Turbulent Mixing and Beyond

Second International Conference and Advanced School

ABSTRACTS

27 July - 7 August, 2009

The Abdus Salam International Centre for Theoretical Physics

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Snezhana I. Abarzhi, Christopher J. Keane, Sergei S. Orlov, Katepalli R. Sreenivasan

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Preface

The goals of this International Conference "Turbulent Mixing and Beyond" are to expose the generic problem of non-equilibrium turbulent processes to a wide scientific community, to promote the development of new ideas in tackling the fundamental aspects of the problem, to assist in application of novel approaches in a broad range of phenomena where the turbulent processes occur, and to have a potential impact on technology.

The Conference and the School provide the opportunity to bring together researchers from areas which include fluid dynamics, plasmas, high energy density physics, astrophysics, material science, combustion, atmospheric and earth sciences, nonlinear and statistical physics, applied mathematics, probability and statistics, data processing and computations, and optics and telecommunications, and to have their attention focused on the long-standing formidable task of non-equilibrium turbulent processes.

Non-equilibrium turbulent processes play a key role in a wide variety of phenomena, ranging from astrophysical to atomistic scales, under either high or low energy density conditions. Inertial confinement and magnetic confinement fusion, light-matter interaction and non-equilibrium heat transfer, strong shocks and explosions, material transformation under high strain rate, supernovae and accretion disks, stellar non-Boussinesq and magneto-convection, planetary interiors and mantle-lithosphere tectonics, premixed and non-premixed combustion, non-canonical wall-bounded flows, hypersonic and supersonic boundary layers, dynamics of atmosphere and oceanography – just to list a few examples. A grasp of non-equilibrium turbulent processes is crucial for cutting-edge technology such as laser micromachining, nano-electronics, free-space optical telecommunications, and for industrial applications in the areas of aeronautics and aerodynamics.

Non-equilibrium turbulent processes are anisotropic, non-local, multi-scale and multi-phase, and often are driven by shocks or acceleration. Their scaling, spectral and invariant properties differ substantially from those of classical Kolmogorov turbulence. At atomistic and meso-scales, the non-equilibrium dynamics depart dramatically from a standard scenario given by Gibbs statistical ensemble average and quasi-static Boltzmann equation. The non-equilibrium dynamics at macroscopic scales are interlinked with the fundamental properties of the Euler and compressible Navier-Stokes equations and with the solution sensitivity to the boundary conditions at discontinuities. The state-of-the-art numerical simulations of multi-phase flows suggests new methods for predictive modeling of the multi-scale non-equilibrium dynamics in fluids and plasmas, up to peta-scale level, for error estimate and uncertainty quantification, as well as for novel data assimilation techniques.

The First International Conference "Turbulent Mixing and Beyond" (TMB) was held in August 2007 at the Abdus Salam International Centre for Theoretical Physics, Trieste, Italy. By all the standards, the Conference was a major success. The TMB Community has identified non-equilibrium turbulent processes as the intellectually rich and highly fascinating problem, whose exploration can have a transformative impact on our understanding of a wide variety of physical phenomena, from atomistic to astrophysical scales, on fundamental principles of mathematical modeling of the dynamics of continuous media and non-equilibrium kinetics, and on the technology development in fusion, nano-electronics, telecommunications and aeronautics. The creation of an environment for multidisciplinary collaboration is essential for achieving success in the solution of this multifaceted problem and enabling the quality of the information yield. Based upon that success and upon recommendations of Round Table Discussions at the first TMB meeting, the Second Conference and School "Turbulent Mixing and Beyond" is being organized.

The objectives of the Second Conference and School "Turbulent Mixing and Beyond" are to:

a. Encourage the integration of theory, experiments, large-scale numerical simulations and state-of-the-art technologies for exploration of physical mechanisms of non-equilibrium turbulent processes, from atomistic to macro scales, in both high and low energy density regimes.

b. Foster the application of innovative approaches for tackling the fundamental aspects of the problem, and understand and extend the range of applicability of traditional statistically steady considerations.

c. Stimulate the application of advanced statistical and stochastic techniques and data analysis methodologies for unified characterization of the experimental and numerical data sets and for the estimation of their fidelity and information capacity.

d. Further develop the TMB Community and enable it with the means of information exchange via a Collaborative Computing Environment, by providing access to the state-of-the-art advanced computational methodologies for data annotation, visualization, storage, transfer and analysis.

The Organizing Committee hopes that this Conference and School "Turbulent Mixing and Beyond" will serve to advance the state of the art in the understanding of fundamental physical properties of non-equilibrium turbulent processes and will have a conspicuously positive impact on their predictive modeling capabilities and physical description and, ultimately, on control of these complex processes.

The Book of Abstracts includes 194 accepted contributions of 385 authors: lectures, talks, posters and tutorials in a broad variety of TMB Themes, sorted alphabetically within each theme. All the accepted contributions have been reviewed by the international team of 24 members of the Scientific Advisory Committee, with every abstract considered by 3 to 8 experts. In the majority of cases, the opinions of referees with the diverse background and expertise converged.

You are cordially invited to take a look at this Book for information on the frontiers of theoretical, numerical and experimental research, and state-of-the-art technology. Welcome to the Turbulent Mixing and Beyond Community.

S. I. Abarzhi, C. J. Keane, S. S. Orlov, K. R. Sreenivasan

CONTENTS

CANONICAL TURBULENCE and TURBULENT MIXING

Turbulent transport and mixing in the presence of flow topology reconstruction

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In the present paper, we consider the influence of weak dissipative effects on the passive scalar behavior in the framework of continuum percolation approach [1-3]. The renormalization method of a small parameter in continuum percolation models is reviewed. It is shown that there is a characteristic velocity scale, which corresponds to the dissipative process. The presence of even small dissipation can considerably change the character of streamlines behavior [4]. It is possible to introduce the rate of energy dissipation by analogy with the Kolmogorov isotropic turbulence theory. In the percolation case under consideration, the weak dissipation leads to increasing the stochastic layer width [5]. The modification of the renormalization condition of the small percolation parameter is suggested in accordance with additional external influences superimposed on a system. In the framework of mean field arguments, the balance of correlation scales is considered [6]. This gives the characteristic time that corresponds to the percolation regime. A new expression for the effective coefficient of diffusion is obtained, which is in agreement with the Zeldovich prediction for strong turbulence limit [1-3].

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Turbulent suspensions of heavy particles

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Dust, droplets and other finite-size impurities with a large mass density suspended in incompressible turbulent flows are commonly encountered in many natural phenomena and industrial processes, such as the growth of raindrops in subtropical clouds, the formation of planetesimals in the early Solar System, and the combustion in Diesel engines. The most salient feature of such suspensions is the presence of strong inhomogeneities in the spatial distribution of particles, a phenomenon dubbed preferential concentration. We show that, depending on the spatial scale at which it is observed, the particle distribution can be of very different natures.

At dissipative scales, where the fluid flow is differentiable, the phase-space density of particles is supported on a dynamically evolving fractal set. This attractor is characterized by non-trivial multiscaling properties, which imply multiscaling of the coarse-grained spatial distribution of the mass of particles. For larger length scales inside the inertial range of turbulence, the particle distribution is characterized by large voids where the mass is orders of magnitude below its average. Such regions are typically correlated with the vortical structures of the flow; this confirms the classical phenomenological pictures that in turbulent flows, eddies act as small centrifuges and eject heavy particles leading to their concentration in the strain-dominated regions. The signature of this voids in the coarse-grained mass probability distribution is an algebraic behavior at small densities. We present a simple model for mass transport that reproduces the same distribution.

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Eulerian and Lagrangian statistics from high resolution numerical simulations of weakly compressible turbulence

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We report a detailed study of Eulerian and Lagrangian statistics from high resolution Direct Numerical Simulations of isotropic weakly compressible turbulence. Reynolds number at the Taylor microscale is estimated to be around 600. Eulerian and Lagrangian statistics is evaluated over a huge data set, made by 1856^3, spatial collocation points and by 16 million particles, followed for about one large-scale eddy turn over time. We present data for Eulerian and Lagrangian Structure functions up to ten order. We analyze the local scaling properties in the inertial range and in the viscous range. Eulerian results show a good superposition with previous data. Lagrangian statistics is different from existing experimental and numerical results, for moments of sixth order and higher. We interpret this in terms of a possible contamination from viscous scale affecting the estimate of the scaling properties in previous studies. We show that a simple bridge relation based on multifractal theory is able to connect scaling properties of both Eulerian and Lagrangian observables, provided that the small differences between intermittency of transverse and longitudinal Eulerian structure functions are properly considered.

Clustering of inertial particles in free jets

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Recently, clustering of inertial particles in turbulence has been thoroughly analyzed for statistically homogeneous and isotropic flows. The most striking result concerns the singular behavior exhibited by the radial distribution function under proper resonance conditions, showing clustering below the Kolmogorov scale. Since anisotropy is strongly depleted through the inertial range, the advecting field anisotropy may be expected inertial for the small scale features of particle configurations. By addressing direct numerical simulations (DNS) of a statistically steady particle-laden homogeneous shear flow, we found instead that the small scales of the particle distribution are strongly affected by the geometry of velocity fluctuations at large scales. The proper statistical tool is the angular distribution function of particle pairs (ADF). Its anisotropic component may develop a singularity whose strength quantities the anisotropy of the small scale clustering. The data provide evidence that the process is essentially anisotropic, even in the range of scales where isotropization of velocity statistics already occurred. In order to show the relevance of the results for a generic shear flow, several cases, ranging from turbophoresis in wall bounded shear flows to the segregation process induced by turbulence in particle laden free jets, will be discussed focusing mainly on particle behavior in free jets, of special interest given the increase with axial distance of turbulent length and time scales. Applications to turbulent combustion in jets will also be addressed with special emphasis on the impact that segregation may have on the accuracy of particle based flow velocity measurement techniques (PIV, LDA) in turbulent flames.

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Study of the influence of micromixing model properties on an averaged chemical reaction rate in a turbulent flow

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The problem on mixing with chemical reacting in the homogeneous turbulent flow was considered. A second-order irreversible isothermal reaction served as chemical reaction. A mixing model was formulated by the method of statistical moments. An unknown averaged chemical reaction rate was determined using both the concepts of mixture fraction f and progress variable Z and the PDF method, and was expressed through the conditional statistical moment of Z and the mixture fraction PDF.

The analyzed models for mixing time scale identically describe the segregation intensity for the initial time. At the intermediate and final mixing stages, a difference lies in the results by the model with a constant time scale ratio R, by the algebraic model considering the R time variation with decreasing Re_t, and by the transfer equation for mixing time scale. Based on the numerical results obtained the multi-zone mixture fraction PDF model, the IEM/LSME, and Langevin micromixing models adopted in the equation for such a PDF are compared.

For the IEM/LSME model, the time PDF variation remains invariable. This fact is untrue proceeding from the physical behavior of mixing. For the Langevin model, the PDF describes mixing from a segregated to a sufficiently mixed state of mixture. At the same time, its behavior is two-mode at the intermediate mixing stages and points to the presence of different-concentration flow regions. The same results are obtained by the multi-zone PDF.

For all PDF models, the averaged progress variable is an increasing time function. As compared to the multi-zone PDF results, others show higher values of Z over the entire time range and at all Damköhler numbers. Such a difference is made by the approximations adopted for the averaged chemical reaction rate, which should be further taken into account at the adequate modeling of mixing with chemical reacting in inhomogeneous turbulent flows.

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Fragmentation under scaling symmetry: application to turbulence and atomization

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We analyze statistical universalities that arise over time during constant frequency fragmentation under scaling symmetry. It has been shown that with increasing time, the initial distribution of size tends to the ultimate steady-state delta function through at least two intermediate universal asymptotics. The earlier asymptotic is the well-known log-normal distribution (Kolmogorov, 1941), with two parameters: the first and the second logarithmic moments of the fragmentation intensity spectrum. The later asymptotic is a power function (stronger universality) with a single parameter that is given by the ratio of the first two logarithmic moments. At large times, the first universality implies that the kinetic evolution equation of fragmentation can be reduced exactly to the Fokker-Planck equation instead of making the widely-used assumption about the smallness of higher than second order moments. At even larger times, the second universality shows evolution towards a fractal state.

We illustrate two examples of application of mentioned universalities. The first example illustrates the stochastic model of spray formation assisted by a high-speed gas flow. In this model, the continuous liquid core is simulated by spatial trajectories of specifically introduced stochastic particles which are governed by stochastic process in the framework of fragmentation under scaling symmetry. The second example illustrates simulation of a high Reynolds number flow. Here the subgrid (unresolved) acceleration is simulated using universalities in fragmentation under scaling symmetry. Both examples are assessed by comparison with experiment.

We propose a model of turbulent eddy cascade on the bases of renormalization of the fragmentation equation and its simple exact solution, when the spectrum of fragmentation is an arbitrary function and the fragmentation frequency is a power function of size. This solution provides the stationary flux of energy, from large scales towards zero scales. A stochastic model of such a cascade is proposed.

Polymer additives in two-dimensional turbulence

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We present a detailed direct numerical simulation (DNS) study of two-dimensional decaying, homogeneous, isotropic, turbulence in presence of polymer additives. Our study shows that the analogue of the viscous dissipation reduction [1] in two-dimensions is palinstrophy reduction. In particular, palinstrophy reduction increases with an increase in the polymer concentration. We also study the change in the behavior of the energy spectrum on the addition of polymers.

Examination of Kolmogorov's idea of universality in turbulence by computational approaches

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According to Kolmogorov's idea of universality in turbulence, there is a certain kind of universality in the small scale statistics of fully developed turbulence. This idea is at the heart of modern theories of turbulence, and applicable to not only turbulence but also turbulent mixing. The confirmation or quantitative examination of this idea by direct numerical simulation (DNS) of turbulence remains a challenge in the study of turbulence.

Kolmogorov's idea is based on the assumption that the Reynolds number as well as the ratio of the scale of energy containing eddies to the scale under consideration are sufficiently large. But they can be only finite in any DNS and experiments, and we are still missing quantitative understanding on the influence of their finiteness on the universality, (if the idea is correct).

After a brief survey of limitations in DNS due to the simple fact that the data size in any DNS must be finite, how large it may be, the talk presents a review on the study of the small scale statistics of incompressible turbulence by DNS with the number of grid points up to 4096^3 and the Taylor micro-scale Reynolds number up to about 1200. An emphasis is put on the influence of the finiteness of the Reynolds number and the ratio of the scales.

The talk also presents a review on computational and closure theoretic studies of the statistics of passive scalar field advected by turbulence of incompressible fluid. An emphasis is put on (i) the influence of the finiteness of the Reynolds number on the inertial subrange statistics of two-particle diffusion, and (ii) anomalous scaling of four point statistics of passive scalar field advected by rapidly changing turbulence (Kraichnan's model) in two dimensions.

Non-standard homogenization theory for transport by a strong mean flow and periodic fluctuations

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The transport of passive scalars has been well studied using the advection diffusion equation in the case of periodic fluctuations with a weak mean flow or a mean flow of equal strength through homogenization techniques. However, in the regime of strong mean flow homogenization seems to breakdown. We study the transport of passive scalars using Monte-Carlo simulations for the stochastic differential equations describing tracer trajectories and obtain the enhancement in diffusivity. We also compute the enhancement in diffusivity by extrapolating the homogenization code for the equal strength case. Comparing the two we note that homogenization theory does in fact seem to work in this case as well. We then develop a mathematical framework of non-standard homogenization theory to explain the numerical result and obtain homogenized equations for the strong mean flow case.

Towards theory of mesoscopic wave turbulence

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Description of transition from regular to random regimes of motion and characterization of the intermediate states where both regular and random wave motions are present and mutually inter-connected, is an intriguing and challenging problem. Such intermediate states where the number of waves is big and yet the discreteness of the wavenumber space still remains important are called Mesoscopic Wave Turbulence. The purpose of my lecture is to summarize an important progress that has been done in characterizing Mesoscopic Wave Turbulence theoretically, numerically and experimentally, as well as to identify important and yet unresolved problems.

Energy spectrum and fluxes in Rayleigh-Benard convection

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We study the spectra and fluxes for the velocity and temperature fields in Rayleigh-Benard convection for a wide range of Prandtl numbers. We use a pseudo-spectral method to simulate the fluid contained in a three-dimensional box with free-slip boundary condition on the horizontal walls. Our spectral and flux studies provide reasonably strong evidence in the support of Bolgiano-Obukhov scaling for high Prandtl number convection, and Kolmogorov-Obukhov scaling for low and zero Prandtl number convection.

Transition to turbulence for flows without linear criticality

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It is well known that plane Couette flow and pipe flow are linearly stable against arbitrary three-dimensional perturbations at any finite Reynolds number, so that transitions from the basic laminar states, if they exist, must be abrupt. Due to this lack of linear criticality, weakly nonlinear analysis does not work in general and only numerical approaches must be resorted. It is only recent that nontrivial nonlinear states for these flows are discovered numerically at finite Reynolds number as the solutions bifurcating from infinity. The onset of turbulence in a subcritical transition is believed to be related to the appearance of steady/travelling-wave states caused by disturbances of finite amplitude which take the flows out of the basin of attraction of the laminar state in the phase space. In the present paper we introduce other flows which, similarly to plane Couette flow and pipe flow, exhibit no linear critical point for the laminar states, namely flow in a square duct and sliding Couette flow in an annulus with a certain range of gap ratio. We shall show our recent numerical investigations on these flows where nonlinear travelling-wave states are found for the first time by a homotopy approach. We believe that these states constitute the skeleton around which a time-dependent trajectory in the phase space is organized and help to understand non-equilibrium turbulent processes.

Inertial particles in a two-dimensional random flow

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We study the dynamics of heavy inertial particles suspended in a two-dimensional random flow, which is piecewise linear in space and piecewise constant in time. This model allows investigating the different regimes that appear when varying the particle inertia (Stokes number) and/or the correlation time of the carrier flow (Kubo number). In the asymptotic regime of very long correlation times, the limiting trajectories can be constructed explicitly, so that the system is amenable to analytical treatment.

Vortex dynamics in turbulent flows: a Lagrangian viewpoint

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We study, by means of state-of-the-art DNS, the dynamics of pointwise particles passively advected by a turbulent fluid. We focus on the connection between preferential concentration of particles with the underlying topological Eulerian structures in general and with vortex filaments in particular. We characterize the latter by tracking particles lighter than the fluid, which tend to accumulate around vortex filaments, actually falling into them and remaining trapped, and looking at the temporal evolution of a kind of momentum of inertia of bunches of particles. From the time lag during which such quantity remains under a certain threshold (indeed very small), one can have an estimate of vortex filaments life–times. Some of the measured coherence times are surprisingly long, reaching values comparable with the large eddies turnover time. The preferential concentration of inertial particles inside/outside vortex filaments has been also used to investigate the fluctuating autocorrelation time of vorticity along particle trajectories. We found a much larger persistency of vorticity fluctuations along light particle paths than for heavy particles, supporting the idea that vortex filaments are somehow quasi–coherent objects moving randomly in the flow. Results on the spatial structure of vortex filaments and on vortex-vortex interactions will be presented, together with direct measurements of vorticity dynamics in such elongated and intense structures. The importance of vortex filaments on statistical averaged observables will be also addressed.

Effect of helicity and rotation on the free decay of turbulent flows

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The self-similar decay of energy in a turbulent flow is studied in direct numerical simulations with and without rotation. Two initial conditions are considered: one non-helical (mirror-symmetric), and one with maximal helicity. The results show that, while in the absence of rotation the energy in the helical and non-helical cases decays with the same rate, in rotating flows the helicity content has a major impact on the decay rate. These differences are associated with differences in the energy and helicity cascades when rotation is present. Properties of the structures that arise in the flow at late times in each case are also discussed.

Chaos and pseudo-chaos in standard and anomalous transport

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We discuss the origin of diffusion in chaotic and non-chaotic systems. Some systems exhibit "strong anomalous diffusion", i.e. the diffusion process is not ruled by a unique scaling exponent. This feature is different from the "weak superdiffusion" regime as in random shear flows. The strong anomalous diffusion can be generated by nontrivial chaotic dynamics, e.g., Lagrangian motion in 2D time-dependent incompressible velocity fields, 2D symplectic maps, 1D intermittent maps and generalized continuous-time random walks.

In addition, we consider models constructed as non-chaotic approximations of chaotic maps showing deterministic diffusion, and represent one-dimensional versions of a Lorentz gas with polygonal obstacles (e.g., the Ehrenfest wind tree model). In particular, a simple construction shows that these maps define non-chaotic billiards in space-time. The models exhibit, in a wide range of the parameters, the same diffusive behavior of the corresponding chaotic versions.

Conditional strain rates along gradient trajectories from various scalar fields in turbulence

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The properties of various scalar variables, for instance, the passive scalar, the kinetic energy and energy dissipation, and also the components of velocity and vorticity, are at the core of turbulence research. For high enough Reynolds numbers, the time dependent term in the Navier-Stokes equations will be balanced by the convection term. This property is valid for other aforementioned scalars as well. From the fact that locally the convection terms of different scalar variables are controlled by the same turbulent velocity, we may expect similar properties for velocity-related parameters, in which the strain rate is of particular interest. Therefore, both the local and non-local statistics conditioned on gradient trajectories have been investigated. With respect to local properties, it has been found that probability density functions of the strain rates conditioned on gradients from various scalars are all non-symmetrical. For non-local properties, we have studied the length distributions of dissipation elements, which are defined as the regions containing all the grid points from which the gradient trajectories share the same pair of maximum and minimum points. By definition, this decomposition is non-arbitrarily determined and space-filling, uniquely different from other diagnoses. All of these length distributions can be approximated well by a theoretically derived equation. The derivation requires the knowledge of the overall strain rate between the two extremal points of a dissipation element. This strain rate is related to the two point velocity difference along gradient trajectories. It is shown that there exists a linear scaling of the velocity difference, with respect to the arclength between two points on same gradient trajectories. This linear scaling, different from the classic Kolmogorov 1/3 scaling, physically can be explained from the preference of gradient trajectories under the action of strain and diffusion.

