Summary of the 8th International Workshop on the Physics of Compressible Turbulent Mixing (9-14 December 2001, Pasadena, CA)

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International Workshop on the Physics of Compressible Turbulent Mixing

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Outline of IWPCTM summary/synthesis

- Introduction
  - Background, previous venues, and 2003 location of the IWPCTM
  - Demographics: how many attendees and from where
  - Difference in format from previous conferences
- Technical summary
  - Experimental research
  - Computational research
  - Theoretical research
- Observations on the IWPCTM
  - Past
  - Present
  - Future

The 8th International Workshop on the Physics of Compressible Turbulent Mixing is a biennial conference originally established by LLNL

1952-2002

- Previous venues
  1) Princeton, NJ, USA (1988) [LLNL]
  2) Pleasanton, CA, USA (1989) [LLNL]
  3) Royaumont, France (1991) [CEA]
  4) Cambridge, UK (1993) [AWE/Cambridge University]
  5) Stony Brook, NY, USA (1995) [SUNY Stony Brook]
  6) Marseille, France (1997) [Université de Provênce]
  7) St. Petersburg, Russia (1999) [RFNC-VNIIEF]
  8) Pasadena, CA, USA (2001) [LLNL]
- Venue for the 9th IWPCTM
  - Cambridge, UK (tentatively Spring 2003) [AWE/Cambridge University]

The 8th IWPCTM was very well attended, with approximately 1/3 of participants from the academic community

1952-2002

- 123 Total Attendees
  - USA: 74
  - Russia: 20
  - France: 8
  - Israel: 8
  - UK: 6
  - Japan: 4
  - Canada: 2
  - Spain: 1

Invited review talks were presented, and more presentations were given than during past workshops

1952-2002

- One hour talks given at beginning of Experimental, Computational, and Theoretical sessions to review state-of-the-art
  - Experimental: "Review on RTI, RMI and TM Experiments" (Haas & Zaytsev) and "The Experimental Study of Excitation and Development of the Hydrodynamic Instability in the Mixing Zone Separating Gases of Different Densities at Their Accelerated Motion" (Zaytsev)
  - Computational: "Review of Numerical Simulation of Mixing due to Rayleigh-Taylor and Richtmyer-Meshkov Instabilities" (Youngs)
  - Theoretical: "Three Dimensional Multi-Mode Rayleigh-Taylor and Richtmyer-Meshkov Instabilities at All Density Ratios" (Kartoon et al.)
- This further stimulated the Panel Discussions at the conclusion of each of the three sessions
- 126 total oral and poster presentations
  - 67 oral presentations
  - 59 poster presentations (staggered format used for more coverage)

Summary of experimental research

1952-2002

- “Complex” Rayleigh-Taylor instability experiments
  - Combined Rayleigh-Taylor and Kelvin-Helmholtz instability
  - “Demixing” experiments
  - Helium-driven gelatin experiments
- Diagnostic developments for Rayleigh-Taylor instability experiments
  - Scalar PIV
  - Wavelet post-processing
  - Moiré interferometry, Fresnel phase zone plate/penumbral imaging
- “Complex” Richtmyer-Meshkov instability experiments
  - Retractable plate shock tube experiments
  - Experiments to study velocity reduction due to large *Ma* and initial amplitude
  - Converging geometry experiments
- Diagnostic developments for Richtmyer-Meshkov instability experiments
  - PLIF, PIV
  - Hot-wire anemometry, laser sheet visualization, and LDV
  - Shadowgraphy
- High-energy density (laser) experiments
- “Laboratory astrophysics”

“Complex” Rayleigh-Taylor instability experiments with shear and “demixing” were reported

1952-2002

- Combined effects of Rayleigh-Taylor instability and shear in tilted interface experiments using double-shielded barrier plate withdrawal (Holford, Dalziel & Youngs E14)
  - Similar to Cambridge University experiments reported in JFM in 1999
  - Shear results in competition between large λ (large-scale) overturning and small λ (large *k*) Rayleigh-Taylor instability growth
  - Turbulence models examining combined shear-buoyancy are under development (Wilson, Andrews & Harlow T33)
  - Chemically-reactive experiments resulting in a fluorescent product envisaged
- “Demixing” experiments in liquids with three different *At* with sign of acceleration reversed (Kucherenko et al. E2)
- 3D periodic perturbation influence on turbulent mixing using gelatin driven by He compressed to 13 atm with $g \sim 3 \times 10^6$ cm/s^2 giving $\alpha = 0.1$ (Bliznetsov et al. E7)

