nozzle segment of this manipulated flow field is presented in Figure 1, with contours of oxygen mass fraction shown.

Figure 1: Oxygen mass fraction contours of the M12REST combustor-nozzle flow path.

Contrasting the previous injection scheme, the manipulator jet penetrated into the core flow. The induced vortical structures act to drag air from the centreline, relocating the unreacted oxygen to the engine cowl side. Following design optimisation of the manipulator jet to reduce the hydrogen flow rate to the minimum required, supplementary boundary layer injectors placed at the combustor entrance may provide improved combustion efficiency as part of a multifaceted fuel injection scheme.

References

Landsberg, W.O., Barth, J.E., Veeraragavan, A., Wheatley, V. and Smart, M.K., 2014 Tailored fuel injection within a Mach 12 shape transitioning scramjet. \textit{19th Australasian Fluid Mechanics Conference. RMIT University}
On the role of internal waves in variable acceleration Rayleigh-Taylor instability

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Recent work on Rayleigh-Taylor instability has extended understanding of the classical case of constant acceleration to more complex acceleration profiles. The accel-decel-accel profile has received some attention (Ramaprabhu et al. (2013), Ramaprabhu et al. (2016)) in the literature, and it is on the ‘decel’ phase of this problem that we focus our attention in the present work. Here, the source of potential energy that drives a Rayleigh-Taylor-unstable flow is removed. In the reference frame of the fluid there is no longer an unstable density gradient, but is replaced with a stable one instead. Stable stratifications have a real-valued buoyancy frequency, and energy is transported horizontally within the mixing layer by internal- and interfacial-wave-like processes. Following the dispersion relation for such waves, their evolution leads to de-correlation of previously coherent bubble and spike structures, and the manner in which this occurs influences subsequent behaviour in the following re-acceleration. Interfacial waves are well-known to follow a dispersion relation of the form

\[ \omega = f(A, k) \]  

(1)

where A is the Atwood number, and \( k = 2\pi/\lambda \) is the mode number. Treating the mixing layer as sharp with respect to an infinite domain, we would expect a range of phase speeds dependent on the spectral distribution present at the acceleration-deceleration transition. Looking in more detail at the structure of the mixing layer, the density stratification has a pronounced change in gradient from top to bottom, so the natural frequency of buoyant internal oscillations is not uniform throughout the thickness of the mixing layer. The dispersion relation for such waves is spatially more complex but on average we would expect vertical transmission of energy towards the middle of the mixing layer, focussing energy away from coherent structures at its periphery. In the present work we report MOBILE simulations that verify these intuitions and identify the relationship between phase-decorrelation of coherent structures during deceleration and the statistical properties of the following re-acceleration.

References

Converging double-interface Richtmyer-Meshkov instability in magnetohydrodynamics

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Abstract

The Richtmyer-Meshkov instability (RMI) occurs when a perturbed density interface is accelerated by a shock, and is relevant in inertial confinement fusion (ICF). Recently Mostert et al. (2015) examined the detailed wave structure and dynamics of implosion of a single interface for various seed magnetic field configurations. Motivated by the presence of multiple density interfaces in ICF, we numerically investigate the RMI when a converging cylindrical shock interacts with a density layer in the presence of a saddle-topology seed magnetic field. The initial setup is shown in Figure 1(t=0) where the converging shock is the result of a cylindrical Riemann problem initialized upstream of the density layer. The parameters of relevance are: the strength of the converging shock, density ratios across both interfaces, the thickness of the density layer, and the seed field strength. Figure 1 shows the time evolution of the density field for both magnetohydrodynamics (MHD) and hydrodynamics (HD). We observe a suppression of the instability at both interfaces in the MHD case. We will explore the parameter space, quantify the growth rates of the interfaces and the transport of vorticity in our adaptive mesh numerical simulations. Moreover, the effect of the re-shock on these RMI flows will also be examined.

Figure 1: Density field: initial condition (t=0), before and after reshock. Top row: HD case. Bottom row: MHD case. The boxes in the center images indicate adaptive mesh outlines.

References

Taylor, Rayleigh-Taylor and Richtmayer - Meshkov Instabilities in Shock Waves of two phase gas - liquid media

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Our preference for Oral presentation.

Shock wave spall off at the free surface

When the shock wave comes out on the free surface of a condensed medium is formed due to a cloud of flying microparticles manifestations such complex phenomena as the spall fracture, instability of the surface of the development environment, cavitation. Despite a long history of studying this process, many questions remain open. Of particular interest is the formation and distribution of the fine droplets in the sizes and speeds, depending on the flow parameters and rheological properties of the medium.

In the present paper the experiments and calculations to study the processes of dispersion layer of water at the outlet at its free surface of the shock wave are developed. In the experiments the shock wave is created in a layer of water by the evaporation of a powerful laser pulse thin target located on the lower surface of the layer of water. The results are shown in Figure 1.

![Figure 1: The spall droplets structure when shock wave comes out the free surface at the boundary water and air.](image-url)
Shock waves in bubble gas-liquid media

The experimental research of shock wave creation in a supersonic flow of gas - liquid mixture ahead of the cylinder is investigated. The experimental setup for the production of a supersonic flow of gas - liquid bubble media at different gas contents, Mach and Reynolds numbers is designed and built. The creation of shock wave and detachment of incident flow to the cylinder are considered. Dependences of the shock wave separation on the gas content and Reynolds number are measured. The results are shown in Figure 2.

![Shock wave visualization at different gas content, Reynolds number Re and Mach number M.](image)

Figure 2: Shock wave visualization at different gas content, Reynolds number Re and Mach number M.

Numerical simulation

The numerical simulation based on the multiphase hydrodynamics is developed. Instabilities and turbulent flows are considered.

References


Testing an analytic model for Richtmyer-Meshkov turbulent mixing widths

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We discuss a model for the evolution of the turbulent mixing width \( h(t) \) after a shock or a reshock passes through the interface between two fluids of densities \( \rho_A \) and \( \rho_B \) inducing a velocity jump \( \Delta V \). In this model the initial growth rate is independent of the surface finish or initial mixing width \( h_0 \), but its duration \( t^* \) is directly proportional to it: \( h(t) = h_0 + 2\alpha A \Delta V t \) for \( 0 \leq t \leq t^* \), and \( h(t) = h^* \left( 1 + \left( \frac{h^*}{\theta^*} \right) (t - t^*) \right)^{\theta} \) for \( t \geq t^* \). Here \( A \) is the Atwood number \( (\rho_B - \rho_A)/(\rho_B + \rho_A) \), \( \alpha \) and \( \theta \) are dimensionless, \( A \)-dependent parameters measured in past Rayleigh-Taylor experiments, and \( \beta \) is a new dimensionless parameter we introduce via \( t^* = (h_0/\Delta V)\beta \). The mixing width \( h \) and its derivative \( \dot{h} \) remain continuous at \( t = t^* \) since \( h^* = h_0 + 2\alpha A \Delta V t^* \) and \( \dot{h}^* = 2\alpha A \Delta V \). We evaluate \( \beta \approx 6 \) at \( A \approx 0.7 \) from air/SF\(_6\) experiments and propose that the transition at \( t = t^* \) signals isotropication of turbulence. We apply this model to recent experiments (Jacobs et al., 2013) on shock and reshock, and discuss briefly the third wave causing an unstable acceleration of the interface. We also consider the experiments of Weber et al. (2012) and argue that their smaller growth rates reflect density gradient stabilization.


Comparing evolution of miscible high Atwood number Rayleigh-Taylor instability between experiments and simulations

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Abstract

Rayleigh-Taylor (RT) instability presents itself in a variety of phenomena. Most of these applications involve complex physics and vary dramatically in length and time scale. In order to understand these complex situations, effort has been made to develop models to describe variable-density mixing and turbulence. The modeling community has also called for experimental results for validation. In this presentation, turbulence statistics from statistically steady RT instability experiments are presented and used to validate numerical simulations.

The experiments are performed in a convective-type two-layer gas tunnel facility using air and an air-helium mixture as the working fluids to develop an Atwood number of 0.73. Visualization techniques are used to collect mixing height and growth rate data and to observe the qualitative structure of the flow. Particle image velocimetry (PIV) and hot wire anemometry collect velocity and density statistics. Significant asymmetry is observed between spike and bubble growth rates in agreement with previous work. Density-velocity statistics show the importance of the spike in increasing turbulent mass flux and driving turbulence production. Numerical simulations were completed using the FLAG hydrocode developed at LANL. One-dimensional simulations using a RANS approach with BHR turbulence closure model were initialized with similar Atwood numbers as those present in the experiments. Resulting growth rates and turbulence statistics were found to be in good agreement with both currently presented experiments and direct numerical simulations found in literature.

