Fundamentals of Compressible Turbulence: Recent Advances and Open Questions

Hosted by Texas A&M – Department of Aerospace Engineering
Dr.’s Diego Donzis & K.R. Sreenivasan

May 20th and 21st
## Fundamentals of Compressible Turbulence: Recent Advances and Open Questions

### DAY 1
Thursday, May 20th

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Friday, May 21st

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DAY 1
Thursday, MAY 20th
PRESENTATION
ABSTRACTS
Sonic Limitation in Highly Compressible Shear Layer Turbulence

Presented by: Dr. Sanjiva K. Lele
Stanford University

High resolution simulations of temporally-evolving compressible shear layers at high compressibility conditions are examined in the context of sonic-eddy hypothesis. It is found that length scales defined by two-point correlations do not span the full flow width of the shear layer mean velocity profile at high compressibility. The effective velocity scale associated with the transverse correlation scale is found to provide good scaling for the reduced turbulent velocity fluctuations, Reynolds shear-stress, pressure fluctuations, pressure-strain rate, and shear layer thickness growth rate.
Mach Number Scaling and Statistics in Chemically Reacting Compressible Isotropic Turbulence

Presented by: Dr. Jianchun Wang  
Nagoya Institute of Technology

Turbulent reactive flows are commonly observed in chemical reactive devices, energy generation plants and combustion engines. Interaction between turbulent flows and chemical reactions over a wide range of time and length scales exerts a significant influence on dynamical evolution of flow quantities and energy transfer. In this report, we introduce some recent progresses in exploring turbulence-chemistry interactions by our group, and concentrate our discussion on the effects of reaction heat release on the statistics of turbulent quantities. First, we discuss heat release effects on the spectra of velocity and thermodynamic variables over a wide range of length scales at turbulent Mach number $Mt$ ranging from 0.1 to 1.0 and at Taylor Reynolds number $Re_{\text{arr}}$ ranging from 54 to 103. Comparisons of the normalized spectra of pressure and dilatational velocity component suggest that the dynamics of the dilatational velocity and the pressure is dominated by acoustic waves and the flow is in strong acoustic equilibrium even at low turbulent Mach numbers. Second, the Mach scaling of normalized kinetic energy and normalized kinetic energy dissipation show irrelevance of turbulent Mach number but dominated by heat release for exothermic reactions. The scaling of normalized rms values of thermodynamic variables exhibit a $Mt$ scaling which is different from the $M2t$ scaling in non-reacting and isothermal reacting compressible turbulence. Third, inter-scale kinetic energy transfer in chemically reacting turbulence at $Re_{\text{arr}} = 160 - 250$ is analyzed through altering techniques. Results indicate that heat release evidently enhances compression and expansion motions, in which both the positive and the negative components of pressure/dilatation, as well as positive and negative components of sub-grid-scale(SGS) kinetic energy flux are greatly enhanced. Thus leading to an increase of both forward-scatter and backscatter of kinetic energy.

Keywords: Compressible turbulence, isotropic turbulence, reactive flow
Universality in compressible turbulence has proven to be elusive as no unifying set of parameters was found to yield universal scaling laws. This severely limits our understanding of these flows and the successful development of theoretically sound models. Using results in specific asymptotic limits of the governing equations in the absence of a mean flow, one can show that universal scaling is indeed observed when the set of governing parameters is expanded to include internally generated dilatational scales regardless of driving mechanisms that produce the turbulence. The analysis, though restricted to homogeneous flows, demonstrates why previous scaling laws fail, and it suggests new venues to identify physical processes of interest and aid in the development of more general turbulence models. We support our results with a new massive database of highly resolved direct numerical simulations along with data from the literature comprising isotropic flows with different forcing mechanisms as well as homogeneous shear flows. In search of universal features, we postulate the existence of classes that bundle the evolution of flows in the new parameter space. An ultimate asymptotic regime predicted by renormalization-group theories and statistical mechanics is also assessed with available data.
Compressible Turbulence: Finite Versus Infinite Re