Fluctuations of dissipation scale and turbulent mixing

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The dissipation scale, defined as a length scale separating analytic and “rough” ranges of turbulent velocity field, is a strongly fluctuating property. The derived expression for probability density of dissipation scales has been numerically tested in isotropic turbulence and experimentally in pipe flows in both vicinity of the centerline and in the logarithmic layer. The observed close quantitative agreement between theory, numerics and experiment points to a possible small-scale universality. Since turbulent mixing involves molecular transport across “dissipation sheets”, these fluctuations must be accounted for in evaluation of reaction/mixing rates and may be responsible for the mixing transition.

Lagrangian statistical theory of fully-developed hydrodynamic turbulence

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Despite a large amount of achievements since Kolmogorov's scaling theory, the exact theory of turbulence based on the Navier-Stokes equation does not exist yet. The understanding of statistical properties of fluid turbulence is still a challenging problem. On the other hand, recent technical progress allows to investigate, both experimentally and numerically, the correlation properties of fully developed turbulence in terms of particle trajectories. That is why the study of statistical properties of turbulence in Lagrangian variables is of significant theoretical interest.

In [1] we proposed a statistical theory of turbulence based on the Navier-Stokes equation. The inertial range of scales in incompressible liquid was considered. The idea of the model is that the main role in statistics belongs to the regions where vorticity is very high. We showed that these regions must take the form of vortex filaments, and derived the equation describing the vorticity evolution. It appeared that growth of vortex filament was caused by large-scale pressure pulsations. This large-scale term was used to introduce randomness in the Navier-Stokes equation, instead of adding non-physical external large-scale random forces.

Now we apply the theory to find the Lagrangian structure functions [2]. For time which is much smaller than the correlation time, the structure functions are shown to obey scaling relations. The scaling exponents are calculated analytically without any fitting parameters. A new relation connecting the Lagrangian structure functions of different orders analogous to the extended self-similarity ansatz is found. All the results agree extremely well with the experimental data [3].

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Tutorial: Transition in plane Couette flow with and without system rotation

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Target audience: graduate and professional

Plane Couette flow is known to be linearly stable at any finite values of the Reynolds number, thus indicating no direct bifurcation from the basic laminar state. In the tutorial we review Nagata (1990)'s investigation where the nonlinear stability analysis of the flow with a spanwise system rotation successfully led to a discovery of 3D nonlinear steady solutions of plane Couette flow for the first time. We show his recent analysis on further bifurcations in this flow. We also show that when a streamwise rotation is added to plane Couette flow the critical Reynolds number approaches the global stability limit determined by energy theory in the limit of large rotation rate. A nonlinear analysis with an attempted continuation of the secondary flow branch to the zero rotation rate shall be discussed. We believe that the tutorial which describes our investigation to follow bifurcation sequence provides useful tools to understand non-equilibrium turbulent states.

WALL-BOUNDED FLOWS

The quest for high Reynolds number wall-bounded experiments - why, where and how

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During the last decade there has been a renewed interest in wall-bounded turbulent flows, especially with regard to various scaling issues of e.g. the mean and fluctuation velocity distributions. However, it is not easy to obtain accurate experimental data at sufficiently high Reynolds numbers to allow definite conclusions to be drawn about such issues. For instance, experimental data in wall-bounded flows that are available today are usually not complete or lack certain parameters. Of special interest in this respect is the wall shear stress which seldom is measured independently, despite the fact the friction velocity, that is derived from the wall-shear stress, is used to scale both the mean velocity and the Reynolds stresses. Another issue is the spatial resolution of the measurement probe; if the resolution is not high enough this will lead to spatial averaging, thereby underestimating the fluctuations and maybe even affecting the mean values.

In this lecture I will try to answer the "why, where and how" in the title of the lecture. The answer to the "why" will be a deliberation on what are the outstanding problems that we want to address in high Reynolds number wall bounded flows. Furthermore I will discuss how large the Reynolds number need to be in order for an experiment to fulfill the requirements of being at high Reynolds number. The answer to the "where" deals with the type of experimental facilities that are necessary to use to be able to finally give these answers, and finally the "how", i.e., what restrictions must we place and what qualities must we require from the measurement techniques and procedures to be used.

Rayleigh instability in a vortex-induced unsteady boundary layer

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Numerical solutions of the unsteady, two-dimensional Navier-Stokes equations are considered for the flow induced by a thick-core vortex. The adverse pressure gradient imposed on the surface by the vortex leads to development of inflectional velocity profiles and formation of a recirculation region within the boundary layer, and the presence and nature of an instability is considered that may dominate the flow development at high Reynolds numbers. The instability ensues in the form of high-frequency oscillations in vorticity and streamwise pressure gradient along the wall, and the dominant wavenumber of the instability is $O(Re^{1/2})$, consistent with a Rayleigh instability. The existence of a Rayleigh instability is further confirmed through evaluation of the Rayleigh equation for velocity profiles obtained from a boundary-layer calculation, and the dominant wavenumber of the instability in the Navier-Stokes solutions agrees very closely with that predicted by the Rayleigh solutions.

Invariant solutions and state-space dynamics in wall-bounded flows

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It has recently become possible to compute precise equilibrium, traveling wave, and periodic orbit solutions to pipe and plane Couette flow at Reynolds numbers above the onset of turbulence. These invariant solutions capture the complex dynamics of unstable coherent structures in wall-bounded flows and provide a framework for understanding turbulent flows as dynamical systems. We present a number of weakly unstable equilibria, traveling waves, and periodic orbits of plane Couette flow and visualizations of their physical and state-space dynamics. What emerges is a picture of low-Reynolds turbulence as a walk among a set of weakly unstable invariant solutions.

Velocity and energy profiles in two- versus three-dimensional channels: effects of inverse versus direct energy cascade

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We provide a model of an ideal two-dimensional (2D) turbulent channel flow for the sake of comparison with such a flow in 3D. The ideal 2D channel flow differs from its 3D counterpart by having a second quadratic conserved variable in addition to the energy, and the latter has an inverse rather than a direct cascade. The resulting qualitative differences in profiles of mean velocity and turbulent kinetic energy as a function of the distance from the wall are highlighted and explained. The most glaring difference is that the 2D channel is much more energetic, with turbulent kinetic energy in wall units increasing logarithmically with the Reynolds number instead of being Reynolds number independent in 3D channels..

Structural characteristics of turbulent flow over irregular roughness

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The structural attributes of a zero-pressure-gradient turbulent boundary layer over an irregular surface topography are compared with those for flow over a smooth wall at $Re_{theta} \sim 13{,}000$. Two-point correlations and proper orthogonal decomposition are employed to study the average spatial characteristics of these flows using extensive particle image velocimetry (PIV) data sets acquired in the streamwise-wall-normal plane and streamwise-spanwise planes within and at the edge of the roughness sublayer for flow over both surface conditions. The rough surface considered is replicated from a turbine blade damaged by deposition of foreign materials and is therefore highly irregular and contains a broad range of topographical scales. While the structural foundations of these flows appear similar, the present roughness induces shortening of the characteristic streamwise extent of the two-point correlation of streamwise velocity that diminishes with distance from the wall. This shortening is explored in the context of very-large-scale meandering motions previously observed in the log layer of smooth-wall turbulence using both time-resolved PIV measurements in wall-parallel planes and instantaneous wide-field-of-view PIV measurements.

The suppression of turbulent vortex shedding from a square cylinder in proximity to a wall

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Flow around a square cylinder subjected to the free-stream flow in proximity to a wall, is a basic geometry for studying flow around bluff body configurations close to the wall. In such flows, various complex physical phenomena, including flow separation, reattachment, recirculation, and vortex shedding occur. Consequently the interaction of these features with boundary layer produces a very challenging flow for experimentalists as well as CFD practitioners. This paper presents two-dimensional and unsteady RANS computations of time-dependent, periodic, turbulent flow around a square block placed near a plane wall. The practical flow situations may involve obstacles located close to a wall e.g., flow past a suspension bridge or pipelines near the ground or water surfaces, flow past heat exchanger tubes near walls etc. The vicinity of a wall can have a distinct influence on the vortex shedding. The influence of the wall is to cause asymmetry in the strength of the vortex sheets. When there is a gap between the cylinder and the wall the onset of vortex formation appears at a critical gap height. The turbulence model used for computations is a zonal nonlinear k-ε model which is sensitive to the anisotropy of

turbulence. The Reynolds number based on the free-stream velocity and obstacle size is Re=22,000. Comparison of numerical results, including velocity and Reynolds stress profiles as well as global parameters such as Strouhal number and the drag coefficient, with experimental data show that the turbulence modeling approach employed in this study is able to produce reliable numerical results. Vortex shedding behind the cylinder is found to be strongly influenced by the presence of the wall and the structure of the vortex shedding changes with the gap distance between the obstacle and wall. For large gap ratios, regular, periodic vortex shedding occurs and vortices move horizontally in the wake. It has been found that the strength of the positive vortices arising from the lower side of the cylinder reduces with the decrease of gap length. The average drag coefficient on the cylinder decreases with the reduction of gap length. We found that the vortex shedding is suppressed at a critical gap length and the wake becomes steady. At the gap length when vortex shedding is suppressed the shear layer which is separated from the lower side of the cylinder attaches on the cylinder itself. When the cylinder is placed on the wall a large region of recirculation zone occurs in the downstream of the cylinder along with a region of recirculating fluid at the upstream corner and top of the cylinder. The proposed paper would present the relevant equations involved and would also present a comprehensive range of comparisons.

Transient thermal radiative convection flow of a heat transfer past a continuously moving porous boundary

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An analysis is carried out to study the effect of radiation on the flow and heat transfer past a continuously moving porous plate in a stationary fluid. The solution of boundary value problem has been obtained analytically. The effects of various parameters like magnetic parameter, suction or injection parameter, radiation parameter and Prandtl number on the velocity and temperature profiles as well as the skin-friction coefficient and wall heat transfer are presented graphically and in tabulated form.

Turbulence modeling for flow control

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The requirements for numerical simulations, in particular for turbulence models, when used for unsteady simulations of flow control are discussed. On the one hand, flow control and feedback flow control necessitates very high resolution near the control actuator. On the other hand, only the flow structures amenable to control need to be resolved and represented correctly. Two examples show the type of analysis performed to date to evaluate turbulence models for flow control simulations.

The first case is the wake behind a circular object at a Reynolds number of Re = 20,000. The simulation results are analyzed using spatial filtering, Fourier transform, and Proper Orthogonal Decomposition (POD) techniques to illustrate the type of spatial and temporal resolution necessary to identify relevant structures in the flow. The second example is the flow over a backward facing step, which is used to illustrate the effect of the turbulence model in unsteady simulations on the developing structures in the shear layer behind the step. POD analysis is used to identify the flow structures and assess the efficacy of turbulence models in simulations for the development of feedback flow control strategies.

Numerical simulation of turbulence transition regimes in pipe flow using solenoidal bases

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Solenoidal basis functions span the space of functions whose divergence is zero. When these basis functions are employed to expand the velocity field in fluid dynamics problems, the continuity equation is automatically satisfied. In addition, usage of the functions renders the solution for the pressure unnecessary, resulting in simpler computer code. More importantly by using solenoidal basis functions, the dynamical system obtained is suitable for use in bifurcation analysis. Thus, the need for separate simulation and bifurcation analysis is eliminated. This is a clear advantage over using Karhunen-Loeve analysis (POD) in conjunction with DNS, however the solenoidal basis functions are not optimal in the energy sense unlike K-L basis functions. In this study solenoidal basis functions will be formulated in the Legendre polynomial space. Working in Legendre polynomial space results in more favorable forms for inner product integrals which arise from the Petrov-Galerkin scheme employed. In the numerical method used, there are two different solenoidal bases. One used for the expansion of velocity and its dual basis. The choice of the pipe flow for this geometry is due to the fact that even the flow is linearly stable, its nonlinear analysis shows rich transitional dynamics. In this study the dynamical system, resulting from the projection of unsteady incompressible Navier-Stokes equations onto the dual basis, will be solved for Reynolds numbers in the transition neighborhood and the results will be compared with those in the literature.

Development of velocity and pressure disturbances in the near-wall region over deforming absorbing surface

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When turbulent flow streamlines a deforming surface, the turbulence structure in turbulent flow formed under action of flow pulsations essentially differs from that over a smooth rigid surface. By varying geometrical and physical properties of the surface material, it is possible to change the time and space scales of the near-wall turbulence. Combining the shape of surface and its properties one can change integral characteristics of a body moving in water.

Theoretical analysis of the problem of interaction of turbulent flow with a deforming surface is performed using the Reynolds stress transport turbulence model, with modified hypotheses for turbulent diffusion, redistribution, dissipation rate, accounting for the pulsation energy exchange between turbulent boundary layer and the deforming surface. The results obtained from numerical modeling allow to explain the mechanism of turbulence structure variation and the mechanism of energy redistribution between components of the Reynolds stress tensor, which lead to changing turbulence anisotropy in the near-wall region of turbulent boundary layer and, consequently, to friction drag reduction at turbulent regime of flow.

We have developed and continue improving the technique of direct numerical solution of the nonstationary Navier-Stokes equations over a deformed and deformable surface at high Reynolds number that allows observing in space and time the appearance and development of velocity and pressure disturbances and their correlation moments in the near-wall region. The DNS results allow revealing the dependence of disturbances scales in a boundary layer on parameters of the deforming surface. The results obtained provide the information for modeling the mechanism of turbulent diffusion and the dissipation rate tensor over a deforming absorbing surface, as well as allow revealing a relation of the mechanism of viscous dissipation and turbulent energy dissipation rate over an oscillating surface.

Plasma controlled turbulence scales around an airfoil model

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Centrifugal forces in a fluid flow around curved surfaces like an airfoil provide necessary and sufficient conditions for natural formation of streamwise counter-rotating vortices. This fact motivated the development of a flow-control concept based on maintenance of streamwise vortices as an inherent flow structure. For that, a boundary condition is imposed as temperature varying regularly with a given step in a spanwise direction. In experiments, it is realized using a spanwise array of localized plasma discharges initiated with microwave radiation in the vicinity of the surface. Matched numerical simulations of the flow field and wind-tunnel measurements of drag and lift coefficients showed correlation between the vortex scale and integral flow characteristics. Numerically obtained patterns of streamwise vortices developing in turbulent boundary layers guided the experimental choice of a distance between the neighboring thermal sources (discharges) and a downstream location of the plasma array over a model. A possibility is demonstrated to improve the lift-to-drag ratio or the airfoil aerodynamic quality as well as to increase a critical angle of attack for certain combinations of basic and control parameters. Another encouraging outcome is a very small energy outlay used for the control system operation.

This multidisciplinary investigation is carried out together with a team of Moscow Radio-Technical Institute which develops the plasma systems for flow-control purposes according to the formulated aerodynamic requirements.

A parallel finite volume-finite element method for transient compressible turbulent flows with heat transfer

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In this paper, a two dimensional numerical scheme is presented for the simulation of turbulent, viscous, transient compressible flows in simultaneously developing hydraulic and thermal boundary layers region. Knowledge of the flow variables in the entrance region is necessary in the compressible flow, especially when the heat transfer effect on the boundary layer development is dominant. The numerical procedure is a finite-volume based finite-element method applied on unstructured grids. This combination together with a new method applied for the boundary conditions allows accurate computation of the variables in the entrance region and for a wide range of flow fields going from subsonic to transonic. The Roe-Riemann solver is used for the convective terms, while the standard Galerkin technique for the viscous terms is applied. A modified κ-ε model with a two-layer

equation for near wall region combined with the compressibility correction is used to predict the turbulent viscosity. A parallel processing is also employed to divide the computational domain among the different processors to reduce the computational time. Using a symmetric multiprocessing (SMP) machine with a peak performance of 64 GFLOPS and 16 processes, the program runs about ten times faster than a single process, with an efficiency of about 62.5 percent. The method is applied to some test cases in order to verify the numerical accuracy. The results show significant differences between incompressible and compressible flow in the friction coefficient, Nusselt number, shear stress and the ratio of the compressible turbulent viscosity to the molecular viscosity along the developing region. A transient flow generated after an accidental rupture in a pipeline was also studied as a test case. The results show that the present numerical scheme is stable, accurate and efficient enough to solve the problem of transient wall-bounded flow.

Tutorial: Theory of drag reduction by polymers in wall-bounded turbulence

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Target audience: graduate and professional

The flow of fluids in channels, pipes, or ducts, as in any other wall-bounded flow (like water along the hulls of ships or air on airplanes) is hindered by a drag, which increases manifold when the fluid flow turns from laminar to turbulent. A major technological problem is how to reduce this drag in order to minimize the expense of transporting fluids like oil in pipelines, or to move ships in the ocean. It was discovered that minute concentrations of polymers can reduce the drag in turbulent flows by up to 80%. While experimental knowledge had accumulated over the years, the fundamental theory of drag reduction by polymers remained elusive for a long time, with arguments raging whether this is a “skin” or a “bulk” effect. In this tutorial the phenomenology of drag reduction by polymers is summarized, stressing both its universal and non-universal aspects, and a recent theory is reviewed that provides a quantitative explanation of all the known phenomenology. Both flexible and rod-like polymers are treated, explaining the existence of universal properties like the maximum drag reduction asymptote, as well as non-universal crossover phenomena that depend on the Reynolds number, on the nature of the polymer and on its concentration.

Participants who are interested in preparing themselves for this tutorial are invited to read Rev. Mod. Phys. vol. 80, p. 225 (2008).

NON-EQUILIBRIUM PROCESSES

Coherence and randomness in non-equilibrium turbulent processes

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Non-equilibrium turbulent processes play an important role in a variety of natural and artificial systems, ranging from astrophysical to atomistic scales. Examples include inertial confinement fusion, supernovae, stellar convection, non-canonical boundary layers and optical free-space communications. Theoretical description of non-equilibrium transports is a challenging problem due to singular aspects of the governing (Euler or Navier-Stokes) equations. Furthermore these processes are statistically unsteady and their fluctuating quantities are essentially time-dependent and non-Gaussian. Based on group theory consideration, we apply a theoretical concept of the rate of momentum loss to capture the anisotropic and non-local character of the non-equilibrium dynamics, in particular, in accelerating flows and buoyancy-driven mixing. It is shown that their invariant, spectral, scaling and statistical properties differ substantially from those of isotropic homogeneous turbulence. We put forward the ideas on how to quantify coherence and randomness in the statistically unsteady non-equilibrium turbulent flows.

Reactive dynamics of materials and interfaces at nonequilibrium conditions using first-principles based force fields

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Advances in theoretical and computational chemistry are making it practical to consider fully first principles based predictions of reactive dynamics under nonequilibrium conditions such as combustion, detonation, and chemical instabilities at interfaces. To simulate the chemical reactions in condensed system, including the extreme conditions of high pressure and temperature, we developed the *ReaxFF reactive force field*, whose parameters are trained to match quantum mechanics (QM) descriptions of reaction barriers and transition states for all plausible chemical bond breaking processes. ReaxFF has been used successfully to simulate chemical reactions processes in energetic materials [1], crack propagation [2], catalysts [3], oxidation [4], propellants [5], and pyrolysis [6] in condensed phase. ReaxFF has been implemented in GRASP and LAMMPS, enabling multi-million atom simulations. Adri van Duin will summarize many of these developments in his tutorial at this Conference.

Recently, we developed an approximate quantum mechanics approach to describe electron dynamics of highly excited nonequilibrium systems [7,8]. This *electron Force Field (eFF)* approximates the wavefunction as a Hartree product of

Gaussian Functions but includes a spin-dependent electron-electron interaction to describe the shell structure and bonding in solids, molecules, atoms, and plasmas. It leads to an excellent description of phases relevant for warm dense hydrogen, correctly describing the transition from molecular to atomic to plasma for temperatures up to 100,000 K and pressures up to 1,000 GPa for systems such as hydrogen, Li, and carbon, including interactions between these materials [7]. It also describes complex materials processes such as Auger induced etching of semiconductors. Thus, eFF provides a valuable and general method for studying the excited electron dynamics of systems with diverse combinations of materials and bonding.

We will highlight some recent advances in methodology and will illustrate them with recent applications to materials problems involving chemical instabilities and excited electron dynamics at the material interfaces.

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On the limits of Navier-Stokes theory and kinetic extensions for gaseous hydrodynamics

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In this talk we discuss some of the modeling and simulation challenges arising from the breakdown of the Navier-Stokes description as characteristic lengthscales become of the order of, or smaller than the molecular mean free path. We will review some basic results from asymptotic analysis of the Boltzmann kinetic equation, and show that these results can be used to resolve a number of "open questions". Examples include the limit of applicability of the Navier-Stokes constitutive relations, the concept and appropriate form of a second-order slip relation, and how to reconcile experimental measurements of slipping flows with theory. We will also discuss a number of recently-developed kinetic descriptions of canonical nanoscale flows beyond the Navier-Stokes regime. Finally, we will discuss efficient particle methods for solving the Boltzmann equation; particular emphasis will be given to recently-developed variance-reduced Monte Carlo formulations which alleviate the poor computational efficiency of existing methods in low-signal flows.