References

Numerical simulation of Rayleigh-Taylor instability development in experiments with increasing acceleration on RFNC-VNIITF facility


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Numerical study of Rayleigh-Taylor (RT) instability development was carried out for two incompressible liquids which are under the influence of increasing acceleration. Atwood number for liquids was 0.5. Results of calculations were compared to the experimental data received on facility in RFNC-VNIITF. The ampoule (Figure 1a) with the investigated liquids is accelerated vertically upwards to the certain velocity, and then it is braked with the acceleration $\ddot{g}(t)$. The heavy matter, ZnCl$_2$, is located below the light one. The RT instability has been growing since the beginning of the ampoule braking. Time dependence of $\ddot{g}(t)$ is close to the linear, the maximum value of acceleration reaches 100$g_0$.

![Figure 1](image-url)

Figure 1: a) the scheme of the experiment; b) the amplitudes of the bubbles ($Z > 0$) and jets ($Z < 0$) vs. parameter $S = \left[ \int \sqrt{\dot{g}(t)} \, dt \right]^2 / 2$. CB – contact boundary

Initial perturbations of contact bound are defined by rings with a diameter of 2 mm arranged in a grid of thin lines. The size of the grid cell equals to 4 mm and determines the length of initial perturbations. The size of the CB area is 5x6 cm$^2$.

Numerical modelling is carried out by FOCUS code in 2D and 3D cases. In the simulation the physical viscosities of matter components were considered. The calculated width of mixing zone is in good agreement with the experimental data (see Figure 1b). The 3D simulation reproduces the growth rate of the mixing zone more accurately than 2D approach. The self-similarity factor, bubbles growth rate, is found to be $\alpha_0 \approx 0.04$. The evolution of a spectrum of turbulent kinetic energy is analysed too.
Spherical Richtmyer-Meshkov in MHD with an octahedrally symmetric magnetic field

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Previous research has suggested that the Richtmyer-Meshkov instability (RMI) resulting from shock interaction with a perturbed density interface may be effectively suppressed by the presence of a magnetic field (Samtaney, 2003; Wheatley et al., 2005; Mostert et al., 2015). Here we present simulations of the RMI in spherical implosions using ideal magnetohydrodynamics (MHD) in the presence of an octahedrally symmetric magnetic field generated physically by a suitably symmetric arrangement of six current loops. The RMI flow is initiated with a spherical Riemann problem. This launches an imploding shock that impacts an interior perturbed spherical density interface. Light-heavy, heavy-light, and light-heavy-light density configurations are considered. For light-heavy RMI flows, results for the octahedrally symmetric field are compared with those obtained using both a uniform, unidirectional field (formed by one current loop) and a field formed by two current loops. We show that MHD suppression of the RMI in the presence of the octahedrally symmetric field is comparable in extent to that observed with a uniform, unidirectional magnetic field, and greater than that for the two-loop field. The mechanism of suppression is generally consistent with that identified in previous studies (Wheatley et al., 2005; Mostert et al., 2015), while the extent of suppression of the RMI varies between different interface types. An interesting result is that the octahedrally symmetric field case suppresses the RMI while maintaining the degree of radial symmetry close to that of the purely hydrodynamic case (Figure 1).

Figure 1: Light-heavy density isosurface in octant domain at comparable time with pressure on principal planes. Hydrodynamic (left) and magnetized with octahedrally symmetric field (right).

References

Cylindrical shock collapse in MHD

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Symmetrical shock collapse producing divergent thermodynamic behavior at the axis (cylindrical) or center (spherical) of shock impact is an important phenomenon in the gas dynamics of Richtmyer-Meshkov instability for converging geometries. It is known that radially-symmetric shock convergence in an ideal gas produces asymptotically singular, self-similar radial profiles for the shock Mach number and also for both the gas pressure and temperature (see Whitham, 2011). In ideal magnetohydrodynamics (MHD), cylindrical convergence of fast MHD shocks can lead to either strong-shock, gas-dynamic like behavior for an applied axial magnetic field (Whitham 1958) or to a weak-shock limit for an azimuthal field produced by an axial line current that is constant in time (Pullin et al., 2014). Presently we discuss cylindrical, fast-MHD-shock convergence in the presence of a time-varying, azimuthal magnetic field produced by an axial line current whose strength varies as $(-t)^\mu$, where $\mu \geq 0$ is a given exponent and time $t$ is defined such that the shock reaches the axis at $t = 0$. Both detailed numerical solutions obtained using a shock-capturing MHD solver (Samtaney et al., 2005), and an analytical approximation based an extension of geometrical shock dynamics (Whitham, 2011) to the time domain will be presented. It is found that the shock collapse behavior is a strong function of $\mu$. For sufficiently small $\mu$, the spatially-singular magnetic field strength dominates the collapse dynamics leading to a weak-shock limit as the shock approaches the axis. As $\mu$ increases from $\mu = 0$, a sequence of transitions occurs where first the pressure, and then the shock Mach number become singular as the shock approaches the axis. For sufficiently large $\mu$, a regime is reached where geometrical convergence overwhelms the tendency of the azimuthal magnetic field to weaken the advancing shock and shock collapse behaves like the strictly gas-dynamic case. The stability of cylindrically converging fast-MHD shocks will also be discussed for both the axial and the azimuthal field cases.

References
The calibration of parameters in the Reynolds Averaged Navier Stokes (RANS) approach to modeling turbulent flows, based on data from Direct Numerical Simulations (DNS) and experiments, has traditionally relied on point estimates. However, it is not guaranteed that such calibration is optimal, particularly since many turbulent states are compatible with a given macro-state. We therefore revisit the question of how DNS and experiments can be used to best inform low-dimensional models of turbulence. This is made concrete by choosing a particular context: the two length scale, second moment (TLSSM) RANS turbulence model recently proposed in Schwarzcopf et al., 2015. The TLSS-MRANS model is designed to be useful for a wide variety of single phase turbulent flows spanning from incompressible flows of single fluids and mixtures of fluids of different densities to flows with shock waves. In the context of homogeneous Rayleigh Taylor (hRT) turbulence, the TLSSM-RANS model represents processes such as production and dissipation, return to isotropy and rapid distortion of second order turbulent velocity correlations, production and destruction of turbulent density-velocity and density-specific volume correlations. Indeed, differing combinations of the above processes becoming dominant at different times and spatial locations is what gives rise to the observed spatio-temporal variability of Direct Numerical Simulation (DNS) of hRT. Nevertheless, in the traditional approach to model calibration, a point estimate of the RANS model parameters is sought. We present results from a Bayesian analysis exercise that attempts to make the calibration of the TLSSM-RANS model more robust. Further implications will be discussed.

Self-similarity analysis of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities using Large Eddy Simulation

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Abstract

High-fidelity large eddy simulation (LES) of a low-Atwood number (A = 0.05) Rayleigh-Taylor (RT) mixing layer is performed using the tenth-order compact difference code Miranda. An initial multi-mode perturbation spectrum is specified in Fourier space as a function of mesh resolution such that a database of results is obtained in which each successive level of increased grid resolution corresponds approximately to one additional bubble merger generation of time integration. The database is then analyzed to determine approximate requirements for self-similarity, and a new metric is proposed to quantify how far a given simulation is from the limit of self-similarity. It is determined that the present database reaches self-similarity after approximately 4.5 bubble merger generations. This process is also performed for a single shock Richtmyer-Meskov (RM) problem with a post shock Atwood number of 0.5. Computational savings are explored by employing a hybrid compressible/incompressible for the RM calculation.
Experimental study heterogeneity in the high Reynolds number gravity-driven turbulent mixing zone of different-density gases

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Abstract

RFNC-VNIITF conducted experiments to study both distribution of heterogeneity coefficients, and also spectral distribution of gases concentration fluctuations in turbulent mixing zones under Rayleigh-Taylor instability conditions. Experiments used a shock tube generating a compression wave and also different-density gases: air – sulfur hexafluoride (Atwood number $A = 0.67$) and air – CO₂ ($A = 0.2$). The “laser sheet” method was used to record turbulent mixing evolution. Calibration curves helped to determine absolute concentrations of either gas mixture in the turbulent mixing zone for different nondimensional coordinates $\xi$. Dimensionless density profiles, heterogeneity coefficients, and also coefficients of turbulent-mixing-zone spectral response characteristics were determined based on the obtained measurement data. The distinguishing feature of our experiments is high Reynolds number (Re ~ 10⁵).
Using flyer impacting induced Richtmyer-Meshkov instability in 2A12 free surface to study yield strength at high strain-rate

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The Rayleigh-Taylor instability (RTI) in metal surface has been used to evaluate the yield strength of metal for decades. However, few researchers use Richtmyer-Meshkov instability (RMI) to study the yield strength of solid materials, for the growth of RMI is more difficult to measure. Here, we use the RMI at the free surface of an aluminum alloy (2A12), induced by using the flyer impacting technique to generate a supported shock wave, to study the material’s yield strength. Compared to the case of unsupported shock loading based on explosion, flyer impacting induced RMI may avoid possible damage/spall near the free surface of metal, which will complicate the behavior of metal surface. The DPS (Doppler Pin System) were used to monitor the velocity profiles of the spike, bubble and free surface, respectively. Under certain conditions, the trough of the initial sinusoid perturbation reverses and grows to spike and then arrests at a maximum amplitude, by which we used to infer the yield strength under high strain rates. The analysis shows that the yield strength of the 2A12 aluminum is 0.33 GPa and 0.35 GPa under shock pressures of about 28 GPa and 38 GPa, respectively. The value of dynamic yield strength does not have obvious increasing compared to static loading, indicating the yield strength of 2A12 aluminum is not sensitive to strain-rate changing even at very high strain rates.
Turbulent Characteristics of a Hypervelocity Mixing Wake

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A Large eddy simulation of the turbulent mixing between gaseous hydrogen sonically injected into a supersonic (Mach 3.5) co-flow of air has been performed. This flow is statistically homogeneous in the span-wise \( z \)-direction and shall be referred to as a mixing wake (see Figure 1). Injection occurs through a slot, 1mm high, in the rear-face of an intrusive centre-body 14mm high. The Reynolds number based upon the co-flow conditions and the height of the centre-body is 56,650.