Presented by: Dr. Sébastien Galtier
Ecole Polytechnique, France

In this short presentation, I will mainly make comments and ask questions about the theory of compressible turbulence in the context of finite versus infinite Re."
A "length scale" in a fluid flow does not exist as an independent entity but is associated with the specific flow variable being analyzed. While this might seem obvious, we often discuss the "inertial range" or the "viscous range" of length scales in turbulence as if they exist independently of a flow variable, which in incompressible turbulence is the velocity field. How should we analyze "length scales" in flows with significant density variations, such as across a shock or in multiphase flows? I will discuss the different possible decompositions and how one of them unravels an inertial range of scales in turbulent flows with significant density variations.
Energy Transfer in Isothermal Compressible Turbulence

Presented by: Alexei Kritsuk
University of California, San Diego

Isothermal compressible turbulence is analyzed in the asymptotic limit of large Reynolds numbers. Based on the inviscid invariance of total energy, a compressible analogue of the von Karman-Howarth-Monin relation describing the scale-by-scale energy budget is derived assuming homogeneity. We use a set of high resolution 3D numerical simulations to illustrate mechanisms of energy transfer across scales under statistically stationary conditions in a range of Mach number regimes from nearly incompressible to transonic turbulence. We discuss the role of pressure dilatation in the energy cascade as well as the impact of shock waves on the energy transfer and dissipation.
Compressible MHD Turbulence and Implications for Solar Wind Turbulent Density Variations Measured by Parker Solar Probe

Presented by: Dr. Hui Li
Los Alamos National Laboratory

Abstract: As the Parker Solar Probe (PSP) gets increasingly closer to the Sun during its each orbit around the Sun, it provides unprecedented measurements of the solar wind properties near the Sun, marked by higher magnetic field strength, lower plasma beta, and possibly stronger turbulence as well. We present data analysis results on how the density variations depend on the turbulent Mach number. To understand this regime further, we have carried out extensive compressible MHD turbulence simulations to investigate the origin of density fluctuations. In particular, the role of parametric decay instability mediated turbulence (PDIMT) of Alfvén fluctuations will be discussed. In addition, we have applied several approaches to analyze the nature of compressible fluctuations. They include the mode decomposition method based on spatial variations only and a spatiotemporal 4D-FFT spectra analysis method. The latter method enables us to distinguish propagating MHD waves versus the non-propagating variations (nearly zero frequency) that contribute to the compressible modes. Overall, we find that the majority of the MHD modes that are identified only by the spatial mode decomposition approach is actually non-propagating (i.e., near-zero frequency). In other words, most of the compressible fluctuations should not be considered as ensembles of propagating MHD eigen-modes. We discuss the implications of our results for understanding the compressible fluctuations of solar wind turbulence and density variations.
Compressible Turbulence in an Experiment

Presented by: Dr. Greg Bewley
Cornell Engineering

We introduce an experiment in which turbulence is both compressible and observable at all scales with existing instrumentation including hot wires and particle tracking. We realize this challenging objective by looking at the flow of a gas (SF6) with a speed of sound almost three times lower than in air. The flow is a free shear flow produced by a fan, and we show that it behaves in a basic way like a compressible jet or shear layer in the sense that it spreads more slowly at higher Mach numbers (up to $M_j = 0.8$) than at low Mach numbers. By switching between air and SF6, we isolate the influence of the Mach number (up to $M_t = 0.2$) on turbulence statistics from the influence of the Reynolds number, which we hold constant (at up to $R_l = 1000$). We discuss our tentative findings, review our plans, and solicit feedback from the audience.
Turbulence under Extreme Thermal Environments