New diagnostics used in Rayleigh-Taylor instability experiments to measure *statistical*, in addition to integral (large-scale), properties

1952-2002

- Splitter-plate experiment similar to classical shear flow experiments (Ramaprabhu & Andrews E32)
  - Small Atwood number ($At \sim 10^{-3}$) in a water channel
  - Cold and hot horizontally-moving streams of water achieving $Re \sim O(10^3)$
  - Scalar PIV with different particle concentrations used to simultaneously measure ρ and v_i fields to obtain $\langle \rho'^2 \rangle$, $\langle v_x'^2 \rangle$, $\langle v_y'^2 \rangle$, $\langle v_x' v_y' \rangle$, $\langle \rho' v_x' \rangle$, $\langle \rho' v_y' \rangle$ and 2D spectra (needed for DNS, LES, and turbulence models)
  - Results in good agreement with previous thermocouple experiments
  - Chemically-reactive fluids to diagnose molecular mixing possible also
- Wavelet post-processing of sequential density data from experiments to denoise, compress, and detect patterns (Afeyan, Ramaprabhu & Andrews T39)
- Moiré interferometry used to diagnose ablative Rayleigh-Taylor instability at small wavelengths and Fresnel phase zone plate/penumbral imaging used for density measurements on lasers (Azechi et al. E45)

Progress in Richtmyer-Meshkov instability experiments was reported, especially at larger Mach numbers and in convergent geometries

1952-2002

- Retractable Cu plate vertical shock tube experiments at *Ma* = 2.9 with imposed perturbations in air/CO_2 (Anderson et al. E27)
  - Heavy → light Rayleigh-Taylor followed by Richtmyer-Meshkov instability diagnosed with Mie scattering
- Experiments studying velocity reduction due to large *Ma* and large initial amplitude with *Ma* = 5 achievable (Sadot et al. E36) and large cross-section shock tube facility (Houas et al. E17)
- Classical and high-energy density convergent experiments reported
  - Detonation-driven 2D shock tube experiments with *Ma* = 2-3 (Holder et al. E13; Hosseini & Takayama E15, E16)
  - "Chevron" (notch) shock tube experiments at *Ma* = 1.26 diagnosed with Mie scattering (Smith et al. E39)
  - Cylindrical direct-drive experiments on OMEGA (Barnes et al. E4; Batha et al. E5; Parker et al. C28)
- Shock/flame interactions studied (Bliznetsov et al. E6)
- Kelvin-Helmholtz instability studied in analysis of impact of oblique metal plates (Bakrakh et al.)

New diagnostics have also been proposed for better imaging and measuring additional quantities in Richtmyer-Meshkov instability experiments

1952-2002

- "Membraneless" shock tube experiments in air/SF_6 at *Ma* = 1.3 (Jacobs & Krivets E18)
  - PLIF shows that interface evolution depends strongly on degree of nonlinearity at time of onset of *second* shock
- Impulsive Richtmyer-Meshkov experiments (Niederhaus & Jacobs E26)
- PIV used to study interaction of a shock with one cylinder (Prestridge et al. E30) and two cylinders (Tomkins et al. E40)
- Triple probe, constant temperature hot-wire anemometry measurements of ρ, v_i, and T at *Ma* = 1.25 (Schwaederlé et al. E37)
- Planar laser sheet visualization and laser Doppler velocimetry (LDV) measurements (Lassis et al. E21)
- Shadowgraphy used to diagnose interaction of a *Ma* = 1.5 shock with a Kr bubble (Layes et al. E22); shock/bubble interactions also simulated using ALE code LEEOR2D (Levy et al. E23)
- Development of a liquid film conductor to rupture membrane with an electric current prior to shock passage (Kucherenko et al. E20, E28, E38)
- Design of novel miniature KrF laser shock tube for experiments with *Ma* > 20 and *p* > 10 kbar in liquids (Lebo & Zvorykin C25)

High-energy density experiments on OMEGA continue to be valuable for studying nonlinear Richtmyer-Meshkov instability growth and ICF

1952-2002

- Study of effects of shock proximity on linear/nonlinear instability growth at *Ma* ~ 10 in C foam with a polycarbonate pusher (Glendinning et al. E12; Robey et al. E46)
- CALE simulations of *Ma* ~ 10 experiments (Miles, Edwards & Glendinning C57); also Mikaelian T20
- 1D/2D CALE simulations compared to 1D/2D FCI simulations (using a K-ε model) of *Ma* ~ 30 RM instability experiments (Seytor & Legrand C35; see Souffland & Renaud C36)
- NIF ignition target development (Haan et al. C22)
- ICF implosion experiments simulated in 2D (Srebro et al. C37)
- High-strain-rate material strength experiments (Kalantar et al. E19; Pollaine et al. E29)
- Rayleigh-Taylor mode-coupling experiments on NOVA simulated using ALE code (Darlington & Budil C9)