Variable-density Rayleigh-Taylor turbulence

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The buoyancy generated turbulence during mixing of a heterogeneous mixture of two pure fluids with different densities is studied using Direct Numerical Simulations in two configurations: a) classical Rayleigh-Taylor (RT) instability using a 3072^3 data set (Cabot and Cook, Nature Phys. 2006; Livescu et al, J. Turb. 2009) and b) an idealized triply periodic Rayleigh-Taylor flow (HRT), using up to 1024^3 meshes (Livescu and Ristorcelli, J. Fluid Mech. 2007 and 2008). The datasets used represent the largest simulations to date for each configuration. For the RT problem, the simulation achieves bulk Reynolds number, Re = 32,000, at an Atwood number, A = 0.5, and a Schmidt number, Sc = 1. The HRT flow starts from rest, with the two fluids in a non-premixed state corresponding to a double-delta density PDF. The cases considered cover the Atwood number range $A = 0.05 \div 0.5$, in order to examine small departures from the Boussinesq approximation as well as large Atwood number effects.

A comprehensive study of the high Atwood number energy budgets for the kinetic energy, mass flux, and density specific volume covariance equations is undertaken. Various asymmetries in the mixing layer, not seen in the Boussinesq case, are identified and explained. Hypotheses for the turbulent transport necessary to close the second moment equations are studied. It is found that, even though the layer width becomes temporally self-similar relatively fast, the transient effects in the energy spectrum remain important for the duration of the RT simulation. Thus, the dissipation does not track the spectral energy cascade rate and the integral length scale does not follow the expected Kolmogorov scaling. As a result, the popular eddy diffusivity expression using the kinetic energy and dissipation does not model the temporal variation of the turbulent transport in any of the moment equations. The buoyancy effects on the large and small scale anisotropies are also discussed.

Implications of entropy stability for the interaction of a shock wave with compressible turbulence

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As applied to the problem of a shock wave interacting with compressible homogeneous turbulence, the standard two-equation turbulent-viscosity model predicts excessive amplification of the turbulence intensity. Examining this model for stability, in the sense of existence of a mathematical entropy, reveals that a dissipation term is missing from the mean pressure. A model that incorporates this term is successful at predicting shock amplification of turbulence intensity.

Vortex reconnections

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It is possible that the reconnection between vortices of opposite sign is an important part of the dynamics of hydrodynamic turbulence. There was a spate of activity on this problem for about a dozen years beginning around mid - 80's (and part of the experience gained there seems to have been diverted lately to exploring the singular dynamics of Euler equations). Reconnection of magnetic field lines seems to have been pursued for a lot longer and with greater persistence. A problem of equal interest is the reconnection of quantized vortices in helium II. This will be the main theme of my talk, which will be based on the work published in the last year or two with Greg Bewley, Matthew Paoletti, Dan Lathrop and Michael Fisher. The novel feature of this work is the visualization of quantized vortices, observation of their reconnection, characterization of the dynamics before and after reconnections, and the measurement of the velocity statistics in the superfluid case. I will highlight some differences and similarities between the quantized and classical turbulence that emerge from these observations.

INTERFACIAL DYNAMICS

A PDF of molecular mix measurements in high Schmidt number Rayleigh-Taylor turbulence

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High Schmidt number molecular mixing measurements in the small Atwood number (~0.001) Rayleigh-Taylor (RT) water channel facility at Texas A&M University are reported, and a PDF obtained for molecular mixing of mass. In the experiments, the pH of the heavy (salt) and light (fresh) water streams is controlled by adding acid or alkali to each stream. As the two streams molecularly mix, the chemical reaction between the acid and alkali is marked by a phenolphthalein chemical indicator, which is imaged under backlit conditions. The high Schmidt number, $Sc \sim 10^3$, experiments have resulted in lower molecular mixing measurements as compared with previous RT experiments and simulations at various Atwood and Schmidt numbers. However, at late-time the molecular mixing parameter appears to be approaching a value comparable with that from hot/cold water RT experiments at a Prandtl number $Pr = 7$. The results suggest a need for late-time (high Reynolds number) experiments to determine the extent to which Schmidt number affects high Reynolds number RT driven mixing.

Oscillatory behavior in the Rayleigh-Taylor instability for compressible fluids

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Superposition of a heavy fluid above a lighter one in a constant acceleration field is a potentially unstable configuration called the Rayleigh-Taylor instability (RTI). In addition to Inertial Confinement Fusion (ICF) and Astrophysics applications, the RTI is a basic academic problem studied for years, and yet not fully understood. In this two-part presentation, we will report on a normal mode stability analysis of this configuration for perfect and Newtonian compressible fluids.

In the first part, we shall confront the RTI characteristics with different thermodynamic hypotheses (isentropic, isothermal and general cases) for the hydrostatic equilibrium and the perturbation. Dimensional analysis leads to two compressibility type parameters: the stratification number, and parameters of the equations of state. We will recall the opposite effects of stratification and compressibility on the stability [1].

In the second part, a systematic exploration of the parameter space shows that oscillatory modes may coexist with the classical RT mode characterized by two real eigenvalues of opposite signs. An oscillatory mode is characterized by a complex growth rate. For perfect fluids, several marginally stable oscillatory modes may exist, corresponding to purely imaginary growth rates. Such oscillatory modes also exist in Newtonian fluids. For these fluids, these modes are unstable, i.e., the real part of the growth rate is positive. The existence of such modes is closely linked with the relative magnitude of time and length scales present in these configurations. The nonlinear stability of these linearly unstable modes is however an open question.

These results have been obtained from a semi-analytical tool in the case of perfect fluids. For Newtonian fluids, the linear boundary value problem is solved within a self-adaptive Chebyshev multidomain method. Eigenvalues and eigenvectors are refined with an iterative Rayleigh method, which leads to accurate and reliable results.

[1] M.-A. Lafay, B. Le Creurer and S. Gauthier, Compressibility effects on the Rayleigh-Taylor instability between miscible fluids, Europhys. Lett. 79, 64002 (2007).

Analysis of hydrodynamic instability growth in a 2D flow

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The paper shows that experiments with gas bubbles rising in water can be used to explore effects related to the joint action and development of gravitational and shear instability in 2D flows.

The paper describes an experimental setup to look at the development of hydrodynamics instabilities on the dome of an air bubble rising in liquid. The processes observed during the development of such instabilities are extremely important as they provide better insight into nonlinear stage of gravitational instability in a 2D case with a curvilinear unstable interface with initial perturbations. Practical relevance of such effects is associated with their occurrence in inertial confinement fusion systems.

It is shown that initial short-wavelength perturbations on the dome of a rising bubble quickly decay. Such decay is not attributed to dissipative mechanisms (viscosity or surface tension); it is a manifestation of rather general hydrodynamic laws that result in a so-called sub-harmonic instability.

The work has been funded in part by RFFI (Project 08-01-00807).

Turbulent Mixing: theory and experiment for model development and validation

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Presented will be a discussion of how theory and experiments go together to develop and validate model(s) describing the turbulent mixing of multi-material flows. It will focus on the development of the second generation BHR turbulence model and how the data from a wide variety of "experiments", the Texas A&M Rayleigh-Taylor channel, the Caltech LES of Richtmyer- Meshkov to the laser-driven CylMix experiment from Los Alamos, has and continues to drive model development by providing a well based physical foundation.

Kinetic theoretical approach to the mixing process due to Rayleigh-Taylor instability

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An analytical and numerical study, is presented, of the time evolution of the velocity probability density functions (VPDF) of the heavy and light fluids in the mixing process due to Rayleigh-Taylor instability (RTIM) . The VPDF compiled from detailed numerical solutions of the Euler equations are shown to be analogous to the velocity distributions of two gases, at local thermodynamic equilibrium around their averaged velocities, with the stress tensors as the "temperatures". The mixing evolves as a flow of the "gases", interpenetrating into one another under the influence of an expanding self consistent potential well. An exact (unclosed) coupled set of kinetic equations for the VPDF in RTIM is derived. A closure of the set, based on mean field approximation is presented. It is shown by a numerical solution of the closed kinetic equation that this closure properly describe the short time evolution of the system. Closure schemes beyond the mean field approximations are discussed.

Specific features of Richtmyer-Meshkov instability growth with 2D and 3D initial perturbation geometry

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According to classical concepts of Richtmyer-Meshkov instability growth mechanism, 3D initial perturbations in material without strength should always grow faster than 2D perturbations, if their initial amplitudes and wavelengths are identical. In order to test this statement for condensed materials, a series of experiments with essentially different intensities of shock waves produced in samples was conducted. Perturbation growth was studied on shock arrival at a free surface of a condensed material with deterministic 2D and 3D initial perturbations of different profiles. In one of the experimental approaches, the shock in the sample was produced by a charge of condensed high explosive, the amplitude of pressure at the shock front in the sample of interest (lead) was ~400 kbar, which caused melting of the metal sample. The resulting perturbations were recorded using pulsed radiography. In the second experiment, the shock was produced in a sample of water solution of gelatin or wet clay using a specially developed two-piston shock tube. Shock intensity in this case was ~0.5 kbar; perturbations were recorded using a streak camera. It was proven experimentally that in the hydrodynamic approximation (experiments with leak) the growth rate of 2D and 3D perturbations are the same. In the case of a rather weak shock waves, it was found that growth rate of 3D initial perturbations depends on their concrete profile and it is possible that perturbation of some profiles will not grow at all. We suppose that this can be attributed to stabilizing effects of dissipative properties of material samples.

Numerical simulations of experiments were performed using LEGAK code. It was demonstrated that the experimental data can be reproduced if for the experiments with weak shock waves the liquid is assumed incompressible (speed of sound $c_0 \to \infty$). The results are analyzed theoretically. It is shown that the perturbation growth in the case of interest resembles the process of shaped charge jet formation.

The work has been funded in part by RFFI (Project 08-01-00807).

Oscillation and pinching phenomenon in the Rayleigh-Taylor and Richtmyer-Meshkov instabilities with surface tension

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Motion of a planar interface in incompressible Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities with surface tension is investigated analytically and numerically. The comparison between the growth rate of an interface with and without surface tension is made, and we show that the growth rate of the interface with surface tension in the RM instability is equal to that without surface tension at the asymptotic stage, however, the growth rate with surface tension in the RT instability differs from that without surface tension for almost all Atwood numbers and surface tension parameters. A phenomenon known as "pinching" in the physics of drops is found in the final stage of calculations for both instabilities. We also present that as the surface tension parameter becomes large, stable oscillatory motion appears for the RM instability. When the gravity is taken into account (RT instability), linearly stable but nonlinearly unstable motion can appear under a certain condition of three parameters, namely, the Atwood number, gravity, and surface tension. We show that the growth rate of this motion is different from that without surface tension in the RT instability for both of the linear and asymptotic stages.

Turbulent mixing at gas-liquid interface with the width of the mixing zone up to 200 mm

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The authors present results of experiments with study of growth of turbulent mixing occurred at Rayleigh-Taylor instability at gas-liquid interface with the width of the mixing zone H of up to 200 mm.

The liquid layer (water) with the mass of 3.3 kg was accelerated by compressed air in a transparent cylindrical channel with a crossection of ∅210 mm. The pressure of compressed air reached 8.4 gauge atmospheres, the acceleration - $g = (0.5\div 1)\cdot 10^3 g_0$ (where $g_0 = 9.8$ m/s^2), the layer displacement - S up to 350 mm, the depth of penetration of gas front in liquid $h_{\text{лт}}$ - up to 50 mm. The Reynolds number of the flow reached:

$$\mathrm{Re} = \frac{H\cdot\sqrt{A\cdot g\cdot H}}{\nu} = 5\cdot 10^6$$ (where A ≈ 1 is the Atwood number and ν is the kinematic viscosity coefficient of water).

It was obtained that:
(1) Coefficient $\beta_{лт}$, describing the average rate of penetration of gas front into the liquid ($\beta_{лт} = \Delta h_{лт}/\Delta 2S$), equals $\beta_{лт} \approx 0.11$ over the range of layer displacements of 10 mm < S < 50 mm (at Re up to $5{\cdot}10^4$);
(2) Coefficient $\beta_{лт}$ falls approximately 35% down when the displacement of the liquid layer increases from ≈ 50 mm to ≈ 100 mm (with the growth of Re from $5{\cdot}10^4$ to $5{\cdot}10^5$), and then, at the further growth of the layer displacement to 350 mm (with the growth of Re up to ≈ $5{\cdot}10^6$) - it doesn't change and equals to $\beta_{лт} = 0.06 \div 0.08$, moreover, some pulsations of the penetration of the gas front into the liquid were observed;
(3) Separate bubbles of the mixing zone become unstable with the lapse of time - the development of secondary bubbles occurs on them.

Molecular dynamic simulations of hydrodynamic instabilities of shocked-interface in planar and cylindrical geometries

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Last decade a great advance in computing power has created feasible opportunities for modeling of hydrodynamic problems via molecular dynamic (MD) simulations. MD simulation can grasp at atomistic level many nonequilibrium processes in material science, shock physics, and hydrodynamic instabilities. We will present some MD simulation results of Richtmyer-Meshkov instability (RMI) in cylindrical geometry and laser ablation in planar geometry. The RMI is quite important in inertial confinement fusion. Special feature of the RMI in cylindrical geometry is the sock reverberation between corrugated interface and the center. The shock reverberation enhances the nonlinear growth of RMI. We also consider a thin layer inserted in a fluid with different mass density. We show that the nonlinear interaction of two unstable interfaces causes rapid increase of many different modes. Ultrashort laser-matter interaction is important for fundamental physics of fast processes and warm dense matter physics. Fast heating of target material results in formation of thermo-mechanically stressed region near surface. We will discuss the frontal cavitations and rear-side spallation of the materials associated with the compression and rarefaction waves driven by unloading of the stress.

The density ratio dependence of self-similar Rayleigh-Taylor mixing

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Very high resolution large eddy simulations (mesh sizes up to ~2000×1000×1000) are used to investigate the properties of high Reynolds number self-similar Rayleigh-Taylor mixing at a range of density ratios from 1.5:1 to 20:1.

In some cases mixing evolves from "small random perturbations". In other cases random long wavelength perturbations ($1/k^3$ spectrum) are added to give self-similar mixing at an enhanced rate, more typical of that observed experimentally. The properties of the mixing zone (dissipation of turbulence kinetic energy, molecular mixing parameter etc.) are related to the Rayleigh-Taylor growth rate parameter, alpha, defined as:

$$\text{bubble distance } h = \text{alpha} \times \text{Atwood number} \times gt^2.$$

Comparisons are made with experimental data on the internal structure and the asymmetry of the mixing zone (spike distance/bubble distance). The main purpose of this series of simulations is to provide data for calibration of engineering models (i.e., RANS models). It is argued that the influence of initial conditions is likely to be significant in most applications and the implication of this for engineering modeling will be discussed.

Tutorial: Review of nonlinear dynamics of the unstable fluid interface: conservation laws and group theory

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Target audience: senior graduate and professional

We observe the development of the Rayleigh-Taylor instability (RTI) whenever two fluids of different densities are accelerated against the density gradient. Extensive interfacial mixing of the fluids ensues with time. Rayleigh-Taylor turbulent mixing plays an important role in a wide variety of natural phenomena, ranging from inertial confinement fusion, material transformation under high strain rates and combustion to mysterious processes of supernovae explosion and Universe formation. The unsteady anisotropic and inhomogeneous turbulent process is a fundamental problem in fluid dynamics. Its complexity constantly expands the horizons of the modern theory of differential equation, calls for new connections to the kinetic processes at atomistic scales, and pushes the numerical simulations to peta-scale level. In this tutorial we overview the theoretical approaches and empirical modeling approaches of the nonlinear Rayleigh-Taylor instabilities, which have been developed over the recent decades, summarize the results of the group theory analysis of the nonlinear coherent dynamics in Rayleigh-Taylor flows, consider the issues of validation and verification of the theories and models, and outline some criteria for the estimate of the fidelity and information capacity of the experimental and numerical data sets. The goal of this tutorial is to review, based on physical intuition and mathematical rigor, what is known and what is unknown of the Rayleigh-Taylor instabilities, what is firm and what is fluffy, to formulate the basic theoretical, experimental and numerical issues and to discuss how to address them. The author hopes this review would expose the generic problems of Rayleigh-Taylor turbulent mixing to a wide scientific community and would serve to advance our understanding of non-equilibrium turbulent dynamics.

S.I. Abarzhi, Review of nonlinear coherent dynamics of the unstable fluid interface: conservation laws and group theory, Physica Scripta T132, 014012 (pp1-18) (2008)

Tutorial: Compressibility effects in fluid flows

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Target audience: graduate

We will present a tentative review of compressibility effects in some buoyant flows [Rayleigh-Taylor (RT) and Rayleigh-Bénard (RB)] and shear flows [Kelvin-Helmholtz (KH)]. The linear, nonlinear and turbulent regimes will be considered. We will first recall the basic equations for compressible flows and some of their properties (initial and boundary conditions). We will then derive the quasi-incompressible limits of the complete Navier-Stokes equations, where the acoustic is no longer present (the low-Mach number, the anelastic and the Boussinesq approximations). We will then recall the classical distinction between the static compressibility or stratification, and the dynamic compressibility due to the finite speed of sound. We will also review some results about stratified compressible flows for which instability criteria have been derived rigorously. Linear stability results for perfect fluids obtained from an analytical approach, as well as viscous fluid results obtained from numerical approaches, will also be reviewed. It is also well known that turbulent compressible KH mixing layers have strong compressibility effects. Indeed, at large convective Mach numbers, the thickening rate of these mixing layers decreases. It has been shown that both the stratification and the dynamic compressibility effects have to be taken into account to reproduce the experimental results. For inhomogeneous flows, the modifications made to statistical models of fully developed turbulence in order to account for compressibility effects will also be treated briefly. Finally, we will point out the analogy between turbulent compressible KH and RT mixing layers and we will suggest some lines for further investigations. KH and RT compressible turbulent mixing layers are part of the TMB conference objectives of a better understanding of turbulence mixing and turbulence in unsteady flows.

S. Gauthier and B. Le Creurer, Compressibility effects in Rayleigh-Taylor instability induced flows, 2009 submitted to Phil. Trans. Roy. Soc.

HIGH ENERGY DENSITY PHYSICS

Nonlinear nonstationary self-organized asymptotic structures in high energy density plasmas and nonequilibrium Euler turbulence

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The creation and persistence of nonlinear nonstationary self-organized asymptotic (NNSA) states in high energy density plasmas (HEDP) has been demonstrated in numerical simulations, theoretical models and optical mixing experiments on the Trident laser facility at LANL. We shall review the novel elements of such states which rely on non-local in space and time wave-particle interactions which self organize the plasma into electrostatic fields with multiple interacting harmonics which can trap, untrap and retrap particles and sustain these interactions coherently long after the driving fields have been turned off. The connections between these coherent nonlinear structures and locally scale invariant features of Euler turbulence will be explored in sheared fluids as well as pair plasmas and galactic self- organization models where the analogies between Euler and Vlasov flows become more potent in the context of nonequilibrium statistical mechanics. HEDP applications include the control of nonlinear optical processes in plasmas.

Suppression of Rayleigh-Taylor instability and impact ignition

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A double ablation scheme to suppress the Rayleigh-Taylor instability (RTI) has been proposed for a direct-drive inertial fusion target, in which two ablation surfaces driven by thermal radiation and electron conduction are formed separately.

The growth of the RTI is significantly suppressed due to the large ablation velocity and long density scale. By employing the double ablation scheme, we performed integrated experiments on impact ignition. In the impact ignition scheme, a portion of a deuterated polystyrene (CD) shell is accelerated to about 600 km/s and is collided with precompressed CD fuel. The kinetic energy of the impactor is efficiently converted into thermal energy generating a temperature of about 1.6 keV. We achieved a two-order-of-magnitude increase in the neutron yield by optimizing the timing of the impact collision, demonstrating the high potential of impact ignition for fusion energy production. We will also present experimental investigation of the ablative RTI.

Blast-wave-driven Rayleigh-Taylor instabilities

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The interaction of a blast wave generated in a supernova explosion with a composition discontinuity in the star's envelope produces crossed density and pressure gradients, which are unstable to the growth of Rayleigh-Taylor modes. This instability is responsible for considerable mixing of nuclear species in the ejecta and produces observable effects in the light curve and spectrum of the explosion. Blast-wave-driven instabilities of this type have been studied numerically as well as experimentally using the Omega Laser at the University of Rochester. Initial comparisons between the numerical simulations and the experiments show poor agreement. The simulations show the classic bubble and spike morphology of the Rayleigh-Taylor instability, with well-developed mushroom caps at the tips of the spikes. However, the mushroom caps appear much smaller in the experimental results than in the simulations for two-dimensional initial perturbations and seem to be completely absent for three-dimensional initial perturbations. Also, some experiments show mass extending beyond the spikes and penetrating almost to the shock front. This effect is completely absent from the numerical simulations. This talk will discuss possible causes of these discrepancies.