Presented by: Dr. Rodney Bowersox
Texas A&M University, Aerospace Engineering

Modeling of turbulence when exposed to extreme thermochemical non-equilibrium environments is limited by a scarcity of physical modeling and experimental data. Of specific interest is the organized vortex content and statistical descriptions within hypervelocity wall-bounded turbulence, and the mechanisms that couple these aspects to changes in the internal energy states of gaseous molecular species and/or chemical reactions. Hence, an opportunity exists to develop closure for flows that include aerothermochemistry and turbulence. Similarly, DNS and physical experiments are required to guide these efforts, where new HPC computing, laser diagnostics, and high temperature facilities are available to advance the state of the art.
Onsager’s “Ideal Turbulence” Theory for Compressible Fluids

Presented by: Dr. Gregory Eyink  
John Hopkins University

We obtain exact results for compressible fluid turbulence with any thermodynamic equation of state, using coarse-graining/filtering. We find two mechanisms of turbulent kinetic energy dissipation: scale-local energy cascade and “pressure-work defect”, or pressure-work at viscous scales exceeding that in the inertial-range. Planar shocks in an ideal gas dissipate all kinetic energy by pressure-work defect, but the effect is omitted by standard LES modeling of pressure-dilatation. We obtain also a novel inverse cascade of thermodynamic entropy, injected by microscopic entropy production, cascaded upscale, and removed by large-scale cooling. This nonlinear process is missed by the Kovasznay linear mode decomposition, treating entropy as a passive scalar. For small Mach number we recover the incompressible “negentropy cascade” predicted by Obukhov. We derive exact Kolmogorov 4/5th-type laws for energy and entropy cascades, constraining scaling exponents of velocity, density, and internal energy to sub-Kolmogorov values. Although precise exponents and detailed physics are Mach-dependent, our exact results hold at all Mach numbers. Flow realizations at infinite Reynolds are “dissipative weak solutions” of compressible Euler equations, similarly as Onsager proposed for incompressible turbulence. The theory extends straightforwardly to compressible MHD, to plasma kinetic theory, and to relativistic fluids.
Active/Passive Density Conundrum in Compressible Turbulence

Presented by: Dr. Itzhak Fouxon
Yonsei University, Seoul

Fluid density in large Mach number turbulence is a multifractal measure that actively reacts on the flow affecting it via the continuity equation. This implies e.g. that Lagrangian chaos in this flow is characterized by vanishing sum of Lyapunov exponents. However simulations showed otherwise. We will consider the reasons for this discrepancy and the closely associated problem of whether density of passive tracers and the fluid density obeying the same continuity equation could differ. The issue can have profound implications in astrophysical context. The presentation will be accessible for graduate students.
DAY 2
FRIDAY, MAY 21ST
The Sonic Scale of Turbulence from a 10,000^3 Simulation

Presented by: Dr. Chritoph Fererrath
Australian National University

I will be presenting results of a compressible turbulence simulation with 10,000^3 grid cells. Resolving the transition ('sonic scale') from the supersonic spectrum (~ k^-1.99) to the subsonic spectrum (~ k^-1.76). The sonic scale is a key ingredient for star formation, as it sets a characteristic size and density scale in the clouds from which stars form.
We derive the exact relation for the energy transfer in three-dimensional compressible two-fluid plasma turbulence. In the long-time limit, we obtain an exact law which expresses the scale-to-scale average energy flux rate in terms of two point increments of the fluid variables of each species, electric and magnetic field and current density, and puts a strong constraint on the turbulent dynamics. The incompressible single fluid and two-fluid limits and the compressible single fluid limit are recovered under appropriate assumption. In the single fluid limits, analyses are done with and without neglecting the electron mass thereby making the exact relation suitable for a broader range of application. In the compressible two fluid regime, the total energy flux rate, unlike the single fluid case, is found to be unaltered by the presence of a background magnetic field. The exact relation provides a way to test whether a range of scales in a plasma is inertial or dissipative and is essential to understand the nonlinear nature of both space and dilute astrophysical plasmas.
Non-Equilibrium Effects in Compressible Turbulence

Presented by:  Dr. Sharath S. Girimaji  
Texas A&M University, Aerospace Engineering