"Laboratory astrophysics" continues to motivate High-energy density experiments on OMEGA

1952-2002

- Shock-sphere interaction experiments
  - Study vortex structure and evolution (Robey et al. E34; see Brouillette & Hébert E8 for classical fluid experiments on vortex rings)
  - Paradigm for interaction of supernova blast wave interaction with interstellar clouds (Klein et al. E42)
  - Simulations of shock-sphere/shock-cylinder interactions using PPM (Peng et al. C29) and shock-planar curtain interactions (Zhang & Zabusky C48)
- Compressible turbulent mixing experiments in support of astrophysics (Drake et al. E9, E10)
- Compressible MHD turbulence application to radiating molecular clouds discussed (Ryutov T25)

Summary of computational research

1952-2002

- Differences between DNS, LES, and MILES
- MILES of variable acceleration Rayleigh-Taylor flow
- Code intercomparisons
  - Spectral/compact, Godunov, and CENO simulations of Shu-Osher problem, Richtmyer-Mehskov instability, and Taylor-Green vortex
  - RAGE, Cuervo, Raptor simulations of shock/cylinder interaction
- High-order and high-resolution methods
  - Filtered spectral and WENO schemes
  - PPM scheme
- Sensitivity of Rayleigh-Taylor mixing to initial conditions and studies of self-similarity
- Effects of small scales on large scales
  - Stabilizing effects of a transitional layer
  - Compressibility effects on supersonic, reacting shear layers
  - Spherical combustion layers
  - Stability of converging shocks
- Numerical simulations and comparisons to bubble merger models
- Subgrid-scale model development and LES of interfacial instability-driven turbulence

Systematic comparisons between simulation methods (direct numerical simulation, large-eddy simulation, and monotone integrated LES) are being conducted

1952-2002

- Differences between DNS, LES and MILES discussed (Youngs)
  - Reynolds-Averaged Navier-Stokes models will still continue to be needed (Youngs C46)
- MILES of variable acceleration Rayleigh-Taylor flow (Youngs & Llor C47)
- Simulations of 1D density-shock interaction, 2D air-acetone/SF_6 *Ma* = 1.2 Richtmyer-Meshkov instability experiment, and 3D Taylor-Green vortex using spectral/compact, Godunov, and CENO schemes to assess numerical effects (Cook et al. C8)
- Eulerian codes RAGE, Cuervo, and Raptor compared in 2D simulations of *Ma* = 1.2 shock acceleration of a diffuse, dense gas cylinder (Greenough et al. C16; Rider, Kamm & Zoldi C31; Zoldi C50)
- 2D simulations of shocked interfaces using high-order and high-resolution methods
  - Aleshin et al. *Ma* = 4.5 experiment using high-order filtered spectral and WENO schemes (Don et al. C54)
  - WENO and PPM schemes (Zabusky et al. C20)
  - Interaction of blast waves with cylindrical/spherical bubbles (Zhang et al. C49)
  - Efficient solver developed (Wang et al. C41)

The sensitivity of Rayleigh-Taylor mixing to the numerical algorithm used remains undetermined, and the "determination" of α remains inconclusive

1952-2002

- 3D simulations (256^2 x 512) using different numerical methods (PPM, ALE, etc.) and same initial conditions have not conclusively determined that α is universal (Dimonte et al. C10; see Weber, Dimonte & Marinak C42 and Dimits C55)
  - Mixing (entrainment) changes the effective *At* at the mixing layer front
  - Now being recognized that the front-tracking result α = 0.07 may be an overestimate as this method inhibits mixing at the interface, i.e., as in immiscible fluids (Dutta et al. C11)
  - Immiscible experiments and simulations inhibit energy cascade to small-scales and dissipation (mixing) at large *Re*, resulting in a more rapid mixing layer growth and larger α
  - Simulations using highly diffusive algorithms result in excessive (numerical) "mixing", reducing *At* locally and the mixing layer growth (giving a small α)
- 3D simulations using TREK code for ρ_1/ρ_2 = 3-40 gave α = 0.06-0.16 (Yanilkin et al. C44); TREK also used for simulating instabilities in plasma clouds during expansion in a magnetic field (Gavrilova et al. C14)
- A turbulence model was developed for magnetohydrodynamic Rayleigh-Taylor instability evolution at the interface of an accelerated plasma and magnetic field (Gubkov, Zhmailo & Yanilkin C19)