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Turbulence generation by a shock wave interacting with a random density inhomogeneity field

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When a planar shock wave interacts with a random pattern of preshock density non-uniformities, it generates an anisotropic turbulent velocity/vorticity field. This situation emerges in shock interaction with weakly inhomogeneous deuterium-wicked foam targets in Inertial Confinement Fusion (ICF) and with density clumps/clouds in astrophysics. We present the exact small-amplitude linear theory describing such interaction. It is based on the exact theory of time and space evolution of the perturbed quantities behind the corrugated shock front for a single-mode preshock non-uniformity [1]. Appropriate mode averaging in 2 and 3 dimensions results in closed analytical expressions for the turbulent kinetic energy, degree of anisotropy of velocity and vorticity fields in the shocked fluid, shock amplification of the density non-uniformity, and sonic energy flux radiated downstream. These explicit formulas are further simplified in the important asymptotic limits of weak/strong shocks and highly compressible fluids. A comparison with the related problem of a shock interacting with a preshock isotropic vorticity field is also presented.

Work supported by: Ministry of Science (MICINN), Junta de CLM, Spain (C. H. R. de L. and J. G. W.), US DoE (A. L. V.).

[1] A. L. Velikovich, J. G. Wouchuk, C. Huete Ruiz de Lira, N. Metzler, S. Zalesak, and A. J. Schmitt, Phys. Plasmas 14, 072706 (2007).

Evolution of small perturbations in the inertial confinement fusion (ICF) targets

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As a part of ICF targets research we consider small (linear) perturbations of a thin shell that is accelerated by a gas piston. We assume that the perturbation wavelength is much greater than the shell thickness and much less than dimensions of the gas piston.

We construct the 4-th order ordinary differential equation that describes the perturbation evolution in plane, cylindrical, and spherical shell. Perturbations are being expanded in plane waves or angular harmonics. We construct as well a set of inequalities that provide the perturbation evolution not to depend on the shell and piston equations of state.

We considered the compression of cylindrical pellets that had been elaborated for the heavy-ion inertial confinement fusion [1]. We present results of computer modeling of compression of these pellets using the 2D numerical code H3T [2]. Results include 2D calculations of evolution of shell perturbations. The initial conditions for these disturbances were chosen as plane waves or angular harmonics on the cylindrical interface between the shell and the piston.

We took the time dependence of the shell radius, velocity, and acceleration from computer modeling and inserted these functions to the differential equation mentioned above. Then the equation was solved numerically using the Runge-Kutta method. The results of solution were compared with the results of computer modeling and proved to be in a reasonable agreement.

[1] D. G. Koshkarev and M. D. Churazov. Inertial Confinement Fusion with a Heavy-Ion Driver-Accelerator and a Cylindrical Target, *Atomic Energy Journal*, vol. 91, no 1 pp.564-570, 2001; [2] V. T. Zhukov, A. V.Zabrodin, and O. B. Feodoritova, Features of the numerical simulation of the target of inertial thermonuclear synthesis in the approximation of heat conduction gas dynamics, *Computational mathematics and mathematical physics*, vol. 34, no 12, pp. 1591-1601, 1994.

Magnetically driven supersonic plasma jets in high energy density experiments

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Collimated outflows (jets) are ubiquitous in the Universe, appearing around sources as diverse as protostars and extragalactic supermassive black holes. Jets are thought to be magnetically collimated, and launched from a magnetized accretion disk surrounding a compact gravitating object. We have developed the first laboratory experiments to address time-dependent, episodic phenomena relevant to the poorly understood jet acceleration and collimation region [1]. The experiments were performed on the MAGPIE pulsed power facility (1.5MA, 250ns) at the Imperial College. The experimental results show the periodic ejections of magnetic bubbles naturally evolving into a heterogeneous jet propagating inside a channel made of self-collimated magnetic cavities. The results provide a unique view of the possible transition from a relatively steady-state jet launching to the observed highly structured outflows.

This work has been done in collaboration with A. Ciardi, F. A. Suzuki-Vidal, S. N. Bland, J. P. Chittenden, G. Hall, A. Harvey-Thomson, A. Marocchino, A. Frank, E. G. Blackman, C. Stehle, M. Camenzind. This research was sponsored by the NNSA under DOE Cooperative Agreement No. DE-FC03-02NA00057, by EPSRC and by the European Community's Marie Curie Actions within the JETSET network under Contract No. MRTNCT- 2004 005592.

[1] A. Ciardi, S. V. Lebedev, A. Frank et al., The Astrophysical Journal, 691: L147-L150 (2009)

The model of energy transport in turbulent sub-critical laser plasmas of porous targets

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To achieve a high gain in laser thermonuclear targets, deuterium-tritium (DT) fuel should be compressed 10^4-10^5 times with respect to its initial density. For this purpose, spherical targets are irradiated by a large number of laser beams (with average intensity 10^{14}-10^{15} W/cm^2), aimed at a uniform irradiation of the target surface and, as a consequence, a uniform heating of its outer layers. In practice, a 100% uniformity of irradiation is impossible due to the nonuniform overlapping of the beams, the interference phenomena in highly coherent laser beams, nonuniform amplification in the laser path, and defects in laser amplification channels. These nonuniformities of irradiation lead to a disturbance of ablation pressure and hydrodynamic instability development in laser target. A low density porous cover on the target could smooth these perturbations. A number of laser fusion laboratories carry out the studies of power laser pulse interaction with low density porous targets.

We propose a physical-mathematical model of energy transport in turbulent plasma of porous target irradiated by laser pulse. 2D numerical simulations have been made with help of Lagrange code "ATLANT" [1]. A good agreement between numerical results and experimental data from "PALS"-facility (Prague Asterix Laser System, Czech republic) has been obtained. Using this model it was possible to explain some challenging phenomena, which have been observed in the "PALS" experiments.

The vortex structures and spontaneous magnetic fields (SMF) are generated in such plasma. We have discussed the possibility to observe SMF with the use of the electron bunch scattering on them [2].

This work is supported by RFBR, project #08-02-00913a.

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Probing matter at the extremes: new frontiers in high energy density dynamics

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Hydrodynamic instabilities, such as the Rayleigh-Taylor (RT) instability and the Kelvin-Helmholtz (KH) instability, are ubiquitous in nature, occurring in widely varying settings from the astrophysical to the microscopic. I will describe four examples of hydrodynamic instabilities in vastly different regimes, spanning light years to microns, and discuss their unique features. The overarching context will be scaled experiments proposed for the National Ignition Facility (NIF) laser at LLNL. The four topics to be discussed will be: (1) scaled core-collapse supernova (SN) hydrodynamics relevant to SN1987A; (2) nonlinear radiative-hydrodynamic instabilities relevant to the dynamics of the Eagle Nebula molecular cloud; (3) high energy density (HED) KH instability experiments; and (4) solid-state plastic flow due to RT evolution at high pressure and ultrahigh strain rates, relevant to hypervelocity impact dynamics.

This work was performed under the auspices of the Lawrence Livermore National Security, LLC, under Contract No. DE-AC52-07NA27344; and LDRD-SI grant No. 10-SI-09.

Tutorial: Instabilities, turbulence and energy coupling into Z-pinch plasmas

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Target audience: graduate and professional

Z-pinch plasmas produced by passing multi-Megaampere (MA), ~100-nanosecond current pulses through cylindrical wire arrays or gas jets are the most powerful laboratory sources of soft [1] and hard [2] X-rays. Z-pinch discharges generated the highest thermonuclear neutron yields ever produced on the inertial confinement fusion facilities [3], and with the development of high repetition-rate current driver technology they show promise for inertial fusion energy production. One of the key issues for most Z-pinch applications is understanding (and mitigation, when necessary) of the Rayleigh-Taylor instabilities of the implosions. Although considerable progress has been made in this direction, many issues related to the instability development and the resulting turbulence generation remain unresolved. There is evidence showing that the turbulence can enhance magnetic energy coupling to the pinch plasma, thereby increasing the peak emitted X-ray power and radiation yield [4,5]. Much better understanding of energy coupling and dissipation issues related to turbulence is needed to confidently predict the radiative performance of, and the prospects of achieving controlled inertial fusion on the next-generation 40 - 60 MA high-current facilities.

I will review the basic physics of the implosion instabilities of fast Z-pinches, their mitigation techniques, with the emphasis on the issues relating instability development and turbulence to the enhanced magnetic energy coupling into Z-pinch plasmas. The goal of this tutorial is to attract the attention of the broader community involved in turbulence research to the interesting and important research area, which can greatly benefit from innovative approaches to analysis and modeling.

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MATERIAL SCIENCE

Experimental, theoretical and numerical investigation into Richtmyer-Meshkov instability in condensed matter

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Experimental, theoretical and numerical results for instability occurring at the emergence of a shock from the free surface of a solid are presented. The range of pressures up to 40 GPa has been investigated on the Pb samples. Photochronographic registration technique and impulse X-ray radiography method were used in experiments. The results obtained in experiments were verified by numerical simulation results carried out according to LEGAK [1] technique.

The work has been funded in part by RFFI (Project 08-01-00807).

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Rayleigh-Taylor instability in a visco-plastic fluid

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Rayleigh-Taylor instability (RTI) usually is considered for such simple media as ideal fluids or ideal gases. In real situation this approach may be too simplified. Effective rheological model including plastic effects is Bingham model (BM). The base feature of BM is existence of yield stress τ_0. The constitutive relations of BM consist of two parts. The first part corresponds to a region of plastic flow with $\tau_{ij}= \tau_0\dot{\gamma}_{ij}/\dot{\gamma} + \mu\dot{\gamma}_{ij}$ for $\tau > \tau_0$, where $\tau_{ij} - p\delta_{ij}$ is a stress tensor, p is the pressure, $\dot{\gamma}_{ij} = \nabla_i u_j + \nabla_j u_i$ is the rate of strain tensor, $\dot{\gamma} = \sqrt{\dot{\gamma}_{ij}\dot{\gamma}_{ji}/2}$, $\tau = \sqrt{\tau_{ij}\tau_{ji}/2}$ are the second invariants of the rate of strain tensor and the stress. In the first region media flow with an apparent viscosity $\mu + \tau_0/\dot{\gamma}$. The second part is a region of motion as a rigid solid body - only translations and rotations as a whole are possible. In this region scales and angles are conserved during motion. This means that $\dot{\gamma} = 0$ for $\tau \le \tau_0$.

In the report we present numerical simulation of RTI at a surface between two Bingham fluids in 2D and 3D cases. The algorithm is based on regularization of constitutive relations of BM. In our algorithm the regions of motion as a rigid body are described as the regions of viscous flow with very high usual viscosity μ_* and very small rate of strain tensor $\dot{\gamma} << 1/t_{RM}$, where $t_{RM} = \lambda/\omega_0$ is characteristic time of the

RTI, λ is the wavelength of a single mode perturbation, and ω_0 is initial perturbation velocity. In RTI velocity field after passing of shock through a rippled surface may be presented as a sum of homogeneous and inhomogeneous velocity fields (λ is the period of the ripples). Homogeneous field may be omitted via Galileo transformation as it corresponds to a shift of the boundary with constant velocity. In the linear case when an initial amplitude $\delta\eta$ of the ripples is small $(\delta\eta)k << 1, k = 2\pi / \lambda$, the amplitudes of inhomogeneous velocities are small in comparison with the speed of sound. Therefore, evolution after shock compression may be well described in subsonic approximation as motion of two incompressible fluids. In this case we can impose the following harmonic velocity distributions: $u = \omega_0 e^{-kz} \sin kx, \omega = \omega_0 e^{-kz} \cos kx \; for \; z > 0$, and $u = -\omega_0 e^{kz} \sin kx, \omega = \omega_0 e^{kz} \cos kx \; for \; z < 0$ as the initial conditions.

Analogy of meteorite impacts in laboratory conditions

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Impact of celestial bodies like asteroids, meteorites, comets, etc. on any telluric planets (Earth, Moon, Mars, Jupiter, etc.) in the Solar System provides a vital clue on our Solar System. In this paper we restrict our discussion to meteorite impact on Earth. Meteorites are endowed with the early history of Solar System and their entry to Earth due to gravitational attraction can last as spectacular shooting stars for pebble like meteoroids or a catastrophic event like in Mexico's Yucatán Peninsula that ensued a major environmental and biological extinction. Although meteorite impacts symbolize the death of the meteoroid, its remnants like ejecta, cratering contours (simple or complex) reveal size, mass, composition, velocity etc of the impactor and cratering physics. Several efforts are made to investigate meteorite impacts in the laboratory and by field study to recognize the natural cratering mechanism.

In the present report we investigate the possibility of studying meteorite craters through laser ablated craters using 0.44 μm laser radiation and energy ≤ 15 J in 450 ps (FWHM). An Aluminium foil of density 2.7 g/cm^3, which could model the Earth's crest (density ~2.67 g/cm^3), was used as a target. We measured the diameter and depth of the laboratory craters by adopting different techniques viz. Laser Scanning Confocal Microscope (LSCM), Focused Ion Beam (FIB) and Scanning Electron Microscope (SEM) and report their scaling with laser energy. We obtained two types of craters viz. simple, bowl-shaped depressions and intricate structures with central peak resembling complex craters produced by large meteorites impact.

Experimental results are also corroborated using 2-D Multi simulation which predicts the possibility of complex cratering in laser-ablated targets and cratering mechanism. Several mechanisms could involve simultaneously in complex cratering including fluid dynamics beneath the impact, shock pressure, impactor size, energy etc. Details will be discussed.

Special features of Richtmyer-Meshkov instability growth on oblique shock arrival at a free surface of a condensed material

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The paper considers special features of Richtmyer-Meshkov instability development on oblique shock arrival at a free surface of a condensed material with deterministic initial perturbations. Two experimental approaches were used that differ fundamentally in terms of intensity of shock produced in the materials under investigation. In the first case the sample was shock-driven using s charge of condensed high explosive, and the amplitude of pressure at the shock front in the test sample (lead) was ~400 kbar. Such pressures cause lead to loose its strength, and the motion can be treated in the hydrodynamic approximation. The resulting perturbations were recorded using pulsed radiography. In the second approach, the shock was produced in a sample of water solution of gelatin or wet clay using a specially developed two-piston shock tube. Shock intensity in this case was ~ 0.5 kbar; perturbations were recorded using a streak camera. Comparison of experimental results revealed the dependence of perturbation growth on shock intensity in samples. Within the hydrodynamic range, jets, being the principal structural component of the perturbations, moved in the direction coinciding with the normal to the shock front surface. In the experiments with small shock intensities, perturbations developed in the direction coinciding with the normal to the initial sample surface.

Numerical simulations of the experiments were performed using the LEGAK code. It was demonstrated that the experimental data can be reproduced if the liquid for the experiments with weak shock waves is assumed incompressible (speed of sound $c_0 \to \infty$). The results are analyzed theoretically. It is shown that the character of perturbation growth in the case of interest resembles the process of shaped charge jet formation.

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High pressure Rayleigh-Taylor experiments at OMEGA and the National Ignition Facility

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The study of solid-state material properties under high pressures (>1 Mbar) and ultrahigh strain rates (> 10^6/sec) are performed utilizing a reservoir-gap-sample configuration to achieve quasi-isentropic high-pressure conditions. We have developed ~1 Mbar ramped drive platform driven by a hohlraum using the Omega Facility. A similar design is expected to reach >10 Mbar using the National Ignition Facility [1]. We have studied high pressure, solid-state material properties by measuring the growth due to the Rayleigh-Taylor instability in accelerated samples containing a pre-imposed sinusoidal ripple. The amount of growth is measured by face-on radiography taken with laser-driven X-ray backlighters. This paper will present our results on vanadium and tantalum from Omega. Our experimental results are compared with constitutive models under these conditions. We find that vanadium is stronger by a factor of two compared to its initial yield strength in the Steinberg-Guinan model [2]. We consider that both pressure hardening and strain rate hardening cause this increase in strength. We also analyze our experimental results using the PTW model [3]. To reproduce our experiments, while leaving the low-strain-rate predictions unchanged, we have significantly lowered the threshold strain rate for the transition from the thermal activation to the phonon drag regime. A new multiscale simulation integrates atomistic physics models of material phases, crystal structures, dislocation density, dislocation mobility, and macro-scale continuum models of elastic and plastic response. Our RT growth factor measurements agree with the multiscale predictions within a factor of two.

This work was performed under the auspices of the Lawrence Livermore National Security, LLC, under Contract No. DE-AC52-07NA27344

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Atomistic simulations of material dynamics and interfaces under high-rate mechanical or thermal loading

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An overview of non-equilibrium molecular dynamics (MD) simulations of material transformation under extremely high loading rates will be presented. These simulations can help to elucidate the mechanisms of structural transformations, instabilities, and phase separation at highly non-equilibrium conditions (for example, at the shock front) created by extremely fast mechanical or thermal loading. At such high rates, experimental studies are very difficult, so the MD simulations can provide important insight into atomistic dynamics on a scale of pico- to nanoseconds and nano- to micrometers. Recent advances both in computational capabilities and experimental technologies significantly reduce the gap between scales achievable by modeling and experiment.

We will highlight recent progress in methodology of both reactive and non-reactive MD simulations of material dynamics and instabilities for the studies of the shock-driven Richtmyer-Meshkov instability, ignition and reaction propagation at the fuel-oxidizer interfaces, and the dynamic fracture of aluminum nanoparticles and films after ultrafast laser heating. Such methodologies should be very useful for determining the atomistic mechanisms governing the transport processes and instabilities to provide constitutive parameters at the material interfaces for continuum-level hydrodynamical simulations and theoretical models.

Tutorial: Wavelet and multiresolution analysis tools in high energy density physics, inertial confinement fusion, hydrodynamic instabilities, and turbulence research

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Target audience: graduate and professional

The use of wavelets and related techniques of modern harmonic analysis will be exposed by exploring data and simulation results in high energy density physics (HEDP), in inertial confinement fusion (ICF) and in hydrodynamic instability and turbulence (HIT) research. The first two lecture will introduce the tools such as wavelet families, curvelets, morphological diversity extraction, de-noising, variational - iterative techniques and Haar and isotropic undecimated WAvelet Square Partition (WaSP) Functions and Jones' Beta numbers from geometric measure theory. The next two lectures will concentrate on the application of these techniques to the multifractal analysis of turbulence data from 30 channel Beam Emission Spectroscopy (BES) from the D-III D Tokamak, to Vortex Crystal Dynamics data from the non-neutral (electron) magnetically trapped rotating plasma at UC San Diego and to ICF target surface imperfection characterization which seed hydrodynamic instabilities during the implosion as well as radiation asymmetry characterization in X-ray hohlraums where again, Rayleigh Taylor and other instabilities can be seeded and cause the failure of inertial fusion schemes. Target fabrication, laser uniformity, X ray drive uniformity, de-noising, pattern detection, turbulence characterization and reduced descriptions of nonlinear, intermittent phenomena will be our focus during these lectures. The connections to Shramm-Loewner evolution models of 2D Euler turbulence and their connection to Vlasov Plasma behavior will also be given. This is a separate subject except for the fact that detecting the multifractality of turbulent contours can also be well served using the techniques expounded in the lectures.

ASTROPHYSICS

Applications of Braid theory in vortex dynamics and in solar astrophysics

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Braid theory has applications in both mixing theory and magnetohydrodynamics. A set of *N* points moving in a plane can stir the surrounding fluid. Boyland, Aref, and Stremler (2000) and others have analyzed how the topology of the motion affects the efficiency of mixing. In particular, a space-time diagram of the *N* point motion gives a braid pattern. The mixing efficiency can be measured by a quantity called the topological entropy of the braid. Thiffeault (2005) pointed out that for any two-dimensional fluid motion, the orbits of *N* tracers also define a braid whose topological entropy provides a measure of the complexity of the flow. Here, we (Andrew Gilbert, Matt Turner, and myself) employ the Braid theory to analyze chaos in a cats-eye vortex flow. We show that a modified form of topological entropy measure works best when analyzing tracers in a rotating flow.

Two great puzzles in solar astrophysics concern the source of coronal heating and the distribution of solar flares. The atmosphere of the Sun is heated to one million degrees or more, possibly by swarms of tiny flares. These tiny flares could be consequences of the braiding of magnetic field lines. Reconnection between braided threads of magnetic flux can release energy stored in the braid. The larger flares exhibit a power law energy distribution. Several authors have suggested that a self-organization process in the solar magnetic field could lead to such a distribution. Here we show how reconnection of braided lines can organize the small scale structure of the field, leading to power law energy release.

Transitional solar dynamics, cosmic rays, and global warming

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Solar activity is studied using a cluster analysis of the time-fluctuations of the sunspots number. It is shown that in Historic period the high activity components of the solar cycles exhibit strong clustering, whereas in a Modern period (last seven solar cycles: 1933-2007) they exhibit a white-noise (non-)clustering behavior. Using this observation it is shown, that in the Historic period emergence of the sunspots in the solar photosphere was strongly dominated by turbulent photospheric convection. In the Modern period, this domination was broken by a new more active dynamics of the inner layers of the convection zone. Then, it is shown that the dramatic change of the Sun dynamics at the transitional period (between the Historic and Modern periods, solar cycle of 1933-1944 years) had clear detectable impact on Earth climate. A scenario of a chain of transitions in the solar convective zone is suggested in order to explain the observations, and a forecast for the global warming is suggested on the basis of this scenario. Relation between the recent transitions and solar long-period chaotic dynamics has been found. Contribution of the galactic turbulence (due to galactic cosmic rays) has been discussed. These results are also considered in a content of chaotic climate dynamics at millennial timescales.