The change in character of pressure from incompressible to compressible flows leads to a marked change in the nature of compressible turbulence. This leads to different types of `non-canonical’ and `non-equilibrium’ effects. In this talk, I will discuss different types of non-equilibrium effects and propose analytical tools to examine the departure from canonical effects. The focus will be on non-local effects and scale-to-scale energy transfer in homogeneous and inhomogeneous compressible turbulence.
Variation of Fluctuation Statistics from Gaussian State to Turbulent State

Presented By: Dr. Toshiyuki Gotoh
Nippon Institute of Technology, Japan

Variation of statistical properties of an incompressible velocity, passive vector and passive scalar in isotropic turbulence were studied for the Taylor micro-scale Reynolds number $R_{\text{\lambda}}$ from 0.13 to 110 by using direct numerical simulation. Emphasis is put on the variation of the dissipations and enstrophy PDFs. It is found that when the Reynolds number is very low, the PDFs of the dissipation rates and the enstrophy are analytically derived and found to be the Gamma distribution. And the left tails of those PDFs obey the power law irrespective of the Reynolds number, and thus universal. On the other hand, the right tails become longer and longer with increase of the Reynolds number.
Towards a Better Understanding of Structure Formation Processes in Solar Convection

Presented by: Dr. Jöerg Schumacher
Touristik Union International, Germany

Turbulent flows are highly chaotic and characterized by a cascade of irregular vortices, however our daily experience shows that such flows are often organized into prominent large-scale and long-living patterns. One example is turbulent convection in the outer shell of the Sun which manifests at the surface in the form of granules which cover the 30 times larger and longer-living supergranules. Numerical simulations demonstrate such a supergranule aggregation in a much simpler flow than solar surface convection – the incompressible turbulent Rayleigh-Bénard convection case driven constant heat flux. We show that this requires very long-term simulations and reveal the basic instability mechanisms that drive the fully developed turbulent convection layer to a supergranule. The role of additional rotation of the extended layer is also investigated. Implications of an extension to the compressible case (which is present in the Sun) will be discussed.
Dissipation and Dilatation Rates in Premixed Turbulent Flames

Presented by: Dr. Vladimir Sabelnikov
Central Aerohydrodynamic Institute (TsAGI)

Velocity dilatation and total, solenoidal, and dilatational dissipation rates of the total flow kinetic energy are extracted from three different direct numerical simulation databases obtained by three independent research groups using different numerical codes and methods (e.g., single-step chemistry and complex chemistry flames) from six different premixed turbulent flames associated with flamelet, thin reaction zone, and broken reaction zone regimes of turbulent burning. The results show that dilatational dissipation can be larger than solenoidal dissipation in the flamelet regime and is substantial in the thin reaction zone regime. Accordingly, the influence of combustion-induced thermal expansion on the dissipation rate is not reduced to an increase in the mixture viscosity by the temperature. A simple criterion for identifying conditions associated with significant dilatational dissipation is discussed, and dilatational dissipation due to the influence of turbulence on mixing in preheat zones is argued to play a role even at high Karlovitz numbers Ka. In particular, the magnitude of dilatation fluctuations and probability of finding negative local dilatation are increased by Ka, thus implying that the impact of molecular transport of species and heat on the dilatation increases with increasing Karlovitz number.

Enhanced Burning Rates in Hydrogen-rich Turbulent Premixed Flames with Mean Shear