The near field turbulent mixing develops as two parallel mixing layers, forming between the hydrogen core flow and air co-flow. Near-streamwise oriented vortices, large Reynolds stress anisotropy and suppressed transverse growth rate of these mixing layers has been observed. Flow recirculation behind the centre-body and shocklets also appear to influence the near-field turbulence.

Further downstream, reducing compressible effects, as measured by the convective Mach number, coincide with a transition in the behaviour of the mixing wake, as large scale span-wise vortex structures resembling a Karman vortex sheet become dominant. This turbulent regime exhibits a notable increase in the spreading-rate of hydrogen, greater entrainment of the faster co-flow into the core flow, and a reduction in Reynolds stress directional-bias. The implications of these observations on the design of devices which utilise compressible turbulent mixing will be discussed.

Figure 1: Visualisations of (i) static density gradient, and (ii) Q-criterion iso-surface.
Experiments from the Los Alamos Vertical Shock Tube

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Experiments at the Vertical Shock Tube at Los Alamos National Laboratory are focusing on the effects of initial perturbations of an air-SF$_6$ interface accelerated by shocks from Mach 1.2 to 1.5. The facility has a 125 mm square cross-section, with 2-D Particle Image Velocimetry and Planar Laser Induced Fluorescence measurements of the initial conditions and one dynamic time per experiment. New measurement stations are being added to increase the number of measurements per experiment. The initial conditions are created using a splitter plate between the air and SF$_6$. The three types of initial conditions studied are created by tilting and moving the splitter plate. The conditions are captured during each experiment, and approximately 80 experiments are used to characterized the spectra of the initial density interface. Figure 1 shows the spectra of the initial conditions calculated two different ways.

Figure 1: Spectra of initial conditions calculated (left) using amplitude variation based on 80 instantaneous 50% density profiles, and (right) taking horizontal lines through the interface.

As the initial conditions are varied, we see dramatic differences in the mixing evolution of the interface. Figure 2 shows the mixing at 3.4 $\mu$s after Mach 1.3 shock passage. Velocity vectors are overlayed on the density field. We will present variations in turbulence and mixing quantities as a function of initial conditions.

Figure 2: Mach 1.3 dynamic velocity and density fields at 3.4 $\mu$s after shock acceleration. Air plus acetone is white, and SF$_6$ is black.
On impulsively-driven instabilities in incompressible fluids

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Recently there has been renewed interest in understanding the scaling behaviours of shock-driven instabilities that appear across several research fields, including ICF, Type 1a supernovae and in combustion processes. One of the key questions is the long-term growth trajectory of instability, quantifying the scaling exponent in the empirical formula for the growth of Richtmyer-Meshkov instability, \(h \sim t^\theta\). We consider a form of Richtmyer-Meshkov instability initiated by impulsive baroclinic deposition in an incompressible fluid. This is distinct from the compressible problem primarily in the mechanism of initiation; interfacial development is not thereafter strongly influenced by compressibility. We study this case with a series of simulations using a miscible incompressible software package, MOBILE, with up to 512 cells resolving the spectrum of initial perturbations. The response of a perturbed interface to impulsive acceleration is a surface of injected vorticity, and we solve the three-dimensional potential flow problem, obtaining a matched pair of velocity and density fields that together form a suitable initial condition. We then evolve the flow using MOBILE, and evaluate the long-term growth of the interface. In the absence of subsequent body forcing, there is no strong source of potential energy and only a weak sink due to dissipative mechanisms, so the flow evolves for a considerable period with slowly decaying kinetic energy. Compressible solvers are time-step-limited by a speed of sound, whereas incompressible solvers scale with flow velocity, so evolving to very late time is practical for MOBILE as time-steps can continually grow. We present our findings for the scaling of such impulsively driven instabilities.
Experimental Investigation of Velocity Evolution in the Richtmyer-Meshkov Instability

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Abstract

The present work describes the evolution of the Richtmyer-Meshkov instability through a focus on the development of the structure and distribution of velocity fluctuations. In the Wisconsin Shock Tube Laboratory at the University of Wisconsin, a broadband, shear-layer initial condition is created at the interface between helium and argon. This shear layer is seeded with particulate TiO$_2$, diameter 300 nm, which is used to track the flow and allow for the Mie scattering of light. Once impulsively accelerated by a $M=1.4$ shock wave, the interface is imaged twice in close succession using planar laser imaging to create particle image pairs. Velocity fields are obtained from these particle images using the Insight 4G software package from TSI Inc. This process is repeated, capturing a total of five different times in the development of the instability, allowing for the study of the evolution of velocity fluctuations in the RMI. For each post-shock time, the velocity field structure is investigated, and probability density functions showing the distribution of velocity fluctuations are compared. Using known length scales from previous studies (Weber et al., 2014), these newfound RMS velocity values are used to give an estimate of the Reynolds number. Vorticity is also extracted from experimental measurements of velocity fluctuations, shedding light on the evolution of vortical structures as well as the distribution of this vorticity. Experimental velocity fields also allow for the calculation of the planar turbulent kinetic energy (TKE) spectrum at each of the five times in the development of the instability. Measurements of higher-order statistics have been obtained, showing a power law relation between skewness and kurtosis dependant on velocity direction. Sample particle images, velocity fluctuations, and vorticity fields are shown at three times in Fig. 1.


Figure 1: Left to right: particle images, transverse velocity fluctuations, streamwise velocity fluctuations, and vorticity fields showing the evolution of the RMI. Top to bottom: t=0.14 ms, t=0.88 ms, t=2.16 ms after shock-acceleration.

References
Porous materials under shock loading as a two-phase mixture

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Extensive mixing of particles mixture is typical in porous materials under shock compression. This mixing is seen as jetting, shear banding, fracture, and sintering in the porous materials. The inter-particle interaction is usually attracts a thorough attention of researchers. However, another aspect attending much less attention is an interaction between the solid and gaseous phases and their mixture. The present work illustrates the mixture process by meso-mechanical hydrocode modelling in a meso-mechanical approximation of particles of a porous material in the presence and absence of the gaseous phase. The modelling shows that at moderate levels of shock loading the discrepancy between these cases is quite noticeable and it diminishes with increase of the loading level. The work analyses this discrepancy and reveals that it correlates with two regimes of shock compression corresponding to abnormal and normal Hugoniot behaviour in porous materials at high porosities. The analysis associates this transition with thermal equilibrium between the condensed and gaseous phases when the porosity is sufficiently large in order to thermally expand the condensed phase due to the heating of adiabatically compressed gaseous phase. The diminishing of this factor when increasing the loading is explained by collapse of pores resulting in the compression of condensed phase in the conventional regime. The approach is illustrated by comparison of Hugoniots obtained from this theory with data available in experiments and the comparison confirms adequacy of the approach.
A Comparative Analysis of RANS Model Predictions for Rayleigh–Taylor Instability and Mixing

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Abstract

Two-, three- and four-equation, single-velocity, multicomponent Reynolds-averaged Navier–Stokes (RANS) models, based on the turbulent kinetic energy dissipation rate $\varepsilon$ or turbulent lengthscale $L$ as the second mechanical turbulence quantity, are used to simulate Atwood number 0.5 Rayleigh–Taylor instability-induced turbulent mixing with constant and complex accelerations. The constant acceleration case is inspired by the Cabot and Cook (2006) direct numerical simulation, and the complex acceleration cases are inspired by the unstable/stable and unstable/neutral cases simulated using direct numerical simulation (Livescu, Wei & Petersen 2011) and the unstable/stable/unstable case simulated using implicit large-eddy simulation (Ramaprabhu, Karkhanis & Lawrie 2013). The model includes mixture molecular transport terms, enthalpy diffusion terms, pressure–dilatation and dilatation dissipation models, as well as a molecular mass diffusion flux with contributions from baro- and thermodiffusion. The four-equation models couple transport equations for the mass flux $a$ and negative density–specific volume correlation $b$ to the $K–\varepsilon$ or $K–L$ equations, while the three-equation models use a two-fluid algebraic closure for $b$. The predicted mixing layer widths, as well as various turbulence statistics, fields, and turbulent transport equation budgets are compared systematically among these models to identify similarities and differences in the turbulence production, dissipation and diffusion physics represented by the closures used in these models. The numerical implementation of the RANS equations and calibration of the model coefficients is based on previous work using the $K–\varepsilon$ model (Morán-López & Schilling 2013, 2014) applied to the Vetter–Sturtevant and Leinov et al. experiments, together with self-similarity analysis of Rayleigh–Taylor mixing applied to the turbulence models.