Transport in hydromagnetic turbulence and dynamos

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Hydromagnetic turbulence can exhibit collective behavior to produce large-scale velocity and magnetic field structures. Examples include the differential rotation of the Sun, its large-scale magnetic field with its 11 year cycle, and the global fields of many galaxies. The leading explanation involves mean-field theory. In recent years it has become possible to bridge the gap between realistic astrophysical conditions and the sometimes uncontrolled approximations by using numerical simulations, where agreement between mean-field theory and direct simulations can be established. Several examples have now been found where it is important to treat diffusive and non-diffusive processes by using integral kernels in space and time. The so-called test-field method has been used to determine the tensorial forms of integral kernels from simulations. Furthermore. the conservation properties of magnetic helicity play an important role in large-scale dynamos that survive in the limit of large magnetic Reynolds numbers.

Weakly compressible turbulence in local interstellar medium and three-dimensional modeling using Large Eddy Simulations method

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Compressible MHD turbulence in the local interstellar medium is studied using the Large Eddy Simulations (LES) method for turbulence modeling and subsequent numerical solution of the system of resolved MHD equations. Notwithstanding the fact that supersonic flows with high values of large-scale Mach numbers are characterized in the interstellar medium, nevertheless, there are subsonic fluctuations of weakly compressible components of the local interstellar medium. These weakly compressible subsonic fluctuations are responsible for the emergence of a Kolmogorov-type density spectrum in interstellar turbulence which is observed from experimental data. In this work, it is shown that density fluctuations are passive scalars in a velocity field in weakly compressible MHD turbulence and demonstrate

Kolmogorov-like spectra in the inertial range of the energy cascade and are coincident with those for kinetic energy. The spectral indices of density fluctuations and kinetic energy are shown to be almost coincident and close to a k^{-3} spectrum in dissipative range. The decrease of energy-containing large eddies and inertial range with time and the increase of dissipative scale are also represented. It is shown that the turbulent sonic Mach number decreases significantly from a supersonic turbulent regime (Ms > 1), where the medium is strongly compressible, to a subsonic value of the Mach number (Ms < 1), describing weakly compressible flow. This conclusion about the reduction of the role of compressibility in turbulent fluctuations is confirmed by examination of time evolution of the velocity divergence which decreases and tends to zero. In the interstellar medium, the transition of MHD turbulent flow from a strongly compressible to a weakly compressible state do not only transforms the characteristic supersonic motion into subsonic motion but also reduces plasma magnetization. This is shown to be because plasma beta increases with time. Thus, the role of magnetic energy decreases in comparison with plasma pressure. Besides, the anisotropy of turbulent flow is considered. It is demonstrated that large-scale flow shows anisotropic properties, while small-scale structures are isotropic.

Turbulence and turbulent mixing in natural fluids

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Turbulent mixing cannot be understood without a precise understanding and a precise definition of turbulence. Turbulence is defined as an eddy-like state of fluid motion where the inertial vortex forces of the eddies are larger than any other forces that tend to damp the eddies out. Inertial vortex forces are defined as the cross product of the velocity with the vorticity. Thus, irrotational flows are non-turbulent by definition and the direction of the turbulent cascade is always from small scales to large, contrary to claims that this is an inverse cascade. Adjacent eddies with the same spin induce inertial vortex forces that cause such eddies to merge. This is the physical basis of the universal similarity hypotheses of Kolmogorov and Obukhov 1941 and of the universal similarity hypotheses of turbulent mixing and fossil turbulence, see http://maeresearch.ucsd.edu/~cgibson/Documents2007/GibsonBB08Nov26_Alist.htm. Turbulent kinetic energy is always created at the Kolmogorov length scale and transported to larger scales by inertial vortex force dynamics. Fluid mechanics, cosmology, astrophysics, astronomy and planetary sciences that fail to take this fundamental property of turbulent flows into account are certain to run into trouble. The physical mechanisms and cascade directions of turbulent mixing, fossil turbulence and zombie turbulence dynamics rely on this new definition of turbulence.

The mechanism of turbulent mixing is for turbulence velocities to overcome diffusion velocities of scalar fields such as temperature and enstrophy. Such fields diffuse to form uniform gradients that are scrambled by the turbulence to form zero gradient points and zero gradient surfaces that tend to move with the fluid motion and achieve Batchelor scale radii of curvature as the basis of turbulent mixing and fossil turbulence similarity theories (see Gibson Proc. Roy. Soc. 1991). Thus, the direction of the turbulent mixing cascade is opposite to that of turbulence.

The statistics of supersonic isothermal turbulence

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I will present results of large-scale three-dimensional simulations of supersonic turbulence with higher-order low-dissipation Godunov methods for compressible (magneto-) hydrodynamics and multiple grid resolutions up to 2048^3 points. Our numerical experiments describe driven turbulent flows with an isothermal equation of state and an turbulent Mach numbers in the range from 1 to 10. I will discuss numerical resolution issues and demonstrate convergence, in a statistical sense, of the inertial range dynamics in non-magnetized simulations on grids larger than 512^3 points. The simulations allowed us to measure the absolute velocity scaling exponents for the first time. The inertial range velocity scaling in a strongly compressible regime deviates substantially from the incompressible Kolmogorov laws. The slope of the velocity power spectrum, for instance, is -1.95 compared to -5/3 in the incompressible case. The exponent of the third-order velocity structure function is 1.28, while in incompressible turbulence it is known to be unity.

We propose a natural extension of Kolmogorov's phenomenology that takes into account compressibility by mixing the velocity and density statistics and preserves the Kolmogorov scaling of the power spectrum and structure functions of the density-weighted velocity $v = \rho^{1/3} \times u$. The low-order statistics of v appear to be invariant with respect to changes in the Mach number. For instance, at sonic Mach numbers $6 < M_S < 10$, the slope of the power spectrum of v is -1.69 and the exponent of the third-order structure function of v is unity. We directly measure the mass dimension of the "fractal" density distribution in the inertial subrange, $D = 2.3 \div 2.4$, which is similar to the observed fractal dimension of molecular clouds and agrees well with the cascade phenomenology. I will discuss our recent results from a series of smaller 512^3 simulations of MHD turbulence with Alfvenic Mach numbers, $1 < M_A < 10$, and $M_S = 10$, which indicate that the 4/3-law of incompressible MHD turbulence derived by Politano and Pouquet (1998) can be generalized to highly compressible regimes using the same "1/3-rule". We find that the corresponding third-order structure functions of the density-weighted Elsasser fields $[Z^{\{+/-\}} = \rho^{1/3} \times (u \; +/- \; B/\rho^{1/2})]$ scale linearly with separation, independent on M_A. If confirmed with higher resolution simulations (that we are running right now), this result suggests an interesting possibility to extend the phenomenological theory of Kolmogorov (1941) to magnetized compressible turbulence.

Shock generated vorticity in the interstellar medium and origins of the stellar initial mass function

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Observations of gas motions in diffuse interstellar medium, as well as dense, star forming molecular clouds, reveal the presence of strong supersonic often interpreted as turbulence. The power law energy spectrum for velocity fluctuations has a typical (but not unique) exponent of -5/3 which characterizes Kolmogorov turbulence. We have examined both the density and velocity structure of interstellar and molecular gas traversed by curved shocks. We demonstrate that the passage of just a few shocks is sufficient to create a log-normal density probability distribution function (PDF) that is seen in numerous numerical simulations as well as observations. The passage of a spherical blast wave through such a medium - expected as a consequence of massive star formation, creates a power-law tail on the lognormal. The velocity spectra, meanwhile, show that turbulence is not required to understand the broad range of scales excited by such gas motions. Focused shocks produce and initial -2 energy spectrum, but the passage of just a few curved shocks reduces this slope. We argue that the Kolmogorov spectrum is a natural limiting case wherein nonlinear processes such as dissipation acts to re-distribute energy that is piled up at small scale. This work is important for star formation studies since the density PDF produced by supersonic gas motions is directly linked to the mass spectrum of stars.

Helioseismology, turbulent convection and the solar tachocline

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The seismic study of the interior of the Sun by helioseismology has revealed the existence of the solar tachocline. The tachocline is a layer of rotational shear that is located near the base of the Sun's outer convective envelope, about 30 per cent of the way from the Sun's surface to its centre. In this lecture I shall review what is known helioseismically about the properties of the solar tachocline, the theoretical understanding of the role of turbulent convective overshoot in maintaining the shear layer. The tachocline is believed to be the seat of the large-scale solar magnetic dynamo and I shall discuss also the role of the tachocline in the solar dynamo.

Joys of highly turbulent solar convection and magnetic dynamos

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We explore the coupling of turbulent convection, rotation and magnetism within stars like the Sun using 3-D MHD simulations carried out in full spherical shells of compressible fluid. The origin of the intense magnetic fields observed at the solar surface must rest with dynamo processes deep within the star. Most striking is that the Sun exhibits 22-year cycles of global magnetic activity, involving sunspot emergence with very well defined rules for field parity and emergence latitudes as the cycle evolves. Such fields are now believed to arise from a global dynamo seated partly within the strong rotational shear of the tachocline (revealed by helioseismic probing) present at the base of the convection zone. Differential rotation, convective turbulence and magnetic buoyancy in the solar interior are all processes expected to play an essential role in the operation of this interface dynamo. The high Reynolds numbers and sharp transition regions which characterize these processes require simulations with high spatial and temporal resolution. We will discuss elements of the solar global dynamo being revealed through an extensive set of simulations carried out with the anelastic spherical harmonic (ASH) code on massively parallel supercomputers, emphasizing both the joys and puzzles raised as we study such complex dynamical systems.

Magnetohydrodynamic simulations of local solar supergranulation

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Three-dimensional magnetohydrodynamic numerical simulation of solar surface convection using realistic model physics is conducted. The thermal structure of convective motions in turbulent zone of photosphere, the range of scales of convective cells and the penetration depths of convection are investigated. Some part of the solar photosphere extending 60 × 60 Mm horizontally and from 0 Mm down to 20 Mm below the visible surface is considered. The standard model of Sun with realistic equation of state and opacities of stellar matter are used. The equations of compressible radiation magnetohydrodynamics with taking into account dynamical viscosity and gravity are solved. The piecewise parabolic method on local stencil (PPML) for the magnetohydrodynamics, the method of characteristic for the radiative transfer and dynamical viscosity from subgrid scale modeling are applied. The simulations are conducted on a uniform horizontal grid of 600 × 600, with 240 nonuniformly spaced vertical grid points, on 512 processors with distributed memory multiprocessors on supercomputer MBC100K in Computational Centre of Russian Academy of Sciences.

Application of control theory to expanding turbulent media

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Many important turbulent processes take place in an expanding or contracting region. A prime example would be the expansion of a type Ia supernova into the surrounding medium. For efficient computing, this requires that the computational grid keep pace. We propose a control mechanism which will automatically keep the region of interest within the computational domain. This allows the user to keep the area of interest at maximum resolution throughout the simulation without recourse to manual correction. We show the effectiveness of this controller in the case of a rarefaction wave and a supernova explosion and present ways to tune this controller to a variety of other situations.

Turbulent instabilities in the interstellar medium

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Many astrophysical flows are observed to have substantial variations in speed and density, resulting from a range of instabilities. These range from familiar interfacial instabilities, such as Rayleigh-Taylor, to more astrophysically specific processes driven by radiation or particle drift. We will describe theoretical and computational studies of a number of these, including ionization front instabilities and the continuum-force driven instability.

Ambipolar diffusion drifts and dynamos in turbulent gases

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In a weakly ionized but still highly conducting medium magnetic fields are frozen to the plasma but drift with respect to the neutrals at a rate proportional to the magnetic force. The drift is enhanced by turbulence, which creates small scale magnetic structure and, hence, large small scale force. This leads to an effective diffusivity for the magnetic field which is of order the eddy rate, and can be much larger than the drift rate in a laminar medium. These small scale drifts also affect the operation of a dynamo, and can prevent the buildup of magnetic power at the resistive scale.

MAGNETO-HYDRODYNAMICS

Recent results on magnetohydrodynamic turbulence

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Magnetohydrodynamic (MHD) turbulence is a starting point for modeling large-scale plasma motions in a variety of systems ranging from astrophysical objects to laboratory experiments. The energy spectrum of MHD turbulence continues to be a subject of intense discussion. We present recent analytical and numerical results on MHD turbulent cascades, and concentrate on the processes that determine the spectrum and structure of strong incompressible MHD turbulence. The results are compared with numerical simulations and geophysical (solar wind) and astrophysical (interstellar scintillation) observations.

Magnetic field reversals: the geodynamo, laboratory experiments and models

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After a short review of dynamo mechanisms and their relevance for planetary and stellar magnetic fields, I will show that the dynamics of the magnetic field generated by a fully turbulent flow of liquid sodium in a recent experiment (VKS experiment) can be easily understood from the interaction of dipolar and quadruple modes. In particular, this interaction generates magnetic field reversals that have been observed in the experiment and display a hierarchy of time scales similar to the Earth's magnetic field: the duration of the steady phases is widely distributed, but is always much longer than the time needed to switch polarity. These results will be understood in the framework of dynamical system theory using low dimensional models and compared to direct numerical simulation. I will finally consider similar phenomena in purely hydrodynamic systems, in which a large scale flow driven by a turbulent background randomly reverses its direction and discuss whether the same type of models can be used.

Magnetic field line reconnection in plasma current systems within magnetic flux ropes and dense colliding plasmas

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Magnetic Field Line reconnection is still considered, by some, to be one of the most important topics in plasma physics and has been in this category for close to thirty years. One reason is most of the models for it are still two dimensional. We report on two very different experiments in which 3D reconnection plays a role. In the first experiment two magnetic flux ropes are generated from initially adjacent pulsed current channels in a background magnetoplasma. The currents exert mutual $\vec{J} \times \vec{B}$ forces causing them to twist about each other and merge. In addition, the currents are observed to filament after merging. Volumetric space-time data show multiple reconnection sites with time-dependent locations. The quasi-separatrix layer (QSL) is a narrow region between the flux ropes. Two field lines on either side of the QSL will have closely spaced foot-points at on end of the flux ropes, but a very different separation at the other end. Outside the QSL, neighboring field lines do not diverge. The QSL has been measured, for the first time in this experiment and its three dimensional development will be shown in movies made from the data. We will also discuss instabilities of the magnetic flux ropes and how they play a role in the reconnection process. In the second experiment three dimensional currents associated with colliding laser produced plasmas are observed. The currents in this situation are those of shear Alfvén waves. The wave fields are a small fraction of the background field; nevertheless, reconnection regions, multiple magnetic "X" points (which are three dimensional) and induced electric fields are observed. These measurements lead one to suspect that reconnection is not an independent topic, which can be studied in isolation, but part of the phenomena associated with a broader subject of 3D waves and current systems in plasmas.

Turbulent interchange mixing in a dipole-confined plasma

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Turbulence in strongly magnetized plasma depends on the geometry of the magnetic field. We report the first comprehensive observations of strong interchange turbulence in a plasma confined by a dipole magnet in the Collisionless Terrella Experiment (CTX) device. Low-frequency plasma dynamics in a dipole field appears two-dimensional, and we observe steady state interchange-like electrostatic turbulence that is observed to be dominated by a limited number of low-order, rotating azimuthal modes which vary irregularly in time and cause chaotic plasma

fluctuations. Simultaneous high-speed measurements of the entire plasma and long digital records permit clear determinations of both local and global structures. When viewed locally, the intense fluctuations exhibit characteristics of fully developed turbulence, with a broad power-law spectrum and finite correlation length. When viewed globally, the dynamics are found to be describable by the chaotic temporal variation of a limited number of simple spatial modes. The fluctuation energy spectrum is calculated to be consistent with the power-law trends for the inverse energy cascade. Using analysis techniques for determining spectral energy flow, it is found that three-wave interaction transfers energy to low wavenumbers, as predicted for two-dimensional turbulence. A fully parallelized, self-consistent simulation is used to test the model equations for interchange mode dynamics, and the model reproduces the rotating, radially broad, large-scale structures observed in CTX.

Turbulence spreading in magnetically confined plasmas

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We study the simplest problem of turbulence spreading in magnetically confined plasmas, corresponding to the spatio-temporal propagation of a patch of turbulence from a region where it is locally excited to a region of weaker excitation, or even local damping. A single model equation for the local turbulence intensity I(x,t) includes the effects of local linear growth and damping, spatially local nonlinear coupling to dissipation and spatial scattering of turbulence energy induced by nonlinear coupling. In the absence of dissipation, the front propagation into the linearly stable zone occurs with the property of rapid progression at small *t*, followed by slower sub-diffusive progression at late times. The turbulence radial spreading into the linearly stable zone reduces the turbulent intensity in the linearly unstable zone, and introduces an additional dependence on the Larmor radius to system size ratio to the turbulent intensity and the transport scaling. Therefore, it can affect cost of future fusion devices. Predictions from our simple nonlinear theory are in broad, semi-quantitative agreements with a number of global gyrokinetic simulation results with zonal flows and without zonal flows. The front propagation stops when the radial flux of fluctuation energy from the linearly unstable region is balanced by local dissipation in the linearly stable region. Finally, the possibility of measuring the turbulence spreading from the experiments is also discussed.

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Gyrokinetic simulations of laboratory and astrophysical plasmas

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More than 99% of the visible Universe is in a plasma state (i.e. partially or fully ionized), embedded in cosmic magnetic fields, and highly turbulent. The same is true of many laboratory systems, most notably magnetic confinement fusion devices like the international ITER experiment. Turbulent mixing turns out to be a key issue in these systems, and it is described most effectively by means of the nonlinear gyrokinetic equations which were first derived in the 1980s. Numerical solutions allow for surprising insights concerning the nonlinear dynamics of magnetized plasmas. An overview of some key results of gyrokinetic simulations will be given, and parallels as well as differences with respect to other turbulent systems will be pointed out.

A quarter-century later: Nonlinear gyrokinetics under attack

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The nonlinear gyrokinetic equation (GKE) for low-frequency microturbulence in magnetized plasmas was first derived about a quarter-century ago. A variety of technical developments occurring since then have refined the GKE into a major analytical and especially numerical tool for the description of both fusion and astrophysical plasmas. However, the GKE is surprisingly subtle. It has spawned various paradoxes and been the recipient of serious attacks on its veracity, some of which will be discussed in the present lecture. In particle simulations, Monte-Carlo sampling noise can be problematical. One must understand the “entropy paradox” relating to the behavior of the system in the complete absence of collisional dissipation.

A recent concern relates to the fundamental assumption that the magnetic moment mu of the gyrating particle is conserved. It has been argued that this cannot be assured in general 3D magnetic fields (torsional or stochastic) because of difficulties related to the use of anholonomic frame fields in the asymptotic construction of mu. This is an interesting issue that probes deeply into the foundations of the theory. It will be argued that there is no problem with the use of anholonomic frame fields, although one must not forget about profound issues involving Hamiltonian stochasticity (of the particle motion, not the magnetic field lines). Finally, concerns have been voiced, and counterarguments raised, about the fidelity of the GKE for the treatment of disturbances with wavelength much longer than the ion gyroradius. The issues relate to the role of certain second-order terms in the pull-back transformation from gyrocenter to particle coordinates, particularly in the presence of collisions. The current status of this debate will be described. Overall, the important lesson to be learned is that an innocent facade can cloak great subtlety. To use a powerful tool like nonlinear gyrokinetics without full understanding of it is to invite disaster.

Two-fluid magnetic reconnection

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A theoretical model of quasi-stationary, two-dimensional magnetic reconnection is presented in the framework of incompressible two-fluid magnetohydrodynamics (MHD). It is emphasized that the electron inertia terms, proportional to the electron inertial length squared, should be included into both Ohm's law and the momentum equation. Two distinct regimes of slow and fast reconnection rate are found. In the slow reconnection regime the resistive and Hall terms are important, while the electron inertia does not play any role. In the fast reconnection regime the electron inertia terms are important in both the Ohm's law and the momentum equation. The presence of the two reconnection regimes can provide a possible explanation for the initial slow build up and subsequent rapid release of magnetic energy frequently observed in cosmic and laboratory plasmas.

Gyrokinetic simulation of turbulent transport in fusion plasmas

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Time permitting, selected research from applications of the gyrokinetic code GYRO [1] simulating all aspects of turbulent transport in the core of tokamak plasmas will be reviewed. GYRO is a physically comprehensive and highly versatile global and electromagnetic continuum code with a large user base. It has been extensively cross-code verified and validated against tokamak experiments. GYRO treats all $\vec{E} \times \vec{B}$ and magnetic flutter transport in all channels: electron and ion energy; particle (plasma, impurity, and energetic); toroidal angular momentum, and energy exchange. The tokamak turbulence can span an enormous range in wave numbers k [i.e., high Reynolds number (high-k/low-k)^2] coupling drift-Alfvenic TAE/EPM at very low-k with ITG/TEM at moderate-k to ETG at very high-k [2]. After outlining the formulation of gyrokinetics and briefly reviewing the recent history of gyrokinetic simulations [3] and their role in the development of accurate theory based tokamak transport models, the presentation focuses on illustration of the "drift wave-zonal flow paradigm" [4] and its basic relation to the more familiar (Rossby wave - geostrophic) 2D Navier-Stokes turbulence, and on the fidelity of the quasi-linear and linear tracer transport approximations to nonlinear simulations.