Presented by: Dr. Jacqueline Chen
University of California, San Diego

The role of sheared turbulence on the turbulent burning velocity is explored for hydrogen-rich fuels being considered for carbon-free energy including hydrogen/ammonia/nitrogen-air blends as a possible drop-in fuel for natural gas. In particular the mutual interactions between chemical reaction and molecular diffusion at the small scales is considered for turbulent premixed combustion at high Karlovitz conditions in the so-called distributed reaction zones regime. DNS of fuel-lean turbulent premixed hydrogen/ammonia/nitrogen-air flames in a turbulent mixing layer at a turbulent Reynolds number of 1100 and Karlovitz number of 626 are considered at 1 atm and at 10 atm. Differential diffusion of molecular hydrogen and fast diffusing atomic hydrogen persist as rate-controlling processes affecting the local structure and dynamics of the turbulent flame even at such high Karlovitz conditions. Turbulent diffusion, flame-flame interaction and molecular diffusion effects contribute to the complex flame structure and its propagation. At elevated pressure the effects of atomic hydrogen diffusion are less pronounced, whereas thermodiffusive effects are enhanced, leading to increased flamelet-like behavior. The thermodiffusive effects due to molecular transport are modulated by turbulent diffusion in the flames preheat zone which differs with pressure for nominally similar global conditions.
Detonation Initiation by Compressible Turbulence
Thermodynamic Fluctuations

Presented by: Dr. Peter Hamlington
University of Colorado, Boulder

Theory and computations have established that thermodynamic gradients created by hot spots in reactive gas mixtures can lead to spontaneous detonation initiation. However, the current laminar theory of the temperature-gradient mechanism for detonation initiation is restricted to idealized physical configurations. Thus, it only predicts conditions for the onset of detonations in quiescent gases, where an isolated hot spot is formed on a timescale shorter than the chemical and acoustic timescales of the gas. In this talk, we extend the laminar temperature-gradient mechanism into a statistical model for predicting the detonability of an autoignitive gas experiencing compressible isotropic turbulence fluctuations. Compressible turbulence forms non-monotonic temperature fields with tightly-spaced local minima and maxima that evolve over a range of timescales, including those much larger than chemical and acoustic timescales. We examine the utility of the adapted statistical model through direct numerical simulations of compressible isotropic turbulence in premixed hydrogen-air reactants for a range of conditions. We find strong, but not conclusive, evidence that the model can predict the degree of detonability in an autoignitive gas due to turbulence-induced thermodynamic gradients.
Supersonic Reacting Turbulence

Presented by: Dr. Alexei Poludneko  
University of Connecticut

Turbulent reacting flows are pervasive both in our daily lives on Earth and in the Universe. Despite this ubiquity in Nature, such flows still pose a number of fundamental questions concerning their structure and dynamics often exhibiting surprising and unexpected behavior. In recent years, the advent of large-scale direct numerical simulations (DNS) has allowed the detailed exploration of the reacting flow dynamics in extreme, previously inaccessible regimes characterized by high flow speeds, significant compressibility effects, and strong coupling between exothermic reactions and the turbulent flow. Such combustion regimes are fundamental to the operation of many modern propulsion applications from scramjets to detonation-based engines. Furthermore, in certain cases these regimes can now be studied with remarkable realism using full-scale systems, realistic fuels, and engine-relevant conditions. This talk will present an overview of a range of phenomena recently discovered in DNS of high-speed, turbulent reacting flows. These include intrinsic instabilities of reacting turbulence, onset of catastrophic transitions, e.g., spontaneous detonation formation, as well as the qualitative changes in the nature of the turbulent cascade in the presence of exothermic reactions.
On the Compressible Primitive Equations of Atmospheric Dynamics

Presented by: Dr. Edriss S. Titi
Texas A&M University, Aerospace Engineering

In this talk, we will show the local-in-time well-posedness of strong solutions to the three-dimensional compressible primitive equations of atmospheric dynamics. We will show that strong solutions exist, unique, and depend continuously on the initial data, for a short time in two cases: with gravity but without vacuum, and with vacuum but without gravity.
Simultaneous Development of Shocks and Weak Discontinuities from Smooth Data

Presented by: Theo Drivas  
Stony Brook University

We will discuss some recent work on shock formation and propagation of singularities for compressible Euler. The aim is to describe precisely the structure of an entropy producing shock in its early phase (starting from smooth initial conditions), and also describe with some detail a collection of weaker singularities that are born with it. These singularities are in the derivatives of the solution fields and travel along different characteristics than the shock.