References


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A Comparative Analysis of RANS Model Predictions for Reshocked Richtmyer–Meshkov Instability and Mixing

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Abstract

Two-, three- and four-equation, single-velocity, multicomponent Reynolds-averaged Navier–Stokes (RANS) models, based on the turbulent kinetic energy dissipation rate $\varepsilon$ or turbulent lengthscale $L$ as the second mechanical turbulence quantity, are used to simulate Mach 1.50 reshocked Richtmyer–Meshkov instability-induced turbulent mixing in the light-to-heavy and heavy-to-light cases, inspired by the classical Vetter and Sturtevant (1995) and Poggi et al. (1998) shock tube experiments. The model includes mixture molecular transport terms, enthalpy diffusion terms, pressure–dilatation and dilatation dissipation models, as well as a molecular mass diffusion flux with contributions from baro- and thermodiffusion. The progression from two equations to three and four turbulence model equations represents a progression from modelling the normalized mass flux in the $K$, $\varepsilon$ and $L$ equations using algebraic closures to modelling this quantity using a transport equation: the four-equation models couple transport equations for the mass flux $a$ and negative density–specific volume correlation $b$ to the $K$–$\varepsilon$ or $K$–$L$ equations, while the three-equation models use a two-fluid algebraic closure for $b$. The simulations are performed using the same initialization procedure and computational grid for each model. The predicted mixing layer widths, as well as various turbulence statistics, fields, and turbulent transport equation budgets are compared systematically among these models to identify similarities and differences in the turbulence production, dissipation and diffusion physics represented by the closures used in these models. The numerical implementation of the RANS equations and calibration of the model coefficients is based on previous work using the $K$–$\varepsilon$ model (Morán-López & Schilling 2013, 2014) applied to the Mach 1.24, 1.50 and 1.98 Vetter–Sturtevant experiments and Mach 1.20 Leinov et al. experiments, together with self-similarity analysis applied to the $K$–$L$, $K$–$\varepsilon$–$a$, $K$–$L$–$a$, $K$–$\varepsilon$–$a$–$b$, and $K$–$L$–$a$–$b$ models.

References


This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
Density ratio and entrainment effects on asymptotic Rayleigh-Taylor instability in two and three dimensions

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The Rayleigh-Taylor instability (RTI) occurs when a light fluid accelerates a heavy fluid. The development of the instability, together with secondary instabilities, creates a turbulent mixing zone (TMZ) between the two fluids which consists of bubbles and spikes. This instability is ubiquitous in natural and engineering systems, including inertial confinement fusion (ICF) experiments and supernovae.

The asymptotic growth of the TMZ width in RTI is self-similar, quadratic in time and dominated by the dimensionless scaling parameter $\alpha$. The value of $\alpha$ from 3D simulations (Dimonte et al., 2004), is smaller by a factor of $\sim2$ than in experiments (Dimonte & Schneider, 2000) and models (for example, Oron et al., 2001). The density of the bubbles in simulations for the case of Atwood number $A = 0.5$, that was used in most of the past simulations (for example, Dimonte et al., 2004), is larger than the initial density of the light fluid also by a factor of $\sim2$. Combining these two results, it was partly shown that mixing in the small scale and entrainment might influence the large scale development of RTI.

In this work, we present a comprehensive numerical study of the following parameters which affect mixing in the small scale: density ratio between the two fluids (Atwood numbers in the range of 0.2 to 0.9), miscibility, and dimensionality (since turbulence in 2D and in 3D differ). An implication of this work is a planned experiment on NIF for measuring $\alpha$ in a range of density ratios.

References
Review of the Hydrodynamic Instability and Mix Campaign for ICF Program on National Ignition Facility

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The mission of the capsule Ignition Science Campaign is to develop a greater understanding of capsule physics in ICF implosions, primarily effects of hydrodynamic instabilities on implosion performance, and to develop techniques to mitigate these instabilities. An indirectly driven implosion begins with an acceleration phase when the hohlraum x-rays ablate the shell surface and the capsule starts to converge. At this stage, outer-shell non-uniformities grow due to the acceleration-phase Richtmyer-Meshkov (RM) and Rayleigh–Taylor (RT) instabilities. As the shell accelerates, these front-surface perturbations feed through the shell, seeding perturbations on the ablator-ice and ice-gas interfaces. After the x-ray drive is turned off, the ablation front becomes stable and the shell starts to decelerate while continuing to converge. During the deceleration phase, the inner surface of the shell is subject to RT instability. In addition, modulations grow due to Bell-Plesset (BP) convergent effects throughout the compression.

Several new platforms have been developed to experimentally measure hydrodynamic instabilities in all phases of implosions on NIF. At the ablation front, instability growth of pre-imposed modulations was measured with face-on x-ray radiography using the Hydrodynamic Growth Radiography (HGR) platform. The instability growth factors were investigated in the linear regime in the range of Legendre mode numbers from 30 to 160. In addition, modulation growth of 3-D “native roughness” modulations was measured to investigate hydrodynamic stability in conditions similar to those in layered DT implosions.

A new experimental platform was developed to measure instability growth at the ablator-ice interface. 2-D modulations were laser-imposed at the inner surface of the plastic capsule for implosions with DT layers to probe stability of the ablator-ice interface using x-ray radiography with this new Layered Hydrodynamic Growth Radiography (LHGR) platform.

In the deceleration phase of implosions, an innovative method was developed to use the self-emission from the hot spot to “self-backlight” the shell in-flight. Capsules used argon dopant in the gas to enhance x-ray emission at the beginning of the deceleration phase that serves as a “backlighter” to image growing shell modulations. To stabilize instability growth, new “adiabat-shaping” techniques were developed at the ablation front using the HGR platform and applied in layered DT implosions. Experimental results from all these campaigns will be presented.

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Mixing and Turbulence Statistics in an Inclined Interface Richtmyer-Meshkov Instability

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Abstract

The interaction of a Mach 1.55 shockwave with a nominally inclined interface is considered. Unlike the classical Richtmyer-Meshkov problem, the interface evolution is non-linear from early time and large highly correlated vortical structures are observed even after reshock. The simulations target the experiment of McFarland et. al. (2014). Simulations are performed using the Miranda code (Cook et. al., 2005) that uses high-order spectral-like numerics (Lele, 1992). Results from multiple grid resolutions up to 4 billion grid points establish grid convergence. Comparisons to the experiments show that the simulations adequately capture the physics of the problem.

Figure 1: CO$_2$ mass-fraction $Y_{CO_2}$ plots at different times in clockwise chronological order. Dark blue indicates $Y_{CO_2} = 1$ and white indicates $Y_{CO_2} = 0$.

Figure 2: Evolution of the mixed width with time. Simulations: solid lines; Experiment: solid circles.

Analysis of the data from the simulations based on variable density turbulence equations in the Favre averaged form will be presented. Statistics of unclosed terms in the variable density RANS equations will also be presented and compared to standard closure models.

We acknowledge computer time provided by NSF PRAC award “Multi-material turbulent mixing” on the Blue Waters system.

References


A comparative study of the turbulent Richtmyer-Meshkov instability

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Abstract

The turbulent Richtmyer-Meshkov instability is investigated through a series of high resolution three dimensional computations of a single initial condition run by multiple independent groups. The initial condition is formulated to ensure that it can be run consistently and reliably in a range of numerical algorithms, converge at a reasonable grid resolution while not impacting greatly the evolution of the instability. The interface perturbation has modes between \(L/8\) to \(L/4\) where \(L\) is the cross-section, and a perturbation power spectrum with constant power at all initialised wavelengths is employed. A diffuse layer of error function form and thickness \(L/32\) is used.