The effects of small scales (molecular mixing) on the dynamics of the large scales was an important experimental, numerical, and theoretical theme

1952-2002

- Stabilizing effects of an intermediate, transitional layer due to molecular diffusion studied (Kucherenko et al. E3, E31)
- DNS of moderate *Re* Rayleigh-Taylor instability examined sensitivity of large-scale properties (mixing widths) and statistics (such as molecular mixing rate) to initial conditions (Cook, Dimotakis & Mattner C56)
- Reduction of growth rate and other effects of compressibility (increasing Ma_c) studied in DNS of a supersonic, reacting shear layer (Pantano & Sarkar C27)
- 3D AMR simulations of a spherical combustion layer resulting from a TNT explosion (Kuhl & Ferguson T37)
- Molecular dynamics simulations to study stability of converging shocks and Richtmyer-Meshkov instability in a dense Lennard-Jones fluid (Nishihara, Zhakhovskii & Abe C26)
- Mechanisms of turbulent diffusion in solar-type stars studied numerically (Toqué C39)

Numerical simulations showed qualitative consistency with statistical bubble merger models

1952-2002

- A general buoyancy-drag model was developed to include shock compression and spherical convergence (Elbaz et al. T11, C12)
  - Multi-mode perturbation evolution is described by evolution of a single, effective λ (mode)
  - Internal density profile of mixing layer studied using a diffusion model
- Bubble merger results in a pure front of low density fluid rising in higher density fluid (Rikanati, Alon & Shvarts T22)
  - Effectively leads to a single bubble of light fluid on top and heavy fluid on bottom
  - In this 2D model, mixing occurs at center and bottom of mixing layer due to Kelvin-Helmholtz instabilities generated when falling spikes shear rising bubbles
- 3D ALE simulations of random perturbation growth with different ρ_1/ρ_2 using front-tracking consistent with this bubble merger model (Kartoon et al. T14)
- Thermonuclear burning in a Type IA supernova explosion modeled using this merger model (Takabe et al. C38)

Limited progress has been made on the development/application of explicit subgrid-scale models for interfacial instability-driven turbulence

1952-2002

- Large-eddy simulation (LES) of Richtmyer-Meshkov unstable turbulent flows generated by a *Ma* = 10 shock (Samtaney et al. C33)
  - Used the Pullin stretched-vortex subgrid-scale model
  - 5th- and 7th-order WENO schemes
  - Evolution of mixing layer, spectra, and statistics studied (with reshock)
- A methodology was extended to study interaction between small and large scales (subgrid-scale dynamics) in Rayleigh-Taylor and Richtmyer-Meshkov instability (Schilling & Cook T28)
  - Applied to a 512^2 x 2040 Rayleigh-Taylor mixing spectral/compact DNS dataset (Cabot, Schilling & Zhou, submitted to *Physics of Fluids*)
  - Examined transfer dynamics of small and large scales as a function of scale and vertical height
  - Extracted eddy viscosity and backscatter

Summary of theoretical research

1952-2002

- Development of models
  - Bubble merger, two-phase flow, and buoyancy-drag models
  - Potential flow, vorticity deposition, and shell models
  - One-dimensional turbulence model
- Modeling of nonlinear instability growth and transition to turbulence
  - Application of Dimotakis transition criterion at $Re \sim 10^4$
  - Modeling of combined shear and buoyancy instabilities
  - Effects of heat transfer and ablation
  - Modified Zhang-Sohn model
  - Compressible Rayleigh-Taylor instability
  - Stability of converging/diverging shock waves
- Turbulent transport and mixing models
  - Two-fluid model for combined Rayleigh-Taylor, Richtmyer-Meshkov, and Kelvin-Helmholtz instabilities
  - Two-equation, single-velocity turbulence models
  - Two-scale turbulence model
  - Simulations using multi-fluid models in ALE and AMR codes

Progress has been made in the theoretical study of nonlinear instability evolution using bubble merger, two-phase flow, and simple models