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Tutorial: A primer on gyrokinetic theory and simulation

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Target audience: graduate and professional

As it is well known, most of the visible Universe is in a plasma state, and embedded in cosmic magnetic fields. Moreover, there are various technological applications of magnetized plasmas, most notably magnetic confinement fusion. These media are usually subject to the cross-field transport of particles, momentum, and energy due to small-scale turbulence. Since the 1980s, the plasma physics community has developed a theory which is ideally adapted to plasma microturbulence, namely gyrokinetics. Its basic ideas shall be described, together with its numerical treatment and several areas of application. Similarities and differences with respect to fluid turbulence will also be addressed.

Tutorial: Nonlinear gyrokinetics: A powerful tool for the description of microturbulence in magnetized plasmas

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Target audience: graduate

Gyrokinetics is the description of low-frequency dynamics in magnetized plasmas. In magnetic-confinement fusion, it provides the most fundamental basis for numerical simulations of microturbulence; there are astrophysical applications as well. In this tutorial, a sketch of the derivation of the novel dynamical system comprising the nonlinear gyrokinetic (GK) equation (GKE) and the coupled electrostatic GK-Poisson equation will be given by using modern Lagrangian and Lie perturbation methods. No background in plasma physics is required in order to appreciate the logical development. The GKE describes the evolution of an ensemble of gyrocenters moving in a weakly inhomogeneous background magnetic field and in the presence of electromagnetic perturbations with wavelength of the order of the ion gyroradius. Gyrocenters move with effective drifts, which may be obtained by an averaging procedure that systematically, order by order, removes gyrophase dependence. The use of the Lagrangian differential one-form as well as the content and advantages of Lie perturbation theory will be explained.

The electromagnetic fields follow via Maxwell's equations from the charge and current density of the particles. Particle and gyrocenter densities differ by an important polarization effect. That is calculated formally by a “pull-back” (a concept from differential geometry) of the gyrocenter distribution to the laboratory coordinate system. A natural truncation then leads to the closed GK dynamical system. Important properties such as GK energy conservation and fluctuation noise will be mentioned briefly, as will the possibility (and difficulties) of deriving nonlinear gyrofluid equations suitable for rapid numerical solution - although it is probably best to directly simulate the GKE. By the end of the tutorial, students should appreciate the GKE as an extremely powerful tool and will be prepared for later lectures describing its applications to physical problems.

CANONICAL PLASMAS

Nonstationary turbulent mixing of multichannel discharge plasma and electrolyte

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Physical and chemical processes occurring in an electrolyte bath when the metal electrode is immersed to conducting liquid are very complicated and insufficiently studied. The goal of this work is to study the influence of thermal and gas dynamic processes on the mechanism of development and burning of multi-channel discharge. The experiments were carried out in the pressure range of 26 to 100 kPa, current range of 0.5 to 100 A, voltage range of 200 to 500 V, the temperature of the electrolyte was in the range of 20°C to 70°C. Water solutions of NaCl, Na_2CO_3, NH_4Cl, $CuSO_4$, and tap water were used as electrolyte. The concentration of solutions varied from 1% to chemical saturation. Anodes made of brass, copper, titanium, tungsten, zinc, aluminum, and steel were employed. The experiments revealed that during 0.01 s after the discharge onset the viscous cylindrical region is formed around the anode. Multi-channel discharge burns along the boundary of the cylinder. At 0.02 s the water "hubcap" shaped as truncated cone is formed. The multi-channel discharge burns at the top of the cone. At 0.03 s the water hubcap is destroyed and the discharge occupies the space around the anode. The electrolyte starts to evaporate rapidly with sprays. The discharge generates shock waves which result in turbulent mixing of plasma and electrolyte. At lower pressures the number of discharge channels and discharge volume increase. The mechanism of turbulent mixing of plasma and electrolyte is revealed by the experiments.

Shock wave instability with interaction of the shock wave with a region of lowered density in a glow discharge column

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It is well known that Richtmyer - Meshkov effect appears with the shock wave propagation from the less dense medium into the denser. A good survey of works can be found in [1]. However, recent experiments [2] show that the manifestation of the effect is also possible when the shock wave propagates from the less dense medium into the denser one, but changes the phase of the perturbation on the contact surface. In our experiments the shock wave enters into the region of positive glow-discharge column with a lowered density of gas [3]. Signal from the piezoelectric pickup, oriented towards the wave, is split into two waves: forerunner and gently sloping second wave. At present, the mechanism of this effect is not still intelligible. It is shown that the electrodynamics reasons are not the reason for the appearance of a second wave, since the effect remains also after the disconnection of discharge in the course of time many times more than the deionization time of gas. In light of the last experiments [2] it is possible to assume that the appearance of a second wave is the consequence of the disturbance of the contact region, which divides cold gas out of the discharge with the hot and less dense gas in the region of the glow discharge.

The authors carried out the experiments on the study of the influence of the type of gas, its humidity and dustiness, on the manifestations of the splitting effect of shock wave in the glow-discharge column, and also in the decay plasma after the disconnection of discharge. A study of influence is carried out on the structure of signal, on the velocity of propagation of shock wave across the positive column, on a change in the course of time of the coefficients of expansion in Fourier series of signal after the disconnection of discharge. It is shown that the concentration of excited states in the plasma of the glow discharge has certain effect on splitting effect. The dustiness of gas influences, but for the sufficiently high concentration of dust, and influence sharply increases with an increase in the shock wave velocity. Finally, specific heat ratio of gas influences the effect. All this speaks about the important role of gas-dynamic aspect in the appearance of the effect.

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Waves in expanding laser-produced plasmas

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The behavior of expanding dense plasmas has long been a topic of interest, particularly for the importance of such phenomena in astrophysics. Of special relevance to space plasma research is the case of a dense plasma expanding within a magnetized background, such as that available at the UCLA Large Plasma Device. Previous experiments at the LaPD have observed the creation of strong ($\delta B/B > 50\%$) diamagnetic cavities, along with large-scale wave activity and hints of fine-scale structure within the expanding plasma itself.

A new series of experiments conducted recently at the LaPD investigates this topic by direct measurement of the fields inside expanding laser-produced plasmas. A novel two-dimensional probe drive system combines small-scale (0.5 mm to 1 mm) magnetic and electric field probes with high-accuracy (within 50 microns) vacuum ceramic motors to allow direct measurements within the laser plasma. The structure of the expansion and related wave activity is mapped over a 2000-point grid at 1 mm resolution, with a large ensemble of data collected at each point.

The data reveal both coherent high-amplitude waves associated with the formation of these structures, and complicated small-scale structure in both the magnetic field and floating potential at later stages of the expansion. In addition to these direct measurements, we will present correlation techniques using multiple independent B and E field probes. This reveals behavior of turbulent, non-phase-locked phenomena. Both the case of a single expanding plasma and two colliding plasmas were studied. The phenomena associated with colliding plasmas is markedly different.

Turbulent mixing of plasma and electrolyte in multi-channel discharge between a droplet and electrolyte

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The multi-channel discharge between electrolyte cathode and electrolyte anode is of significant scientific and practical importance. The physical properties and characteristics of these type of discharges at atmospheric pressure are not studied yet. This work is devoted to studying of the multichannel discharge between an electrolyte droplet cathode and electrolyte cell anode. The experiments were carried out in the current range of 0.01 to 1.5 A and the voltage range of 50 V to 1,300 V. The flow rate of droplet forming electrolyte was 0.2 g/s. Water solution of NaCl was used as an electrolyte.

The experiments revealed that when the dielectric tube used for droplet forming is immersed into the electrolyte, the bubbles are generated in the electrolyte at the voltage of 115.8 V and the current of 1.53 A. Transversal standing waves are generated on the electrolyte surface. The multi-channel discharge burns between two electrolyte droplets. The discharge bridges to the metal electrode serving as a potential supplier. At this moment the first shock wave is formed which generates a large number of bubbles of various diameter. The discharge at the tip of the dielectric tube generates small bubbles. Turbulent mixing of the discharge plasma and the electrolyte is observed. Then a series of shock waves are generated. The mechanism of shock waves formation and their influence on the turbulent mixing is analyzed.

Controlled study of ionospheric plasma turbulence in radio-wave injection experiments

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The lecture is aimed at discussing the theories and experiments in Puerto Rico and Alaska for the generation of large plasma turbulence in the ionosphere by injected radio waves. Various plasma instabilities can be excited by the vertically transmitted radio waves from the ground, producing ionospheric density fluctuations with a broad range of scale lengths from centimeters to kilometers. Large-scale sheet-like plasma density and magnetic field fluctuations can be simultaneously created by the HF heater waves via the thermal filamentation instabilities. While O-mode heater wave-generated sheet-like structures tend to be parallel to the meridional plane, those produced by X-mode heater waves are inclined to be orthogonal to the meridional plane. As the ionospheric plasmas are heated continuously by O-mode waves, thermal expansion together with enhanced chemical reactions will yield a depleted magnetic flux tube and, subsequently, a rising plasma bubble. Laboratory simulation of the RF-induced space plasma turbulence was performed at MIT, confirming some results from our Arecibo experiments.

The radio wave-induced large-scale plasma turbulence, in the form of either parallel-plate waveguides or ducts, can guide VLF transmitter-launched signals to propagate from the ionosphere through the magnetosphere and reach the magnetic conjugate point, as demonstrated in our Arecibo (Puerto Rico) - Trelew (Argentina) experiments. Whistler waves launched by ground-based VLF transmitters are intense enough to interact with ionospheric and magnetospheric plasmas. Lower hybrid waves and short-scale plasma density fluctuations can be excited at the wake of whistler waves, leading to electron accelerations, airglow etc. in the ionosphere. Energetic particle precipitation can be triggered by whistler waves interacting with radiation belts. This tutorial lecture will show that (1) plasma turbulence can be adequately investigated in ionospheric RF heating experiments, and (2) radio and optical techniques can be developed for diagnoses of space plasma environment.

Correlation analyses of simultaneously excited large-scale ionospheric plasma turbulence and magnetic field fluctuations produced by a high-frequency heater at Gakona, Alaska

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We reported that large plasma sheets were generated in the ionosphere by vertically transmitted HF heater waves via thermal filamentation instability, in a series of experiments conducted at Arecibo, Puerto Rico in the summer of 1997 [1]. While the O-mode heater wave-created plasma sheets form parallel-plate waveguides within the meridional plane, those generated by the X-mode heater waves are orthogonal to the meridional plane. It is expected from the theory of thermal filamentation instability that both ionospheric plasma density fluctuations (irregularities) and magnetic field fluctuations can be generated simultaneously in the following process. After thermal filamentation instability is excited, the differential joule heating, resulting from the interactions of HF heater waves and excited high frequency sideband mode, yields a thermal pressure force on electrons. The thermal pressure force (f) across the geomagnetic field (B_0) leads to a $f \times B_0$ drift motion of electrons and, consequently, induces a net electron drift current. Thus, the induced current and magnetic field fluctuations are perpendicular and parallel to the background magnetic field (B_0), respectively. However, experimental verification of simultaneously excited fluctuations in plasma density and magnetic field could not be done until recently, in our experiments at Gakona, Alaska with suitable diagnostic instruments. The recorded magnetic filed fluctuations (δB) have three components (δB_D, δB_H, δB_Z) where the subscripts, D, H, and Z refer to the geomagnetic east-west, the geomagnetic north-south, and the vertical directions, respectively. According to our theoretical expectation, δB_D and δB_Z (δB_H and δB_Z) are correlated for O-mode (X-mode) wave-induced geomagnetic fluctuations. This prediction is indeed confirmed in our summer and fall 2008 ionospheric HF heating experiments at Gakona. How this research can contribute to the remote diagnoses of space plasma turbulence will be discussed.

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Instabilities and turbulent mixing in electrohydrodynamics

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Electrohydrodynamics (EHD) is the flows where hydrodynamic phenomena interacts with electric phenomena. The EHD electric and hydrodynamics flows in many cases required self consistency, i.e. there is influence of external and induced internal electric fields to the flow and vice versa, the flow creates induced electric fields. In EHD flows to hydrodynamic forces like pressure gradient, stress tensor and the gravity forces electric forces have to be added. These forces consist of two parts - forces with space charge media and forces for media without space charge due to dipoles existing in the liquid. Expression for these forces could be found in Landau and Lifshitz [1] and Tamm [2] textbooks. In hydrodynamics well known that important values is vorticity which creates instabilities, mixing and turbulence. The expressions for vorticity generation are found for different EHD flows and instabilities. The theory and numerical simulation are developed for Rayleigh-Taylor, Kelvin-Helmholtz and Tonks-Langmuir instabilities. The comparison with experiments for flows, waves, fountains for incompressible and compressible flows are considered. One of the interesting features of EHD consists of linear character of nonlinear interaction electric and hydro dynamical modes [3] which creates some special peculiarities in nonlinear EHD flows. Example of EHD in compressible flows is the plasma flow control systems based on flow detachment in the boundary layer [4]. It is found that vorticity generation defines by the outer product of the gradient of space charge and total electric field. As the result vorticity generated by plasma located at points where nonzero space charge gradient and electric field exist. The analysis of maximum influence of the electric field on the hydrodynamic flow has been developed for different examples such as dielectric barrier discharge (DBD), helical discharge and capacity discharge in a flow. The theory and numerical simulations for the supersonic experiments are presented.

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Tutorial: When dense plasmas collide

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Target audience: graduate

Here we present an experiment in which two plasmas, initially far denser than a background magnetoplasma ($n_e = 3\times10^{12}$ cm^{-3}, B_{0z} = 600 G, L = 18 m, dia = 60 cm), collide as they move across a magnetic field. In the course of the interaction many basic plasma processes (underlined in this abstract) occur and will serve as a springboard to study their fundamental in the spirit of this summer school. The dense plasmas are formed when two laser beams, nearly orthogonal to the background magnetic field strike two targets in the presence of background plasma. The initial high beta plasmas expel the background magnetic fields and create diamagnetic bubbles. The bubbles undergo instabilities and radiate MHD waves into the background plasma. The merging plasmas also shed electrons aligned along the background magnetic field. This spawns the generation of intense lower hybrid waves, solitons and whistler waves in the background plasma. Initial bursts of fast electrons Cherenkov radiate Alfvén waves. The wave currents are fully three-dimensional. Magnetic field line reconnection events, magnetic flux forced together by the motion of the currents, occur at many locations throughout the plasma volume and electric fields are induced. The currents in the magnetoplasma are those of Alfvén waves and the physics of these waves plays a great role in the interaction. The magnetic fields and currents derived from them were measured at tens of thousands of spatial locations and as a function of time. They will be displayed in detailed images and movies. The moving dense plasmas churn up the background plasma and generate ion acoustic waves and effect the plasma they move through. The relation of this experiment to several phenomena in astrophysical and space plasmas will be discussed.

PHYSICS of ATMOSPHERE

Forecasting atmospheric turbulence for adaptive optics application: models comparison of vertical turbulence profile

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Turbulence in the Earth's atmosphere is a major obstacle to the detection of planets with coronographic and interferometric methods from the ground. It limits the contrast achievable with high-resolution imaging and the precision of astrometric measurements. As a whole atmosphere turbulence limits the performance of ground-based astronomical telescopes [1]. The crucial parameter used for optical turbulence effects is known as the astronomical "seeing". The adaptive optics technique has the purpose minimize the effect of turbulence [2]. Forecasting atmospheric turbulence is very important for this. The key to the design of adaptive optics systems is vertical profile of atmospheric turbulence. There are various models to forecast vertical turbulence profile, but nature varies a lot around the standard models: spatial layering, temporal intermittency. All of them bases on statistically averaging experimental date and depend on a number of factors, including geography. For example, turbulence profile can be calculated using various version of Hufnagel - Valley model [3]. Here, we calculated the definitions of the parameters of atmospheric turbulence, which are of the most importance to adaptive optics from models of vertical turbulence profiles. Paper demonstrates the effectiveness of an optical turbulence models which, when combined with our development-forecasting algorithm, can predict astronomical "seeing" conditions in advance. The results of analytical and numerical calculations are compared.

[1] A. Quirrenbach, *The Effects of Atmospheric Turbulence on Astronomical Observations*, Springer 2001, p.129 -144; [2] J. C. Dainty, *Adaptive Optics*, Springer Series in Optical Sciences 2007. Vol. 87, p. 307-327; [3] R. E. Hufnagel, *Propagation through Atmospheric Turbulence*, Ch. 6 in The Infrared Handbook 1985.

One-dimensional vertical model for the atmospheric boundary layer

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The atmospheric boundary layer is the part of the atmosphere where the direct effects of the surface are noticeable. The formation of the layer is a consequence of the interactions between the atmosphere and its subjacent surface. The understanding of complex boundary layer interactions and description of turbulent mixing processes in the atmosphere, caused by wind shear and buoyancy, are important for environmental modeling and weather forecasting. The aim of our study is to represent an one-dimensional vertical model comprehensive enough to describe accurately boundary layer characteristics, such as diurnal variation of the boundary layer height, potential temperature, momentum, specific humidity and pollutant concentration profiles as well as wind speed profiles. During conditions of stabile and neutral static stability, when the scale of turbulent motion is much smaller than the scale of mean motion, the model describes turbulent mixing by eddy diffusion local closure scheme. During convective conditions much of the mixing is caused by buoyant plumes originate in the surface layer, rise to the top of the boundary layer and penetrate into the capping inversion. The convective vertical transport of atmospheric properties and air contaminants is driven by eddies of different sizes simultaneously. The model simulates convective mixing using combined local and nonlocal mixing scheme, the total mixing is represented as a split between small-scale subgrid and large-scale supergrid turbulent transport.

Hyper-cooling in the atmospheric surface layer: radiative processes

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On calm and clear nights, a peculiar temperature distribution called the `Lifted Temperature Minimum' (LTM) develops, in which a local minimum in the vertical temperature profile occurs a few decimeters above the ground. The LTM is characterized by the (1) intensity of the minimum, which is the difference between the minimum temperature and the ground temperature, and (2) height of the minimum, which is the height at which the minimum temperature occurs. An intriguing aspect is that, in spite of the layer below the minimum point having Rayleigh numbers in the range of 10^5 to 10^6, the profile is surprisingly stable and persists throughout the night. In this work, results of field observations and laboratory experiments of the LTM are presented. The field observations show that the phenomenon is sensitive to turbulent transport, with the intensity of the minimum decreasing when turbulence levels increase. The time for the profile to relax to a steady state after a turbulent perturbation, which indicates the role of radiation in enhancing the stability, is estimated form the data. Though the relaxation is faster than the conduction time scale, it is still smaller (by at least two orders of magnitude) than the value required to stabilize the layer. Results are presented on the effect of surface properties on the LTM. A reflective surface significantly increased the intensity of the minimum. On the high cooling rate surface, an inversion profile, with the minimum at the ground, replaced the LTM. However, with turbulence levels falling to exceptionally low values, minima with very low heights and intensities did form. A decoupling of conduction-convection and radiation boundary conditions is crucial for the formation of the LTM. A laboratory set-up was fabricated in which this

decoupling is effected, allowing the study of a wider range of problems. With appropriate boundary conditions, an LTM type of profile was obtained in this set-up.

A regularized inhomogeneous statistical dynamical turbulence closure and its application to problems in atmospheric dynamics

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We describe the development of a computationally tractable statistical dynamical turbulence closure for inhomogeneous two-dimensional turbulence and its application to problems in atmospheric dynamics. Based on a generalization of Kraichnan's direct interaction approximation and a quasi-diagonal approximation to the covariances the quasi-diagonal direct interaction approximation (QDIA) is formulated for the interaction of mean fields, Rossby waves and inhomogeneous turbulence over topography on a generalized β-plane has a one-to-one correspondence between the dynamical equations, Rossby wave dispersion relations, nonlinear stability criteria and canonical equilibrium theory on the sphere. We consider not only the underlying theoretical basis but also the numerical methodology required to integrate the resulting non-Markovian integro-differential closure equations over the long time periods typical of the growth and decay of coherent structures in the atmosphere. We discuss the problem of vertex renormalization and consider a regularization methodology in which eddy-eddy, eddy-topographic and eddy-mean field interactions are localized in wavenumber space. We examine application of the closure to a range of problems in numerical weather prediction such as the role of non-Gaussian initial perturbations and small-scale noise in determining error growth; the parameterization of subgrid-scale energy and enstrophy transfers; and the development of generalized Kalman filter methods for data assimilation in strongly nonlinear flows. We also consider the relationship to minimum enstrophy, maximum entropy and entropy production arguments. Throughout the dynamics, kinetic energy spectra, mean field structures and mean streamfunction tendencies contributed by transient eddies are compared with ensemble-averaged results from direct numerical simulations (DNS).

Using satellite measurements of stellar scintillation for mapping turbulence in the stratosphere

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When the stellar light passing through the atmosphere is measured on-board of a satellite with a high-frequency device, the stellar flux exhibits fluctuations that may exceed their regular values by several hundred percents. This effect is called scintillation. Stellar scintillations are caused by air density irregularities generated mainly by internal gravity waves (GW) and turbulence.

The strength of scintillation measurements is that they cover the transition between the saturated part of the gravity wave spectrum and the isotropic turbulence. This allows visualization of gravity wave breaking and of resulting turbulence. We analyzed the scintillation measurements by GOMOS fast photometers on board of the Envisat satellite in order to quantify GW and turbulence activity in the stratosphere.

The analysis is based on reconstruction of GW and turbulence spectra parameters by fitting the modeled scintillation spectra to the measured ones. We use a two-component spectral model of air density irregularities: the first component, anisotropic, corresponds to the gravity wave spectrum, while the second one describes locally isotropic turbulence resulting from GW breaking and other instabilities. The retrieval of GW and turbulence spectra parameters - structure characteristics, inner and outer scales of the GW component - is based on the maximum likelihood method.