Finally, it employs deterministic random numbers to define mode amplitudes and phases, however these are the same at all grid resolutions such that a grid refinement study can be achieved with the same interface shape. To complete the specification, the density ratio is 3:1, \(\gamma = 5/3\) for both gases, the shock has strength Mach 1.84 and the two unshocked species are initially at identical pressure and temperature. The full paper will present a comparative study of mix widths, mixing parameters, spectra and plane-averaged properties.
Direct Numerical Simulation of Turbulent Mixing Induced by Richtmyer-Meshkov Instability Under Re-shock Conditions

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Turbulent mixing induced by Richtmyer-Meshkov instability (RMI) at late times is under increasing concern. In this report, we implement 3D simulations of shock, re-shock and material interface interactions with discrete-broadband initial perturbations, which ultimately lead to turbulent mixing. Initially, the shock is set in the light gas side and the Atwood number is -0.6. The simulation is done in a long cube with a universe-square cross section. For spatial derivatives, an improved fifth order MP scheme is used, and for time advancement, the fourth Runge-Kutta scheme is used. Multi-phase Navier-Stokes equation is solved on uniform Cartesian grids with grid number of 512*2049*512.

By using the numerical data, we compute the basic statistics of the turbulence and scalar turbulence to study turbulent mixing at late times of RMI. The mixing width and its growth rate are computed by using an integral definition of mixing width. The molecular mixing degree is computed to measure the mixing process at small scales. We then compute the skew-ness, flatness of scalar fluctuation, skewness, flatness of spatial derivative of scalar fluctuation. In addition, the total kinetic energy, Reynolds stress, Taylor micro scale, Kolmogorov scale and other quantities about turbulence of the mixing zone are calculated. Details of analysis of these statistical quantities and their comparison with corresponding quantities in isotropic turbulent mixing will be discussed. (This work is supported by NSFC with grant No. 11472059)
Effect of the initial conditions on the evolution of Richtmyer-Meshkov instability turbulent quantities

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Abstracts

The inclined shock tube facility at Georgia Tech is used to study the evolution of turbulent quantities for a Richtmyer-Meshkov instability initiated from an inclined interface and a complex interface. The complex interface is formed by perturbing the inclined interface with counter flowing jets, which create shear and buoyancy effects. Experiments are performed using an incident shock wave with strength of Mach 1.55 to impulsively accelerate an interface with 80° angle of inclination between N₂-Acetone mixture and CO₂ gas resulting in an Atwood number of 0.23, after gas compression. The evolution of quantities such as turbulent stresses and the cross correlation across the mixing width along with density field are obtained by implementing simultaneous high resolution PLIF and PIV measurement techniques. In the current investigation, the given data are compared between experiments initiated with complex initial interface and experiments initiated with flat inclined initial condition, thus outlining the effect of the initial perturbations on mixing evolution at intermediate and late-time as well as the transition to turbulent regime before and after re-shock.

Figure: Evolution of Richtmyer-Meshkov instability with 80° angle initial complex inclined interface. a) Initial mole fraction field of perturbed interface before incident shock wave arrives. b) Mole fraction of mixing layer width after 4.75 ms from shock-interface interaction. c) Mixing layer width mole fraction after re-shock interacts with developed instability 8.5 ms.

This work was partially supported by the National Science Foundation Faculty Early Career Development (CA-REER) Award (Award No. 1451994) and the Air Force Office of Scientific Research Young investigator Award (Grant number FA9550-13-1-0185)
Numerical study of the converging Richtmyer–Meshkov instability in a conventional shock tube

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For a few years the CEA/DAM, in collaboration with the IUSTI laboratory, studies the Richtmyer-Meshkov instability (RMI) in shock tubes. Recently, by adding a specific wedge to a conventional shock tube (Vandenboomgaerde & Aymard, 2011), experimental results about the RMI have been obtained in the cylindrical geometry (see the companion talk by Biamino et al. in this workshop). In these experiments, the interface is materialized by a membrane which is supported by a stereolithographed grid. This grid is sinusoidally shaped, and its polar equation in the reference frame where the apex is the origin, writes as:

\[
\rho(\theta) = 0.1 - 0.0015 \left(1 - \cos(24 \theta)\right) \quad \text{with} \quad -\frac{\pi}{12} < \theta < \frac{\pi}{12}
\]

The incident shock wave goes from Air to SF\(_6\) and its Mach number equals to 1.15.

We will present a numerical study of these experiments. Numerical simulations are performed with the Hesione code. Figure 1 presents the initial interface and after 380 \(\mu\)s after the shock passage.

![Figure 1: Numerical simulation: RMI in cylindrical geometry at \(t = 0\) and \(t = 380 \mu\text{s}\) after the shock passage through the interface.](image)

Previous work in planar geometry (M. Vandenboomgaerde et al. 2014) showed that additional small scale perturbations are generated by the grid and the membrane at the interface. Attempts to improve the agreement between the numerical and experimental data by taking into account these small scale perturbations will also be presented.

References


Convergent geometry and finite thickness effects on hydrodynamic instabilities

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It was realized that the nonlinear growth of hydrodynamic instabilities plays a crucial role in the performance degradation of central ignition of ICF implosions. Converging geometry hydrodynamic instabilities are of critical importance in fields of inertial confinement fusion (ICF) and astrophysics. In this research, a weakly nonlinear (WN) model has been developed considering the growth of a small perturbation on a cylindrical interface between two incompressible fluids which is subject to arbitrary radial motion. It is shown that interface profiles are determined mainly by the inward and outward motions rather than bubbles and spikes. The amplitudes of inward-going and outward-going parts are strongly dependent on the Atwood number and the initial perturbation. For low-mode perturbations, the linear growth of fundamental mode cannot be saturated by the third-order feedback. On the other hand, a WN model has been developed for the Rayleigh-Taylor instability of a finite thickness incompressible fluid layer (slab). We derive the coupling evolution equations for perturbations on the (upper) “linearly stable” and (lower) “linearly unstable” interfaces of the slab. Our third-order model can depict the WN perturbation growth and the saturation of linear (exponential) growth of the perturbation fundamental mode on both interfaces. It is found that the finite-thickness effects play a dominant role in the WN evolution of the slab, especially for thin shell. Thus, it should be included in applications where the interface coupling effects are important, such as inertial confinement fusion implosions and supernova explosions.

Reference
Three- and Two- Dimensional Simulations of Re-shock Experiments at High Energy Densities at the National Ignition Facility

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\textbf{Abstract}

We present simulations of recent high-energy-density (HED) re-shock experiments on the National Ignition Facility (NIF). The experiments study the Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instability growth that occurs after successive shocks transit a sinusoidally-perturbed interface between materials of different densities. The shock tube is driven at one or both ends using indirect-drive laser cavities or hohlraums. X-ray area-backlit imaging is used to visualize the growth at different times.

Our simulations are done with the three-dimensional, radiation hydrodynamics code \textit{ARES}\textsuperscript{1}, developed at LLNL. We show the instability growth rate, inferred from the experimental radiographs, agrees well with our 2D and 3D simulations. We also discuss some 3D geometrical effects, suggested by our simulations, which could deteriorate the images at late times, unless properly accounted for in the experiment design.

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\textbf{References:}


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Numerical investigations of Rayleigh-Taylor instability in aluminum plate driven by explosive

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Abstract

The classical hydrodynamic Rayleigh-Taylor instability occurs when a low-density fluid accelerates a high-density fluid, which also happens in metallic materials. In this paper, an experiment of Rayleigh-Taylor instability in aluminum driven by high explosive is carried out, an evolution image of perturbation is obtained by the radiography. Then this experiment is numerically simulated by our in-house high-fidelity detonation and shock wave code (HDS), in which the JWL equation of state and the steinberg-Guinan constitutive model is used. The calculated free surface velocity and displacement agree well with experiments, but the calculated amplitude is of about 57% larger than the experimental values. There may be two reasons to cause this large discrepancy, one is that the precision of experimental measurement is low and result in the blur of perturbed interface, the other is that the experimental flyer plate of 1050 aluminum is replaced by 6061-T6 aluminum with the closer property in simulation because of the lack of the mechanical properties of 1050 aluminum. In another simulation, the calculated amplitude achieves a good agreement with the experiments by increasing the initial shear and yield strengths to ten times, which indicates that the strength can stabilize the growth of instability. Additional numerical results show that the shear modulus does not affect the perturbation growth in a substantial range, and the aluminum sample is always an approximate quasi-isentropic-adiabatic state.

References

Modeling and measuring fuel-ablator interface mixing in inertial-confinement fusion implosions


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The performance of inertial confinement fusion (ICF) implosions can be degraded by instabilities at the fuel-ablator interface. Mixing at this interface could reduce the compression of the deuterium-tritium (DT) fuel or pollute and cool the burning fuel. This can be limited by controlling the density profile at the interface and its Atwood number. The density profile can be tailored by limiting the amount of x-ray preheat that reaches this interface by shielding it with high-Z dopants embedded within the ablator. Implosion experiments at the National Ignition Facility (NIF) have been fielded with various levels of interface stability control, resulting in various levels of expected interface mix. Recent experiments using high-density carbon (HDC) ablators did not contain additional high-Z dopant. In these cases, models predict that the DT fuel and the HDC ablator were mixing due to the Rayleigh-Taylor instability. Interface mix helps explain the measured ratio of down scattered-to-primary neutrons, a measure of fuel compression, but the models require several times more mixing than expected to reach the experimental neutron-scattering values. Experimental platforms are being designed to directly measure interface stability, which will help constrain models and better understand the integrated implosions. These platforms include face-on measurements of interface perturbation growth and side-on measurements of mixing-layer width.