1952-2002

- A model for mixing layer width evolution was described (Cheng, Glimm & Sharp T7)
  - Bubble merger model based on a renormalization group fixed-point
  - Center-of-mass model coupling bubble and spike mixing zone edges
  - Buoyancy-drag model calibrated against above models
- A buoyancy-drag model was used to model dependence of spatial dimensionality and density ratio on Richtmyer-Meshkov instability evolution (Yosef-Hai et al. T35)
- A vorticity deposition model was developed for single-mode Richtmyer-Meshkov instability growth at large *Ma* and large initial amplitude (Rikanati et al. T23)
- Extensions of Layzer potential flow model used to study bubble/spike front evolution with modal interactions (Abarzhi T1, T3; Abarzhi, Glimm & der Lin T2)
  - Regular and singular asymptotic solutions studied for $At < 1$
  - Group theoretical methods used to study morphology/topology of large-scale structure of periodic bubble/spike arrays (Inogamov et al. T12, T13)
- Layzer-type and *shell* models including effects of entrainment and diffusion on mixing layer growth used to study Rayleigh-Taylor evolution and examine α (Dalziel T10)
- One-dimensional Turbulence (ODT) model used to study large *At*, small *Ma* mixing (Ashurst & Kerstein C4)
- A model of inhibition of Rayleigh-Taylor mixing was developed (Breidenthal T5)

Progress has been made in the theoretical study of nonlinearity and the transition to turbulence

1952-2002

- Dimotakis criteria for transition to turbulence at *Re* ~ 10^4 applied as a function of time to:
  - Cambridge University experiment and an OMEGA experiment (Zhou et al. T36)
  - Rayleigh-Taylor unstable plasma flow (Robey et al. E35)
- Turbulence modeling of combined shear and buoyancy instabilities (Wilson, Andrews & Harlow T33)
- Effects of heat transfer/ablation on turbulent mixing investigated (Clark & Harlow T8)
- Predictions of Nikiforov's turbulence model in the VIKHR code was shown to be in good agreement with:
  - LEM data (Kozlov, Razin & Sapozhnikov C51)
  - Poggi et al. RM instability data (Kozlov & Razin C52)
- A modified Zhang-Sohn model was developed for single-mode, nonlinear growth of the Rayleigh-Taylor and Richtmyer-Meshkov instability (Vandenboomgaerde T31; Vandenboomgaerde et al. T32)
- Growth rates of linear (Wouchuk T34) and nonlinear (Nishihara, Matsuoka & Fukuda T19) Richtmyer-Meshkov instability studied
- Rayleigh-Taylor instability in compressible fluids was studied (Tricottet & Bouquet T30)
- The stability of diverging shock waves (Ktitorov T15) and of converging shock waves (Ktitorov T16) was studied

Progress has been made in turbulent transport model development for turbulent mixing induced by interfacial instabilities

1952-2002

- A 1D two-fluid model incorporating combined Rayleigh-Taylor/Richtmyer-Meshkov/Kelvin-Helmholtz instabilities with arbitrary *g(t)* was developed (Bailly & Llor T4)
  - Mass transfer between fluids and diffusion (K-ε model) included
  - Self-similarity studied in "0D", i.e., as a function of time only (Llor T18)
- A family of two-equation models was developed for 2D/3D single-velocity, compressible, multi-component flow (K-Z: K-ε, K-l, K-ω, K-τ) (Schilling T26)
  - Includes closures for compressibility, reaction terms not previously included
  - Special cases studied analytically (decay, shear layer, boundary layer, jet)
- A 1D two-scale K-ε model was formulated using spectral and scaling concepts,and preliminary validation studies were performed in the ALE code sKULL (Eliason, Cabot & Zhou C53)
- Youngs multi-fluid turbulence model was implemented in the 2D finite-element ALE code CORVUS (Grieves C17)
- Multi-fluid simulations of Rayleigh-Taylor mixing using 2D AMR code (Vold C40)
- A 1D diffusive mixing model was used to study neutron and charged-particle yields in laser implosion experiments (Epstein et al. C13)
- A K-ε model was developed for applications to the atmospheric surface layer (Anuchin, Neuvazhayev & Parshukov C2)

Concluding observations: past, present, and future of the IWPCTM

1952-2002

- In the past, many presentations had limited relevancy to *compressibility*, *turbulence*, or *mixing*
  - Experiments and simulations limited to very small *Re* and *Ma*
  - Euler simulations generated “numerical mixing” and “numerical turbulence”
  - Analytical models were limited to linear and weakly-nonlinear regimes
- Presentations this year were more focused on the subjects of the Waorkshop, with good progress in:
  - Experimental designs/diagnostics,especially for classical fluid experiments
  - Higher accuracy and higher resolution simulations in 2D and 3D
  - Multi-fluid interpenetration, turbulent transport and mixing model development
- Future focus should include:
  - Diagnostic methods that can experimentally measure <u>statistical quantities</u>
  - Experiments, simulations, and modeling of *reacting* turbulent flows
  - Analysis of DNS data, and development of subgrid-scale models
  - LES of compressible turbulent mixing
  - Refined turbulence models validated against experiments and LES