In this presentation, we show global distributions, seasonal and interannual variations of turbulence structure characteristic C_T^2 in the stratosphere, for altitudes of 30 to 50 km.

Tutorial: The application of statistical dynamical turbulence closure theory to data assimilation in geophysical flows

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Target audience: graduate

The calculation of the error covariance of fields described by an evolving nonlinear system requires the solution of an infinite hierarchy of moment equations; this problem is formally identical to the closure problem that arises in statistical approaches to turbulence. Typically, Kalman filter methods simply discard cumulants of third order and higher, although these cumulants are often required to ensure that regime transitions in nonlinear models are accurately tracked. Thus it would seem to be desirable to develop a tractable data assimilation scheme that incorporates information about the higher order terms in the probability density function (PDF). To this end, we formulate a statistical dynamical Kalman filter (SDKF) methodology for the general statistical problem of mean fields interacting with inhomogeneous turbulence and topography with prognostic equations for the statistics of the mean field and the inhomogeneous covariance. We will demonstrate the unique insights that turbulence closure theory can bring to a problem of fundamental importance in numerical weather prediction.

GEOPHYSICS and EARTH SCIENCE

Recent developments in stratified turbulence

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Transport across a stratified interface is an essential aspect of many geophysical processes. In order to accurately deduce the vertical and lateral transport occurring when a turbulent flow impinges on a stratified interface, the turbulent entrainment and vorticity generation mechanisms near the interface must be clearly understood and quantified. This information is critical if one is to predict accurate concentrations of a certain species downstream of a jet impinging on a stratified interface for example. Such scenarios can include biochemical releases in a stratified environment and pollutants transported above an inversion by strong convection.

We performed laboratory experiments in three different flow configurations: a vertical thermal, a sloping gravity current and a vertical jet with various tilt angles and precession speeds in order to fully understand and quantity interface processes related to entrainment and mixing. All three flows impinged on an interface located in a two-layer stably stratified environment. The entrainment rate and vorticity generation were quantified for each flow using Laser-Induced Fluorescence and Particle Image Velocimetry.

Possible applications of transport across stratified interfaces include the contribution of hydrothermal plumes on the global ocean energy budget, turbidity currents on the ocean floor, the design of lake de-stratification systems, modeling gas leaks from storage reservoirs, weather forecasting, and global climate change.

Statistical properties of wind wave breaking crests from field measurements

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Breaking waves is a widespread strongly nonlinear turbulent phenomenon at the sea surface. Whitecaps start to occur at wind speeds starting from 4 to 5 m/s and play significant role for majority upper ocean layer processes at high wind speeds. Despite of the importance of wave breaking it is scarcely studied and existing theories exhibits unsatisfactory results. In order to avoid extraneous effects essential for field measurements, numerous experiments have been conducted in laboratory conditions. But their relation to the natural conditions needs to be additionally determined. An experimental study of breaking wave's properties was performed during two field campaigns on the Black Sea research platform. Simultaneous recordings of wave breaking measures (with video camera) and wave 2D-spectra (with an array of resistance wave staffs) were obtained under variety of wave and wind speed (U = 4 ÷ 20 m/s) conditions. Individual whitecaps corresponding to active breaking phase were extracted from the video records using processing technique based on physical considerations of sea surface brightness and whitecap dynamics empirical information. In order to evaluate geometrical properties all whitecaps were approximated with ellipses. The values of ellipses eccentricities appeared to be very close. This result supports an idea of wave breaking self-similarity - a basic assumption for a majority of analytical theories but not tested experimentally at field conditions, until now. Also, experimental variability of values of eccentricities can be explained with frequency-directional wave spectrum properties. Large set of experimental distributions of different breaking waves characteristics were analyzed. It is concluded that the breaking crests lengths and the whitecaps duration time are distributed according to the exponential law, while the time-spatial volumes of breaking waves can be described with a power law. Empirical parameterizations are also obtained for wide range of wave and wind conditions.

Dynamics of oceanic zonal jets

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There is recent computational and observational evidence that point to the existence of alternating zonal jets that are superposed on the larger scale midlatitude ocean circulation. We consider modulational instability of Rossby waves and the inverse cascade of geostrophic turbulence as possible mechanisms for the jets. Further, since nonlinear mechanisms are at play in the dynamics of both the jets and the gyre circulation, significant interactions are expected between these features. We present results about such interaction in the small Rossby number limit using diagnostics of the interaction across scales of energy. For the first time, we find parameter regimes where alternating zonal jets can arise from purely steady and large-scale forcing.

Rotating turbulent flows in the presence of helicity

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Rotation, as measured by the Rossby number (the ratio of the rotation period to the eddy turn over time, $Ro = U_0/[L_0\Omega]$ where U_0, L_0 are characteristic velocity and scale, and Ω is the rotation rate), is present in many astro- and geophysical flows. The Rossby number for mid-latitude atmospheric synoptic scales is $Ro \approx 0.1$ whereas in the solar convective zone, $Ro \approx 0.1 \div 1$. For rapid rotation, significant progress has been made in the past by developing resonant wave theory, two-point spectral closures, and weak turbulence. However, at high Reynolds number *Re*, small scales are excited with a characteristic timescale proportional to the eddy turnover time, that decreases as the scales become smaller leading to a break-down of the weak turbulence hypothesis.

Invariance properties of a physical system are known to govern its behavior: energy conservation in turbulence drives a wide distribution of energy among modes, as observed in geophysics, astrophysics and engineering. In hydrodynamic turbulence, the role of helicity, which measures departures from mirror symmetry in the form of correlations between the velocity and vorticity and which is an invariant of the ideal Euler equations, remains unclear since it does not alter the energy distribution. However, we show that the interplay of rotation and helicity leads to significant differences. The effect of helicity, down to a Rossby numbers of $Ro \approx 0.06$ has been studied using direct numerical simulations (DNS) up to a grid of 1536^3 points. We show the occurrence of long-lived laminar cyclonic vortices together with turbulent vortices, somewhat reminiscent of recent tornado observations but in a much simpler context [1]. Furthermore, the small-scale energy cascade (with spectrum $E(k) \sim k^{-e}$ and transfer rate ε) is completely self-similar with no deviations from the Gaussianity and is dominated by the helicity cascade (with spectrum $H(k) \sim k^{-h}$ and transfer rate $\acute{\varepsilon}$). This result points to the discovery of a new small parameter in rotating helical turbulence, namely $\varepsilon/[L_0\acute{\varepsilon}]$. We also find that the spectral indices obey the scaling law of $e + h = 4$ when taking into account the inertial wave mediation of nonlinear transfer to small scales.

In view of the cost of such massive DNS, the search for proper Large Eddy Simulation (LES) modeling is in order. Using an isotropic model based on two-point closures of turbulence, and taking into account the contribution of helicity to eddy viscosity and eddy noise, we show that we can recover the DNS results at substantially lower costs, up to almost four order of magnitude less: indeed, the previously mentioned run on a grid of 1536^3 points can be reliably modeled using grids of 96^3 points [2]. The data indicates that this LES is more faithful to the DNS than under-resolved DNS at the same resolution, and thus one can pursue such substantive runs to longer times using LES. This model is now going to be used for exploring parameter space, e.g. in terms of Rossby and Reynolds numbers.

[1] P. Mininni and A. Pouquet, "Persistent cyclonic structures in self-similar turbulent flows," submitted, Phys. Rev. Lett.; see also arXiv:0903.2294 (2009); [2] J. Baerenzung, P. Mininni, and A. Pouquet, "Large Eddy Simulation using spectral modeling of fluid turbulence: the combined roles of helicity and rotation," in preparation (2009).

Tutorial: Anisotropic large-scale circulations and transport and zonostrophic turbulence

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Target audience: graduate

The general theme of this tutorial is the transport of momentum and scalar in anisotropic turbulence with dispersive waves. We shall concentrate on flows with small-scale forcing, inverse energy cascade and its anisotropization due to the presence of Rossby waves. It is well known that anisotropic dispersive waves play a fundamental role in systems where they coexist with turbulence. In each of the cases of stable stratification, system rotation or a beta-effect, the large-scale flows become anisotropic and a slow manifold develops in a lower-dimensional subspace normal to the wavevector corresponding to the direction with zero frequency. The resulting flows would appear, respectively, as a system of vertically decorrelated horizontal layers, or large-scale cyclonic vortical columns, or stable systems of alternating zonal jets. Turbulent transport in these systems is fundamentally affected by the structural transformations.

We shall concentrate on two-dimensional (2D) flows in the framework of the barotropic vorticity equation on beta-plane or the surface of a rotating sphere. We shall elucidate a new regime of anisotropic turbulence - zonostrophic turbulence - discovered in our studies. The commingling of strong nonlinearity, strong anisotropy and Rossby waves underlying this regime is highlighted by the emergence of stable systems of alternating zonal jets and a new class of nonlinear waves, or zonons. This presentation will elucidate the physics of the zonons and their relation to the large-scale coherent structures. In the first lecture, the basics of the theory will be explained in the format of 2D turbulence on a beta-plane. The second lecture will expand these results to the surface of a rotating sphere. The third lecture will deal with the zonostrophic turbulence and zonons. Finally, the fourth lecture will elaborate the transport of momentum and scalar in zonostrophic turbulence and compare it with transport characteristics in stably stratified flows.

Tutorial: Turbulence in the presence of waves

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Target audience: graduate

An introduction to the problem of turbulence in fluids will be proposed, giving first some facts, experimental and observational, the going to a description of structures and Fourier spectra, and going on to some theory, modeling and what can be done numerically in view of the petascale effort in the world.

In the second part, we shall look at different ways to model such flows and specify this effort on the interactions of eddies and waves, either for magnetohydrodynamic turbulence or for a neutral fluid in the presence of solid body rotation.

Tutorial: A quasi-normal theory of turbulence and its applications in geophysical fluid dynamics

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Target audience: graduate

The Quasi-Normal Scale Elimination (QNSE) theory is a new theory of turbulence whose first steps can be traced to the early 90s. It was prompted by the technique used in the Renormalization Group (RG) theory of turbulence whose essence is the coarse-graining of the flow description via successive “weeding out” of the small scales and compensating for their effect on the flow field by rigorously derived, flow-dependent, “renormalized” viscosities and diffusivities.

Turbulence is a nonlinear, stochastic phenomenon presenting a challenge to the theoretical analysis. In addition, geophysical flows are strongly anisotropic and encompass waves. Such flows were beyond reach of analytical theories. Simplifying assumptions and closure hypotheses are not general enough and do not always represent the correct physics. The QNSE theory offers more systematic and rigorous approach to treat anisotropic turbulent flows with waves.

The lectures to be presented will summarize the progress and show how the QNSE theory can be used in practical applications. It is proposed that the basics of the theory will be elaborated in the first two lectures that will deal with neutrally stratified flows. The last two lectures will deal with the expansion of the theory to flows with stable stratification and its applications in modeling of the atmospheric boundary layers.

COMBUSTION

Selectivity of competitive - consecutive reactions depending on turbulent mixing conditions in a co-axial jet mixer

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Jet flow is one of the most widespread types of shear flows that are encountered in resolving practical tasks on designing various sewage devices, burners, chemical reactors, heat exchanges, etc. In this case, of much interest is the problem on turbulent jet mixing. The present paper considers the numerical results on the interaction between a turbulent co-axial jet and a co-flow of incompressible liquid (Schmidt number Sc ≈ 1000) with competitive-consecutive reactions to occur in a co-axial jet mixer.

Firstly, RANS modeling was made with intent to predict flow phenomena. Two different mixing regimes were analyzed with and without a recirculation zone near a mixer wall. To describe the problem mathematically the two-parameter turbulence k-ε model and various models for computation of averaged mixture fraction f and its variance σ were used and verified by their comparing with the experimental and LES data. The results revealed that the decay of f and σ obtained by the developed RANS mixing model with the low-Reynolds number effects (the mechanical-to-scalar time ratio and the turbulent Schmidt number in the transfer equation for σ as a function of Re_t) was similar to the one found by LES and from experiment.

Secondly, the behavior of competitive-consecutive reactions ($A+B \rightarrow P$, $B+R \rightarrow S$) in a co-axial mixer was considered. To calculate averaged chemical reaction rates the transfer equations for concentrations adopted two approaches: with no regard to concentration fluctuations and the Li-Toor model with the Gaussian PDF of mixture fraction. The yield of a desired product R was found to strongly depend on the mixing regime. The regime without a recirculation zone appeared to be more preferable as the reaction selectivity was smaller within the whole range of Reynolds number and the initial reagent concentration ratio. This means that the amount of undesired by-product S to be formed is minimal.

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The effects of burning on the development of 2D turbulence

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We present results from 2D direct numerical simulations of a Boussinesq fluid in the presence of gravity. Initially a dense, cool fluid is placed over a light, hot fluid and the interface between the two fluids is perturbed. Because of presence of gravity, the system is Rayleigh-Taylor unstable and mixing of the two fluids occurs. We compare this Rayleigh-Taylor mixing problem to the exact same setup but with premixed combustion occurring at the interface between the two fluids. As the gravity is increased, the flow behind the flame transitions from an ordered, laminar state to a chaotic, turbulent state. Our simulations explore the effect of burning on the development of the turbulent state, especially the effect of burning on the energy and enstrophy cascades, the mixing of the temperature field and the shape of the flame front.

Melt-dispersion mechanism for reaction of aluminum nano- and micron-scale particles

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Aluminum nano- and micron- scale particles are widely used in various energetic and material synthesis applications, including thermites, thermobaric, and reactive materials, and synthesis of biomaterials. A new and unexpected mechanochemical mechanism for fast reaction of Al nanoparticles covered by a thin oxide shell during fast heating is proposed and justified theoretically and experimentally. For nanoparticles, the volume change due to melting of Al induces pressures of 1 to 2 GPa and causes spallation of the oxide shell. A subsequent unloading wave creates significant tensile pressures resulting in dispersion of small liquid Al clusters, their mixing with oxidizer and reaction, which is not limited by solid-state diffusion (in contrast to traditional mechanisms). All processes (heating, melting, nanomechanics of stress development, fracture of the oxide shell, wave propagation, cavitation and dispersion) are treated analytically and numerically. Physical parameters controlling this process are determined by our analysis. A number of experiments have been performed that confirm predictions of the melt-dispersion mechanism. Methods to improve efficiency of energetic nanoparticles, as well as to promote the melt-dispersion mechanism for micron particles have been suggested. Experiments indirectly confirm the melt-dispersion in 1 to 3 micron particles. Our ultimate goal is to design and synthesize an optimal micron Al core-strong shell particle that transforms in situ (in flame) into multiple nanoscale bare particles that react like the best nanoscale particles. Cost of the micron size particles is

30 to 50 times smaller than that of the nanoparticles, and they do not pose safety and environmental issues.

Two-point closure method for turbulence with reacting and mixing chemical elements of type A + B → C

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The turbulence with reacting and mixing chemical elements of type A+B→C has been investigated by using the two-point closure method. For implementation of this method two-point correlation functions and two-point triple correlation functions are defined first. The equations describing the turbulence under study which describe the dynamical behavior are written in terms of two-point correlation functions and two-point triple correlation functions. These describe the dynamical behavior of the two-point double reactant fluctuation correlation functions. These equations reveal that in each of these equations the two-point triple correlation functions appear. Thus, the characteristic difficulty of indeterminacy in turbulence theory is noticed in these equations too. A simple closure hypothesis for two-point triple correlation functions is proposed with a view to overcome the indeterminacy. This hypothesis enables to obtain the closed set of equations for double correlation functions as desired. The resulting equations for double correlation functions provide the theoretical information about the turbulence under investigation. Having obtained the closed set of equations for double correlation functions the relationships for reactants eddy diffusivity functions are derived. Also, reactants' energy functions and reactants transfer function in fluid space are obtained. Having expressed the Karman-Howarth equations for present investigation in dimensionless form these are rewritten in terms of energy functions in fluid space. The system of equations for scales of segregation relating to the reactants A and B are derived. Various length scales involved in present study can be evaluated on the integration of these equations which in turn generates the theoretical information about the turbulence under investigation.

Turbulent mixing and large-scale coherent vortical structures inside the vortex chamber with fixed dead-end

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Experimental results on the influence of a vortex chamber geometry and flow regimes on formation and development of coherent vortical structures and turbulent mixing process inside the vortex chamber are submitted. The beneficial swirl effect of

the injected air and fuel are widely used for improvement of high-intensity stabilization processes of combustion. Experiments were realized in the aerodynamic vortex chamber with the complex of devices for flow visualization, fast-response camcoders. Velocity and wall-pressure fluctuations are measured by hot-wires and miniature pressure fluctuation probes. The vortex chamber included cylindrical tube with internal diameter d = 0.102 m and fixed dead-end in various positions [L/d = (0.6 to 4.4)]. The air entered through changeable single-jet nozzles or a series of inlet windows with tangential and axial angles for different Reynolds numbers. The mean and fluctuation velocity profiles in the vortex chamber were obtained. Power spectral densities of the longitudinal velocity fluctuations along the vortex chamber and its first moments were measured. The spectrum has four characteristic frequency peaks which correspond to peripheral velocities of large-scale coherent vortical systems, which were also obtained from visualization. Two pairs of large-scale spiral vortex structures are formed at interaction of the turnaround jet and input jet under the nozzle of the vortex chamber. The internal tornado-like vortex and external wall zigzag vortex structure are convected from the dead-end of the vortex chamber into its active part. Goertler vortices are formed under the input nozzle on concave surface of the vortex chamber and their scale increases with displacement along of the vortex chamber. Intensity of the vortex structures and turbulent mixing are a function of the dead zone length (L/d) of the vortex chamber and tangential and axial angles of the input nozzle.

Effects of dissipation rate models of mixture-fraction on stable and unstable solutions of SLFM

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For different stoichiometric ratios of reactants, the effect of dissipation rate models of mixture-fraction on stable and unstable solutions of steady laminar flamelet model (SLFM) is reported in single-step reversible reactions. The dissipation rate models adopted mapping closure model $\chi = \chi_{st} \exp\left(-2erfc^{-1}\left(2Z\right)^2\right)$ and phenomenological model $\chi = \chi_{st}$, where the subscript "st" denotes that value of mixture-fraction which equals to the stoichiometric value, Z = Z_{st}. The stoichiometric ratio is 1:1 and 1:2, corresponding Z_{st} is 0.5 and 0.33, respectively. In mixture-fraction space SLFM was solved, the whole S-shaped curve was gotten. When SLFM is used to turbulent combustion, only stable branch according to $\chi_{st} <= \chi_q$ and extinction line according to $\chi_{st} > \chi_q$ of S-shaped curve are employed. When progress variable approach (PVA) is used to turbulent combustion, however, the whole S-shaped curve including stable branch, unstable branch and extinction line is employed. The following are the results. The dissipation rate model has a remarkable impact on value of χ_q, which is solved from phenomenological model less than one from mapping closure model. In the range of $\chi_{st} < \chi_q$, solutions at stable branch and unstable branch, are less different between the phenomenological and the mapping closure model, and maximal temperature is located at $Z = Z_{st}$ for stoichiometric ratio of 1:1. But for stoichiometric ratio which is 1:2, the location of maximal temperature departs from $Z = Z_{st}$. The departure of solutions at stable branch is small, but the departure of solutions at unstable branch is large, which implies that prediction of flame surface will have large deviation, by using the database contained solutions at unstable branch. The above results for implement of PVA are more important than for implement of SLFM.

Tutorial: Development of the ReaxFF reactive force fields and applications to combustion

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Target audience: graduate and professional

While quantum mechanical (QM) methods allow for highly accurate atomistic scale simulations, their high computational expense limits applications to fairly small systems (generally smaller than 100 atoms) and mostly to static, rather than dynamic, approaches. Force field (FF) methods are magnitudes faster than QM-methods, and as such can be applied to perform nanosecond-dynamics simulations on large (>>1000 atoms) systems. However, these FF-methods can usually only describe a material close to its equilibrium state and, as such, can not properly simulate bonds dissociation and formation.

This tutorial will describe how the traditional, non-reactive FF-concept can be extended for application including reactive events by introducing bond order/bond distance concepts. Furthermore, it will address how these reactive force fields can be trained against QM-data, thus greatly enhancing their reliability and transferability. Finally, this lecture will describe recent applications of the ReaxFF reactive force fields to a wide range of different materials and applications, focusing specifically on applications associated with combustion.

MATHEMATICAL ASPECTS of NON-EQUILIBRIUM DYNAMICS

Unstable periodic orbits for the Navier-Stokes equations

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We present a novel algorithm for the identification of periodic orbits in differential equations. With this new approach, both space and time are parallelized, and a search procedure minimizes a functional simultaneously towards the trajectory of the orbit in phase space and its period. We discuss in detail the methodology followed for the identification of unstable periodic orbits (UPOs) in the Navier-Stokes equations (NSE) for incompressible viscous fluid flow, simulated using the lattice Boltzmann method.