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Shock driven mixing processes

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We compare detailed simulation and RANS model results for shock driven mixing, for plane surfaces and for localized clumps of material. We compare Reynolds-averaged properties with varying density ratios and surface perturbations. The techniques used to study the internal structure of Rayleigh-Taylor mixing layers at the last workshop are applied to these additional geometries. We discuss the prospects for reaching asymptotic convergence in simulations of the Richtmyer-Meshkov growth of mixing layers.

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Energy transfer in Richtmyer-Meshkov instability induced turbulent mixing

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An in-house high-order turbulence solver (HOTS) has been developed for numerical simulation of multi-phase compressible flows with discontinuities, in which high-order compact finite difference schemes and localized artificial diffusivities are employed to satisfy the requirements for high accuracy and discontinuity capturing [1, 2]. The Richtmyer-Meshkov instability (RMI) [3, 4] induced mixing flows in a rectangular shock tube [5] are numerically investigated based on HOTS. Focus is placed on the analysis of the scale-to-scale energy transfer of kinetic energy both in Fourier and physical spaces. It is the nonlinear advection flux that predominates over other components for the total spectral energy flux across a given scale. The kinetic energy injected from the perturbation scales is transferred both backward to larger scales and forward to larger scales in an average sense with the IMZ at early times, and is mainly passed down into small scales at the late stage. The energy flux across the upper limit of the initial perturbation scales due to the work done by the coarse-grained strain rate against the subgrid-scale (SGS) stress is further studied in physical space using a filtering approach with particular emphasis on the physical origin of the scale-to-scale kinetic energy transfer process. It is found that pointwise kinetic energy transfer due to the SGS stress effect is highly associated with the local structures in the IMZ. At early times the positive SGS fluxes occur dominantly in spike regions while the negative ones in bubble regions as well as the central region of the IMZ. In the late stage, however, only forward transfer of kinetic energy can be observed, which takes place in the spike-side regions. Moreover, it turns out that the mean SGS energy flux is mainly ascribed to the component in the direction of shock wave propagation.

References


Numerical Dissipation Control in High Order Shock-Capturing Schemes for DNS & LES of Wide Range of Compressible Flow Speeds

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\textbf{Abstract.} The Yee & Sjögreen adaptive numerical dissipation control in high order schemes (High Order Filter Methods for Wide Range of Compressible Flow Speeds, ICOSAHOM 09, 2009) is further improved for DNS and LES of shock-free turbulence, low speed turbulence with shocklets and turbulence with strong shocks. There are vastly different requirements in the minimization of numerical dissipation for accurate turbulence simulations of different compressible flow types and flow speeds, including turbulent mixing. Traditionally, the method of choice for shock-free turbulence and low speed turbulence is by spectral, high order central or high order compact schemes with high order linear filters. With a proper control of a local flow sensor, the appropriate amount of numerical dissipation in high order shock-capturing schemes can have spectral-like accuracy for compressible low speed turbulent flows. The development of the nonlinear filter method includes an adaptive flow sensor with automatic selection on the amount of numerical dissipation needed at each flow location for more accurate DNS and LES simulations with less tuning of parameters for flows with a wide range of flow speed regime during the entire time-accurate evolution, e.g., time varying random forcing.

Moreover, simulation of turbulent flows with shocks employing subgrid-scale (SGS) filtering may encounter a loss of accuracy in the vicinity of a shock. This paper also addresses the accuracy improvement of LES of turbulent flows in two ways: (a) from the SGS model standpoint and (b) from the numerical method improvement standpoint. The high order low dissipative method of Yee & Sjögreen (2009) using local flow sensors to control the amount of numerical dissipation where needed is used for DNS and LES simulations with less tuning of parameters for flows with a wide range of flow speed regime during the entire time-accurate evolution, e.g., time varying random forcing. In this study we use a canonical shock-turbulence interaction problem for comparison of the considered modifications of the SGS filtering procedure. In addition, 3D temporally evolving mixing layer test cases are compared with experimental data.
Study of an indirect-drive ignition capsule with the main pulse shape of decompression and recompression

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Hydrodynamics in the low-foot (LF) implosion \cite{1} during the National Ignition Campaign is highly nonlinearity, which results in significant amount of CH(Si) ablator material mixing into the hot spot and low-mode non-uniformity of the shell areal density. The high-foot (HF) implosion \cite{2} after the NIC largely suppresses mediate- and high- mode hydrodynamic instabilities, in which neutron yields go up an order of magnitude compared to the LF implosion, but the hot spot pressure is still low and the hot spot shape goes bad when the peak power is increased for larger implosion velocity \cite{3,4}. In our new ignition capsule design \cite{5}, first, the HF prepulse similar to the HF implosion on NIF is adopted for resisting the CH(Si) ablator mix problem; second, the new main pulse shape of decompression and recompression (DR) is proposed to improve performance of the HF implosion on NIF. In this scheme of the DR, the secondary auxiliary shock (SAS) is produced during the late of the main pulse by the recompression pulse to raise the shell density for improving the hot spot pressure. The decompression pulse is used for reducing ablative pressure in order to relax the limit of the peak drive power for SAS production. The SAS colliding with the rebound shock from the center also improves the hot spot pressure and temperature, which is very useful to stabilize the hydrodynamic instabilities during the deceleration stage of implosion for the hot spot ignition. Decompressing the outer part of the ablator thickens the shell to lessen feed-through of perturbations from the ablative to inner interfaces. In this presentation, good 1D and 2D performance of implosion of the DR scheme is reported, especially reduced growth of perturbations at the interface between the hot spot and the main DT fuel.

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\cite{5} Wang Li-Feng, WU Jun-Feng, YE Wen-Hua, FAN Zheng-Feng, HE Xian-Tu, Design of an Indirect-Drive pulse shape for \sim 1.6MJ inertial confinement fusion ignition capsules, CHIN. PHYS. LETT. 31(4), 045201(2014).

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High-order numerical methods for the simulation of Richtmyer-Meshkov instability with complicated equations of states

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This work concerns the application of high-order schemes to Richtmyer-Meshkov instability governed with complicated equations of state, with focusing on the effects of high-order schemes.

Firstly, a uniform treatment of different equation of state, including ideal EOS, stiffened EOS, van der Waals EOS, Jones-Wilkins-Lee EOS, Chran-Coran EOS and HOM EOS, is given. Based on this uniform treatment and the iso-pressure closure of the five-equation model, the process of mixing is just the volume-fraction-weighted mixture of two newly functions of density. Thus the effective EOS of the numerical diffusion zone which can be mixed from materials of different type EOS can be given explicitly, and this uniform treatment is very convenient for coding. Coupled with the strategies developed for the four-equation model, the final algorithm with different high-order schemes yields feasible results, which demonstrates the effectiveness of the proposed algorithm.

Furthermore, typical high-order schemes, including the WENO scheme, the WENO-Z scheme, the MP-R scheme, are used respectively to simulate one- and two-dimensional multi-material flows with complicated equations of state case by case. Their results are compared with that of TVD scheme with van Leer limiter. By this comparative study, the issues of high-order schemes can be summaries as following. Among high-order WENO-type schemes, the WENO5-JS scheme, though shows very promising robustness, is too diffuse. In contrast, the WENO5-Z scheme improves remarkably the resolution of the original WENO5-JS scheme. However, the WENO5-Z scheme may not have proper dissipation to suppress numerical oscillations in some extreme cases (see the liquid-van der Waals gas shock-tube problem and the liquid-gas shock-interface interaction problem). In contrast, high-order limiting-type scheme may show less dissipation than WENO-type scheme of the same order. Specifically, the MP5-R scheme, which follows the limiting strategy oriented from van Leer, shows the highest resolution among these typical schemes. However, it is found that, in the spherically symmetric underwater detonation problem, the MP5-R scheme is still prone to produce nonphysical parasitic solutions. Therefore, MP5-R scheme is needed to be investigated further for simulating symmetric problems.

As for strong rarefaction waves, both low-order scheme and high-order scheme may show severe numerical oscillations. As reported in the single-material problems, when the strong rarefaction wave is present adjacent to a contact/interface line, the averaging step in Godunov-type method over the wave will produces larger errors. The cumulative error is very large which violates the strength of the contact line adjacent to which, in turn, affects the speed and hence the location of the shock on the other side of the contact. For the multi-material flows with complicated equations of state, we show that this phenomenon is more severe. This phenomenon is in accordance with the report where two-material flows. Richtmyer-Meshkov instability with complicated equations of states is simulated, and results of different schemes are analyzed.
An accurate close-form theory for the growth rate of Richtmyer-Meshkov instability in compressible fluids with all density ratios

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Richtmyer-Meshkov instability in compressible fluids is a very complicated phenomenon. It is very difficult to provide accurate theoretical predictions for the growth rates of fingers at the unstable material interface between compressible fluids. This is due to the complication of the shock waves and the rarefaction wave presented in the compressible fluid systems and due to the nonlinearity of finger growth at late times. Therefore, theoretical studies usually approximate the fluids as incompressible and the incident shock as an impulsive force. Numerical simulations have been the main tools for studying the finger growth in Richtmyer-Meshkov instability in compressible fluids. In this talk, we present a new close-form approximate solution for the growth rate of fingers of Richtmyer-Meshkov instability in compressible fluids. Our theoretical approach is based on analyzing the solutions at early and late times and asymptotically matching these two solutions. Our theory contains no fitting parameters. Furthermore, our solution has no singularity for all physical parameters including all density ratios and all incident shock strength. We show that our theoretical predictions for the growth rates of fingers of Richtmyer-Meshkov instability in compressible fluids are in remarkably good agreements with the results from numerical simulations in the literature over the entire periods of numerical simulations. Even for a compressible fluid system with a Mach number of the incident shock being as high as 15.3, our theoretical predictions are still in an excellent agreement with the data from the numerical simulations.
Asymptotic behaviour of the mixed mass in Rayleigh-Taylor and Richtmyer-Meshkov instabilities induced flows

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Rayleigh-Taylor instability (RTI) and Richtmyer-Meshkov instability (RMI) are serious practical issues in inertial confinement fusion research and also have relevance to many cases of astrophysical fluid dynamics. So far much of the attention has been paid to the late-time scaling of the mixed width, which is used as a surrogate to how well the fluids have been mixed. However, the actual amount of mixed mass could be viewed as a more direct marker of the evolution of the mixing layers due to hydrodynamic instabilities. Despite its importance, there is no systematic study as yet on the scaling of the mixed mass for either the RTI or the RMI induced flow. Here, measurements of the mixed mass, as well as the normalized mixed mass, are used to indicate the progress of the mixing process. Six large numerical simulation databases have been employed: the RTI cases with heavy-to-light fluid density ratios of 3/2, 3, and 9; the single shock RMI cases with density ratios of 3 and 20; and a reshock RMI case with density ratio of 3.

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Quantitative study of the shock-accelerated elliptic gas cylinders

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The evolution of an elliptic heavy-gas (SF₆) cylinder accelerated by a planar weak shock wave is studied experimentally using particle image velocimetry (PIV) diagnostics, and the emphasis is on the aspect ratio effect on shock-elliptic cylinder interaction. Experiments are conducted at five different aspect ratios (the ratio of length in streamwise and spanwise directions) varied from 0.25 to 4.0. PIV raw images and quantitative flow field data are obtained at t=0.6 ms after the shock impact. As the aspect ratio increases, the interface morphology develops faster owing to more vorticity produced along the interface and smaller vortex spacing between the two vortex cores. For each case in this study, the maximal fluctuating velocity locates at the middle point of the two counter-vortices. The histograms of fluctuating velocity reveal that a distinct double-peak structure appears in the largest aspect ratio case in comparison with the single-peak structure in the smallest aspect ratio case. The vortex velocities predicted by the theoretical model [Rudinger and Somers, J. Fluid Mech. 7, 161-176, (1960)] agree well with the experimental ones. With the increase of aspect ratio, the maximal value of vorticity increases as well as the circulation, and more low-magnitude quantities are generated, which indicates the formation of multi-scale flow structure in the late mixing process. Finally, some recent results on the double-elliptic-cylinders evolution and planar laser induced fluorescence (PLIF) diagnosis are introduced and analyzed.

Figure 1: PIV raw images of five cases at t=0.6 ms after the impact of shock wave. (a) a/b=0.25; (b) a/b=1; (c) a/b=2; (d) a/b=3; (e) a/b=4.

This work was supported by the National Natural Science Foundation of China (Grant Nos. 11302201, and 11472253) and Science Foundation of China Academy of Engineering Physics (Grant No. 2014B0201017).

References
Richtmyer-Meshkov growth of a flat interface

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Richtmyer-Meshkov instability at a flat and uniform interface subjected to diffracted and reflected waves, is experimentally studied using the laser sheet and high-speed schlieren techniques. The initial interface is formed in a vertical shock tube by two opposing gas flows. The downward flow of light gas (N₂) and the upward flow of heavy gas (SF₆) meet at the top of test section and exit through the lateral slots of the tube wall as shown in Fig. 1(a). The initial flat interface is first impacted by the incident diffraction shock over cylinder and then re-shocked by the reflected shock from the end wall of the tube. The non-uniformity of the incident diffraction shock is clearly illustrated in the schlieren sequences (Fig. 1(b)), which seeds the local perturbation in the initial flat interface. Compared with the development caused by the incident impaction, the interface width increases much quickly under the re-shocked condition. In terms of the diameter of cylinder and propagating distance of diffracted shock, three typical evolution morphologies characterized by phase reversal, bubble and spike are identified in Fig. 1(c). Finally, the growth rate of interface mixing width is compared and analyzed based on the impulsive linear model and the weakly nonlinear model [Dimonte & Ramaprabhu, Phys. Fluids, vol. 22, 2010, 014104].

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![Diagram](a) Cylinder Interface Diffracted shock

![Images](b) case 1 case 2 case 3

Figure 1. (a) Sketch of the shock tube facility; (b) Diffracted shock wave; (c) Evolution morphologies for three typical cases
Poster Abstracts
AWE Results for a Richtmyer-Meshkov Test Problem in Collaboration with the θ-group. (Poster)

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AWE is interested in turbulent mixing processes that are induced by fluid instabilities such as Rayleigh-Taylor and Richtmyer-Meshkov. To study such phenomena AWE has developed the MILES code TORMIL3D which has the capability to undertake both LES and DNS calculations. The θ-group collaboration provides an opportunity to validate TORMIL3D for a Richtmyer-Meshkov test problem through comparison with other LES and DNS codes.

A grid convergence study of the test problem will be presented in this poster, using the recommended grid sizes of 180x128x128, 360x256x256 and 720x512x512. Mix and turbulence kinetic energy statistics will be presented as well as volume fractions and density spectra. Calculations will be conducted using LES and DNS in TORMIL3D.

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Simulation of Richtmyer–Meshkov instability by FOCUS code in \( \Theta \)-group statement

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Abstract

Perturbations evolution during the development of Richtmyer-Meshkov instability (RMI) depends on the initial amplitude of the perturbations. When the amplitude of the interface between matters or front disturbance of the incident shock wave (SW) are rather small, there is a linear stage of RMI. Then the evolution process enters into nonlinear stage. If the intensity of falling SW is great enough, development of perturbations in time reaches the stage of the developed turbulence.

Development of RMI is simulated by 3D code FOCUS. The task statement was taken from (Youngs, 2004). To analyze the results of the calculations in accordance with (Thornber et.al., 2010) time dependence of the certain values were calculated: width of a perturbation zone \( W \), degree of molecular mixing \( \Theta \), mixing parameter \( \Xi \) (see Figure 1a). Also the spectrum of turbulent kinetic energy (TKE) was defined for the sequence of time moments. The spectrum was calculated as the sum energy spectra of the velocity pulsation components, see Figure 1b. Initial perturbations with the wave length from \( L/8 \) to \( L/4 \) gradually transfer energy to smaller vortices. For scales \( L/10 \) and for the smaller sizes the shape of the spectrum practically is not changed with time.

Figure 1: a) Diagnostics: \( W \) – red; \( \Theta \)– blue; \( \Xi \)– green. b) Evolution of TKE spectrum

References


The effect of Engineering features on ejecta production
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Abstract

One example of Richtmyer-Meshkov instability is the production of ejecta from shocked materials. In experiments engineering features are usually needed to keep the experiment intact long enough for the diagnostics to record the results.

In some cases shocks can interact with these engineering features and produce ejecta. This ejecta can be a cause of concern if it generates a signal in the diagnostics that changes the results.

High resolution three dimensional simulations of an engineering feature subject to a strong shock have been performed. These are examined and the resulting ejecta has been calculated, as shown in Figure 1. Modifications to the engineering features that reduce the produced ejecta are suggested.

Figure 1: Ejecta cloud produced by an Engineering feature

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Experimental and numerical investigation of the growth of an air/$SF_6$ turbulent mixing zone in a shock tube

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Shock induced mixing experiments have been conducted in a vertical shock tube of square cross section $13 \times 13\,\text{cm}$ based in ISAE/DAEP (Bouzgarrou et al. 2014). A shock of Mach 1.2 in air hits an interface with $SF_6$, a gas 5 times heavier than air, filling a chamber up to the end of the shock tube. Both gases are initially separated by a $0.5\mu\text{m}$ thick nitrocellulose membrane maintained flat and parallel to the shock front by two wire grids. The upper grid of square mesh imposes an initial perturbation for the Richtmyer-Meshkov instability (RMI) while the lower grid with square mesh spacing $1\,\text{mm}$ prevents the membrane from bulging due to the weight of $SF_6$. Two different upper grids have been used with mesh spacing $m_s=1.8\,\text{mm}$ or $m_s=12.1\,\text{mm}$. The experiments were carried out for different lengths $L$ of the $SF_6$ chamber: 10, 15, 20, 25 and 30 cm. Time resolved Schlieren images are processed to evaluate the turbulent mixing zone (TMZ) thickness. At the time of the reshock, the TMZ measures 10 to 14 mm depending on $L$. After reshock, the TMZ grows initially almost linearly with a velocity around $28\,\text{mm/ ms}$ whatever $L$ and $m_s$ (Bouzgarrou et al. 2013, Bouzgarrou 2014).

Purely hydrodynamic numerical simulations, i.e. without wire grids or nitrocellulose membrane, are performed and compared to the experiments. There is no obvious way to initialize such computations and two different ones are used to take the mesh spacing $m_s$ into account. Though the TMZ history and mixture appearance can be matched for $m_s=1.8\,\text{mm}$, applying the same numerical initialization procedure for $m_s=12.1\,\text{mm}$ does not match the experiment: either the TMZ is predicted too large, or the structures of $12.1\,\text{mm}$, discernible in Schlieren images, are not retrieved.

It was expected that $m_s$ should be the main characteristic length for TMZ evolution. However, dimensional reasoning on that ground would lead to a different behaviour. Therefore, these results remain paradoxical.

References
Modulation of pressure spectrum properties owing to particle-liquid interaction in oscillating-grid turbulence

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Format of the presentation: Oral

Abstract

Experimental studies of velocity and pressure distributions in a homogeneous and isotropic system are of fundamental significance in order to provide insight into the flow characteristics. For instance, particle-liquid or bubble-liquid interaction including drag and lift forces, flow separation, eddies shedding, and regime transition, are affected by the variation of velocity and pressure in the flow field. Fluid flow possesses kinematic characteristic that has close relationship with its velocity distribution and a dynamic aspect which is representable by the fluctuating fluid dynamic pressure. These two distinct behaviours play prominent role in fluid turbulence and further interpretation provides essential information in understanding the governing flow physics. However, the pressure spectra are not considered and understood as extensively like velocity spectra. One of the reasons could be the difficulty involved in measuring pressure in laboratory experiments. Also, in systems where the amount of pressure is very low of the order of few Pascal (Hoque et al. 2015b), measurement of pressure is difficult to carry out. The limitations of measuring pressure using invasive manner disturbing the flow and inaccuracies involved can be reduced by pressure estimation from velocity data. The available literature in this area highlights a continued inconsistency on the scaling of pressure spectrum for homogeneous and isotropic flow system. Recently, Hoque et al. (2015b) investigated the scaling of pressure spectrum and related statistics inside an oscillating grid system. To the best of the authors’ knowledge, to date results on modulation of pressure spectrum scaling due to particle-liquid interaction have not been published. Thus, it was thought desirable to conduct a systematic experimental study to investigate the modification of pressure spectrum scaling in the presence of a single particle of different sizes in an oscillating grid system which is known for generating near-isotropic turbulence with nearly zero mean flow (Hoque et al., 2015a).

To achieve this aim, the experiments were carried out for the single glass particle size in the range of ~10 to 77 times of the Kolmogorov scale of the system. The velocity fluctuations of liquid and particle-liquid phase were simultaneously measured by using time resolved particle image velocimetry (PIV) technique for grid frequency varying from 0.5 to 5.0 Hz. The corresponding pressure profile was evaluated directly from Navier-Stokes equation using fluctuating velocity data. The pressure spectra for liquid and particle-liquid phase were evaluated by using Fast Fourier Transformation technique (Hoque et al. 2014) and found the existence of Kolmogorov’s -7/3 slope in inertial subrange. For particle-liquid phase, the ratio of pressure integral length scale to the velocity integral length scale is about > 0.67 and the pressure Taylor microscale is approximately close to one. The obtained results were compared with liquid phase and available DNS results.

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Hoque M.M., Sathe M.J., Mitra S., Joshi J.B., Evans G.M. 2015a Comparison of specific energy dissipation rate calculation methodologies utilising 2D PIV velocity measurement. Chemical Engineering Science, 137: 752-767.
The Onset of Box Constraint in three dimensional multimode Richtmyer-Meshkov

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Abstract

Both experiments and computations are naturally constrained by boundary conditions. In fundamental problems such as homogeneous decaying turbulence or shock-induced mixing layers a size constraint naturally limits the size of the large scales in the problem, dramatically modifying the physics observed. This poster investigates for two fundamental flows the point at which the size of the computational or experimental domain impacts the accuracy of the predicted large scale statistics. It is shown through simulations from $64^3 - 1024^3$ that for both HDT and the Richtmyer-Meshkov instability (Fig. 1) the prediction of integral lengths or widths becomes inaccurate as it approaches 10% of the box size, however kinetic energy is reasonably predicted beyond this point for HDT. It is also noted that as the grid resolution increases, expected time development of length-scales is achieved and the time duration of simulation validity increases dramatically. For the TML, key errors arise due to the lack of statistical averages. These results are expected to be generally applicable regardless of numerical method. In addition, the poster gives an update on the physical behaviour of HDT and RM as predicted through Large Eddy Simulation run at high resolution and/or very late dimensionless times.

Figure 1: Contours of heavy fluid volume fraction between the isosurface 0.1 and 0.9 for the RM case at $\tau = 2250$ for the $512^3$ resolution. Red highlights the bubbles of light fluid penetrating into the heavy fluid.
Measurement of fluid velocity distributions in the different-density gases mixing zones evolving in expansion waves

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Abstract

A multi-purpose shock tube was used to conduct experiments in conditions of unstable expansion of gases into “vacuum”. Due to Rayleigh-Taylor instability, the turbulent mixing zone was observed to develop at the gaseous fluids interface moving at a decay rate. Experiments used unstable systems comprising different-density gases with Atwood numbers: 0.2, 0.67, and 0.8. Mixing visualization was done and boundaries of the turbulent mixing zone evolution were determined using the Schlieren method. Laser Doppler anemometry determined velocity fluctuations in the flow under consideration.
Reynolds Number Effects on the Single and Multimode Richtmyer-Meshkov Instability

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The Reynolds number effects on the non-linear growth rates of the Richtmyer-Meshkov are investigated using 2D numerical simulations. A decrease in Reynolds number gives an increased time to reach non-linear saturation, with Reynolds number effects only significant in the range $0 < \text{Re} < 256$. Within this range there is a sharp change in instability properties. Using the 2D simulations, a ‘just-saturated’ model of broadband multimode growth for a low Reynolds mixing layer is developed. Viscous forces are shown to modify the mix layer growth exponent, and the sensitivity of the growth rate to the spectral width of the broadband perturbation and the shape of the spectrum is detailed.

![Figure 1: RMI evolution with Reynolds number 2048.](image)

References

Calculation of equation of state of a material mixture

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Abstract: Based on the volume sum rule for the equation of state (EOS) of mixture materials, a physical model to determine the mixture temperature is built. Constituents of a material mixture are in temperature and pressure equilibrium. Combining the adding principle by pressure-density iteration algorithm EOS of a material is calculated. The corresponding program is developed to compute EOS of a material mixture comprised of two constituents. The study shows that EOS of a material mixture is reasonable by using the temperature model in practical work. EOS of the mixtures with different mass ratios of the light component to the heavy component are calculated. Meanwhile EOS of the mixture is computed when the state of either of the constituents change locally. The studies supply the understanding of law for the mixture states in the field of ICF and high-speed collision.
Universality among fingers of different density ratios in Rayleigh-Taylor and Richtmyer-Meshkov instabilities

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A material interface is unstable under the acceleration of the gravity (known as Rayleigh-Taylor instability) or a shock wave (known as Richtmyer-Meshkov instability). Fingers develop at the unstable material interface. The portions of the heavy fluid penetrating into the light fluid are known as spikes and the portions of the light fluid penetrating into the heavy fluid are known as bubbles. It is well known that spikes and bubbles can have quantitatively, even qualitatively, different behaviors. For example, the spikes are more unstable than the bubbles, and the fingers in a system with a high-density ratio are more unstable than those with a low-density ratio. In this talk, we present our recent theoretical study on both spikes and bubbles in systems with all density ratios and predict a very surprising new result: by appropriately scaling the physical quantities, the main behaviors of growth rates of all fingers collapse onto a single curve. This curve is universal because it is applicable among bubbles of different density ratios; among spikes of different density ratios; and even between bubbles and spikes of different density ratios. We further show that the data from numerical simulations are indeed in excellent agreement with our theoretical prediction of universality.
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