It has been known for quite some time that driven dissipative systems exhibit finite-dimensional attractors which are replete with UPOs. The attractors can be thought of as the closure of the set of all such UPOs. The UPOs in turn provide a countable sequence of trajectories from which dynamical averages can be extracted using the zeta function formalism. Averages thus obtained are not stochastic in nature, i.e., they do not suffer from the problem of having the statistical error decay as the inverse square root of the number of decorrelation times. In this presentation, we discuss the numerical difficulties involved in the numerical relaxation procedure for systems with very many dimensions such as the NSE, and describe the application of the conjugate gradient method to the problem. Since this method requires the storage in memory of space-time trajectories, huge computational resources are required, which places the work firmly in the emerging field of petascale grid computing. We present results obtained on the IBM BlueGene/P at the Argonne National Laboratory and on the Sun Constellation Linux Cluster at the Texas Advanced Computing Centre, two of the world's current largest resources for open science. Results of turbulent flow simulations are presented and discussed and preliminary periodic orbits are presented. The insights that the identification and classification of these UPOs are expected to bring to turbulence theories are discussed.

Lagrangian approach to weakly nonlinear stability of an elliptical flow

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Rotating flows with elliptically strained streamlines suffer from a parametric resonance instability between a pair of Kelvin waves whose azimuthal wavenumbers are separated by two. We address the weakly nonlinear evolution of amplitude of three-dimensional Kelvin waves, in resonance, on a flow confined in a cylinder of elliptical cross-section. In a traditional Eulerian approach, derivation of the mean-flow induced by nonlinear interaction of Kelvin waves stands as an obstacle since the nonlinear disturbance field, of quadratic in amplitude, is required. We show how topological idea, or the Lagrangian approach, facilitates calculation of the wave-induced mean flow. A steady incompressible Euler flow is characterized as a state of the maximum of the total kinetic energy with respect to perturbations constrained to an isovortical sheet, and the isovortical perturbation is handled only in terms of the Lagrangian variables. The criticality in energy of a steady flow allows us to work out the wave-induced mean flow only from the linear Lagrangian displacement. With the mean flow at hand, the Lagrangian approach provides us with a bypass to enter into weakly nonlinear regime of amplitude evolution of three-dimensional disturbances. Unlike the Eulerian approach, the amplitude equations are available directly in the Hamiltonian normal form. Their coefficients are represented to a large extent in compact form, and thereby a novel feature of the short-wavelength asymptotics manifests itself.

Transport of pollutions by termoconvective currents under frozen parametric disorder

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We study the problem of thermal convection under frozen parametric disorder when localization effects (similar to the Anderson localization) play a significant role. Specifically, we consider a thin horizontal layer of porous medium saturated by fluid heated from below, while frozen parametric disorder means stationary in time, random inhomogeneities of the parameters (the heating intensity or the porous medium permeability). Irregular sets of spatially localized flow patterns which are excited are treated in the context of the convective transport of pollution. The problem addressed is not only interesting from the viewpoint of mathematical physics but is also important due to ecological (transport of pollutions by underground waters) and technical (cooling of the reactors, filtration etc.) applications.

We present (i) the interpretation of the localization effect of formal solutions to the linearized equations of the problem, (ii) results on the localization properties and the effect of a horizontal pumping of fluid on them, (iii) observations of these properties in the nonlinear (not linearized) system, (iv) and results on the influence of the effects under consideration on the convective transport of pollutant through the porous medium.

Though the currents irregularity is actually not a turbulent one, approaches well developed for the problems of turbulence (eddy diffusivity, statistical theories, etc.) are seminal for the problem outlined.

Cancellation exponents in helical and non-helical flows

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Helicity is a quadratic invariant of the Euler equation. As the energy, in helical flows helicity cascades to smaller scales where it dissipates. However, the role played by helicity in the energy cascade is unclear. In non-helical flows, the velocity and the vorticity tend to align locally creating patches with helicity. Being a non-positive definite quantity, global studies considering the scaling of its spectrum in the inertial range are inconclusive.

In both helical and non-helical flows, helicity changes sign rapidly in space. In order to measure fast oscillations in sign of a field on arbitrary small scales, the cancellation exponent was introduced by Ott et al. The exponent is a measure of sign-singularity and can be related to the fractal dimension and to the first order scaling exponent. We present studies of the cancellation exponent for helical and non-helical hydrodynamic flows. Flows with different forcing functions and at different Reynolds numbers are studied. We show that the cancellation exponent is useful to study scaling laws in quantities that present fast fluctuations around zero.

Dynamics on shocks and the optimal transport problem

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Viscosity solutions of the Burgers equation and more general the Hamilton-Jacobi equations are closely related to the dynamical properties of the minimizers for the corresponding Lagrangian action. However, most of the characteristics are merging with shocks. In this talk we shall discuss how the dynamics of such trajectories can be naturally defined after such a merger. In the one-dimensional case the problem is simple since the shocks are isolated points. On the contrary, in the multi-dimensional situation the shock manifolds are submanifolds of a finite co-dimension which allows for a rather non-trivial dynamics. Although the velocity field has jump discontinuities on shocks, one can determine, essentially in a unique way, the effective velocity field on the shock manifold. The effective dynamics have interesting connection with the optimal transport problem.

The kinematic instability in nonstationary gasdynamics

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It is known that the growing small perturbations carries the exponential nature in a stationary gasdynamics. The self-similar (automodel) solution of the all-round compression (expansion) is unstable in nonstationary gasdynamics. This instability carries the power-mode nature and depends on equations of the state. It is analysed uniform, isotropic, automodel decision: $U(r,t) = (r/R(t))U(R(t))$, $U(R(t)) = \text{const}$, $\rho(t) = \rho(0)(R(0)/R(t))^{q+1}$, $P(t) = P(0)(R(0)/R(t))^{(q+1)\gamma}$. Here $R(t)$ is the external radius, $U(r,t)$ is velocity, $P(t)$ is pressure, $\rho(t)$ is density, and γ is adiabatic factor, while $q = 0, 1, 2$ corresponds to plane, cylindrical, and spherical geometries.

The compression is unstable for $\gamma < 5/3$ for spherical, for $\gamma < 2$ for cylindrical and for $\gamma < 3$ for plane geometries, correspondingly. The instability of the isothermal compression depends on the wavelength of the perturbations. The perturbations $\Delta\rho/\rho$ grow slowly:

$$\Delta\rho(t)/\rho(t) \sim (\Delta\rho(0)/\rho(0))(\rho(t)/\rho(0))^{\alpha},\ \alpha = 0.5(q + 1)^{-1} - 0.25(\gamma - 1)$$

The expansion is unstable where firm compression is stable and conversely. This instability is weak, however. For instance, for $\gamma = 4/3$, if the spherical compression density will increase 10,000 times, than the initial perturbation will increase only by a factor of $10^{1/3}$. As it is shown, the same situation exists in the nonstationary isotropic turbulences: all-round compression isotropic turbulences is unstable for $\gamma < 5/3$, and the expansion - for $\gamma > 5/3$.

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Quantum and classical turbulence in superfluids

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Turbulence in superfluid liquids, such as He-4 and He-3 at very low temperatures, is an intriguing physical problem because it comprises a system where the classical physics gets gradually transformed into the quantum one during the energy cascade from large to small scales. Recent progress in experimental and computational techniques has led to (at least) a conceptual understanding of classical and quantum limits of the superfluid turbulence. In this talk we will describe recent attempts to shed light on the physics of the superfluid turbulence behavior in the intermediate region near the classical-quantum crossover scale. We will see that transition of the turbulent energy cascade from the classical to the quantum scale is accompanied by a change from strong hydrodynamic to weak wave turbulence, and this, in cases where the turbulence is produced by “classical means”, is accompanied by a bottleneck stagnation of energy at the crossover scale.

The helicity cascade in isotropic and homogeneous turbulence

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Helicity is a quadratic invariant of the Euler equations in three dimensions. As the energy, helicity cascades to smaller scales where it dissipates. However, the role played by helicity in the energy cascade is still unclear. In non-helical flows, the velocity and the vorticity tend to align locally creating patches with opposite signs of helicity. In helical flows helicity also changes sign rapidly in space. Being a non-positive definite quantity, global studies considering its spectral scaling in the inertial range are inconclusive, except for cases where one sign of helicity is dominant. We present studies of the helicity cascade in direct numerical simulations of turbulent flows up to spatial resolutions of 1024^3 grid points and under different mechanical forcings. We consider the shell-to-shell energy transfer and structure functions. We show that after doing the SO(3) decomposition, helical and non-helical flows show the same scaling in the inertial range for all orders computed, independently of the helicity content. Finally, we use the cancellation exponent to characterize the scaling laws followed by helicity fluctuations in helical and non-helical flows. The exponent is a measure of sign-singularity and in some cases can be related to the fractal dimension as well as to the first order scaling exponent of the helicity. The results show that the statistics and scaling laws followed by helicity fluctuations are independent of the global helicity of the flows, and confirms that the geometry of helical structures is filamentary.

On temperature in a rotating gas tube

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On the 11th of May 1942 P. A. M. Dirac wrote to R. E. Peierls after joining his research group in the UK atomic bomb project identified by the code name "Tube Alloys": "*I have written up my work about the circulation in a self-fractionating centrifuge and have enclosed it forthwith. I have not done any calculations on the effect of temperature variations along the tube, but I believe the effect is important and someone should work it out.*" [1]

The present paper is devoted primarily to the temperature effects predicted. Based on the general construction [2], a new *exact solution* of the system of mass, momentum, and energy conservation laws is obtained for a viscous and heat conductive normal gas mixture.

The gas is rotated with a cylindrical envelope with no-slip boundary conditions. It is heated with the viscous dissipation due to the angular velocities of ends $\upsilon_{\pm}$.

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Freak waves and modulational instability in ocean

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A freak wave in ocean is a catastrophic event when energy and momentum of the wave field spontaneously concentrate in a localized area of space generating a short wave-train consisting of several (typically three) waves with energy and momentum density, an order of magnitude exceeding the background level. The freak waves could be disastrous for ships, drilling platforms, lighthouses and other coastal constructions. The train of freak waves (freakon) is a quasisolitonic solution of the Euler equation. It can propagate for a long distance, but usually its lifespan is short due to wave- breaking. The freakons could demonstrate a complicated inner dynamics, both quisiperiodic or chaotic.

The freakons appear as inevitable nonlinear stage of the modulational instability for the finite amplitude Stokes waves. The freakons are generated also by narrow-band spectra of waves of moderate steepness. We performed more than 10,000 numerical experiment and calculated PDF for freakon appearance for spectra of different steepness and spectral width.

Tutorial: Utility of topological ideas for wave interactions on vortices: wave energy and wave-induced mean flow

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Target audience: graduate

A steady incompressible Euler flow is characterized as a 'stationary point' (an extremum) of the total kinetic energy with respect to perturbations constrained to an isovortical sheet. An isovortical perturbation preserves vortex-line topology and is expressible only by the Lagrangian variables. We show how topological ideas help to calculate nonlinear interaction of three-dimensional waves on vortices. The Lagrangian approach is indispensable for calculating nonlinear quantities, being quadratic in amplitude, such as the wave energy and the mean flow induced by nonlinear interaction of waves, and serves as a new mathematical machinery to calculate transport property associated with vortex-wave interactions, nonlinear instability of vortices and hopefully transition to turbulence. Our theory owes to the non-canonical Hamiltonian structure of the Euler flows whose character is shared by a diversity of fields as represented by plasmas and Earth sciences. This lecture focuses on fundamentals of the Hamiltonian character of waves.

Tutorial: Burgers turbulence and KPZ scalings

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Target audience: graduate and professional

In this tutorial we shall describe the basic facts of the theory of Burgers turbulence. While the statistical behavior in the case of periodic boundary conditions is well understood, there are still many interesting open questions in the non-compact setting. The theory is closely related to the problem of KPZ scalings and the random matrix theory. We shall also discuss the cases where the mathematical analysis is possible due to special statistical properties of the forcing potential.

STOCHASTIC PROCESSES and PROBABILISTIC DESCRIPTION

Large-scale flows in natural and mixed convection

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Convective turbulence in closed volumes is associated with large-scale circulations of the flow (LSC). They depend sensitively on the geometry and the physical parameters, such as Rayleigh and Prandtl numbers. Here, we consider two systems: natural convection in cylindrical cells and mixed convection in a complex rectangular setting with local heat sources. While the former represents a typical laboratory experiment, the latter mimics indoor ventilation problems as present in a passenger cabin of an airplane. The LSC and the amount of heat transferred through both systems is determined by a so-called proper orthogonal decomposition (POD) of the turbulent fields. We apply the so-called snapshot method to extract the modes from DNS data. The most energetic POD modes give us insight into the dynamic dominance of coherent flow and temperature patterns, and how well the original inhomogeneous flow can be modeled with a reduced number of modes in a low-dimensional model. For example, in case of the cylindrical cell the primary POD mode transfers about half of the total amount of heat through the vessel. The influence of the geometry and the inflow conditions in the mixed convection case on these large scale circulation structures is also addressed.

The dynamics of droplets bouncing on a liquid interface: a macroscopic type of wave-particle duality

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It was first pointed out by Michael Berry [1] that similar phenomena can be observed in surface waves and in quantum waves. However, the behavior of the fundamental objects of physics at quantum scale is dominated by the wave-particle duality. This characteristics is usually thought to have no equivalent in macroscopic physics where mass-like objects and waves are distinct entities. We have shown recently [2-4] that a droplet bouncing on a vertically vibrated liquid interface can become dynamically coupled to the surface wave it excites. It thus becomes self-propelled symbiotic object we have called “a walker” formed by the droplet and its associated wave.

Through several experiments we will address one single central question. How can a continuous and spatially extended wave have a common dynamics with a localized and discrete droplet? We will show that in all cases (diffraction, interference, tunneling. etc.) where the wave is split the droplet has a random response but that a deterministic behavior, due to the wave, is statistically recovered when the experiment is repeated.

For instance we observe a type of "single particle" diffraction (or interference) phenomenon [5]. Passing through a slit, a walker is deviated in an apparently random direction but when the experiment is repeated fringes show-up in the probability of deviation. Similarly, an analog to the tunneling effect can be observed: a walker can with a non zero probability escape out of a trap with walls of finite thickness.

We will show how these properties result from the non-local properties of the walkers and how the truncation of the wave can generate a "Fourier uncertainty" on the drop's motion. The limits in which these results can be compared to those at quantum scale will be discussed.

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Anomalous transport and reactions in turbulent flow

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The theory of anomalous transport is well-established and leads to the integral equations or the alternative fractional diffusion equations for number densities. Despite the progress in understanding the anomalous transport most work has been concentrated on the passive density of the particles, and comparatively little is known about the interaction of non-standard transport with chemical reactions.

This work is intended to address this issue by utilizing the random walk techniques in order to model the anomalous transport with reactions in turbulent flow. In particular, we apply the concept of a random time which allows us to obtain a super-diffusion of tracer particles without an assumption of the heavy-tails for a jump density. We use the "random time" as a probabilistic model for the stochastic intensity of non-homogeneous turbulent flow. We derive the mesoscopic integro-differential equations for the number densities that take into account the memory effects and long-range interactions. We find that the reaction and anomalous transport are not separable, that is, their combined influence on the rate of change of the densities is not additive.

Analyzing transient turbulence in a stenosed carotid artery by proper orthogonal decomposition

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Atherosclerotic plaques inside an arterial wall result in a local occlusion of the artery lumen - a stenosis. The stenosis may trigger transition to turbulence and the onset of turbulence downstream of severe occlusions has been observed in the laboratory experiments. Flow in a stenosed carotid artery has been studied experimentally and numerically by many authors. We have performed model-free, high-resolution three-dimensional simulations (involving 100 million degrees of freedom) to study transient turbulent flow in a carotid arterial bifurcation with a stenosed internal carotid artery (ICA). The geometrical model of the arteries was reconstructed from MRI images, and *in vivo* velocity measurements were incorporated in the simulations to provide inlet and outlet boundary conditions. Due to high degree of the ICA occlusion and variable flow rate, a transitional and intermittent flow between laminar and turbulent states was established. Time- and space-window Proper Orthogonal Decomposition (POD) was applied to quantify the different flow regimes in the occluded artery. A simplified version of the POD analysis that utilizes 2D slices only - more appropriate in the clinical setting - is also investigated.

Evidence of turbulence power laws from image data

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Based on energy cascades describing the multi-scale structure of turbulent motion, we propose an inverse motion modeling method able to infer the most evident power laws model given some image sequence. Inference relies on the spatial regularization principle, used in image velocimetry techniques in order to cure the ill-posed inverse motion estimation problem. Regularization is adapted here to the case of power laws behaviors occurring in bi-dimensional or quasi bi- dimensional flows: motion increments are constrained to behave through scales as the most likely self-similar process given the data. More precisely, in a first level of inference, motion estimation formulated as a hard constrained minimization problem is optimally solved by taking advantage of Lagrangian duality. It results in a collection of first-order spatial regularizers acting at different scales. This estimation is non-parametric since

the optimal regularization parameters at the different scales are obtained by solving the dual problem. In a second level of inference, the most likely self-similar model given the data is optimally selected by maximization of Bayesian evidence. The motion estimator accuracy is first evaluated on a synthetic image sequence of simulated bi- dimensional turbulence and then on a real meteorological image sequence. Results obtained with the proposed physical based approach exceeds the best state of the art results. Furthermore, selecting from images the most evident power law model enables the recovery of energy dissipation rate and other physical quantities which are of major interest for turbulence characterization.

Probability distribution function for self-organization of shear flows

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Understanding multi-scale interactions is an outstanding problem in turbulence. Despite complex nonlinear dynamics, coherent structures such as shear flows often form from small-scale turbulence, which then feed back on small-scales. A remarkable consequence of this mutual interaction is self-organization, which provides a powerful paradigm for understanding complexity in many systems (e.g., population, forest fires, reaction-diffusion). In particular, self-organization has emerged as one of the key physical processes governing transport and mixing in plasmas, with a growing body of observational evidences. A non-perturbative statistical theory [probability distribution functions (PDFs)] is absolutely necessary for a proper modeling of self-organization due to inherent intermittency, instead of traditional mean-field theory based on Gaussian distribution.

Here we present a novel statistical theory of self-organized shear flows, modeled by a nonlinear diffusion equation driven by a stochastic forcing. A non-perturbative method based on a coherent structure is utilized for the prediction of the PDFs, showing strong intermittency with exponential tails. We confirm these results by numerical simulations. The predicted power spectra are also in a good agreement with simulation results. Our results reveal a significant probability of supercritical states due to stochastic perturbation, which could have crucial implications, in transport in many systems. To elucidate a crucial role of relative time scales of relaxation and disturbance in PDFs, we present numerical simulation results obtained in a threshold model where the diffusion is given by discontinuous values.

Our results highlight the importance of the statistical description of gradients, rather than their average value as has conventionally been done. We discuss some of the important implications of these results for the dynamics of shear flows in fluids, which is vital not only in momentum transport, but also in transporting chemical species.

What can be simulated by using particles with mixing and competition?

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Physical similarity and mathematical equivalence of continuous diffusion and particle random walk forms one of the cornerstones of modern physics and the theory of stochastic processes. In many applied models used in simulation of turbulent transport and turbulent combustion, mixing between particles is used to reflect the influence of the continuous diffusion terms in the transport equations. We show that the continuous scalar transport and diffusion can be accurately specified by means of mixing between randomly walking Lagrangian particles.

Recent successes in computationally efficient modeling of turbulent combustion is related to introduction of Sparse-Lagrangian models where the number of Lagrangian particles used in simulations is insufficient for evaluating average quantities locally at every point. The sparsely distributed particles can still be accurate in specifying stochastic properties of the scalars provided a high-quality mixing model is used in simulations. Stochastic particles with properties and mixing can be used not only for simulating turbulent combustion but also for modeling a large spectrum of physical phenomena; for example, these particles can model some features of gene diffusion in a selected population.

Traditional mixing is conservative: the total amount of scalar is (or should be) preserved during a mixing event. It is worthwhile, however, to consider a more general mixing which does not posses these conservative properties. In non-conservative mixing the particle post-mixing average becomes biased towards one of the particles participating in mixing. The extreme form of non-conservative mixing can be called competition: after a mixing event the looser particle simply receives the properties of the winner particle. The particle with non-conservative mixing can be used to emulate various phenomena. In particular we will investigate so-called leaping cycle attributed to behavior of complex systems with competition.

Long-time behavior of stochastic flows

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We review various results on the evolution of points and sets carried by stochastic flows. In particular, we report on the results (obtained jointly with D. Dolgopyat and V. Kaloshin) concerning the long time behavior for a typical realization of the stochastic flow. We prove the Central Limit Theorem for the evolution of measures carried by the flow, which holds for almost every realization of the flow. We show the existence of a zero measure but full Hausdorff dimension set of points that escape to infinity at a linear rate. Also, in the 2-dimensional case, we study the set of points visited by the original set by time t. Such a set, when scaled down by the factor of t, has limiting non-random shape.

Hybrid stochastic-statistical strategies in climate science

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Discussion on systematic mathematical strategies for low-dimensional statistical-stochastic mode reduction for turbulent large dimensional dynamical systems and their application to modeling low frequency weather dynamics, prediction, and climate change. A remarkable fact of Northern Hemisphere low frequency variability is efficiently described by only a few teleconnection patterns that explain most of the total variance. These few teleconnection patterns not only exert a strong influence on regional climate and weather, they also relate to climate change. These properties of teleconnection patterns make them an attractive choice for climate models with a highly reduced number of degrees of freedom. The development of such reduced climate models involves the solution of two major issues: 1) how to properly account for unresolved modes, a.k.a. the closure problem; and 2) how to define a small set of basis functions that optimally represent the dynamics of the major teleconnection patterns.

Examples of stochastic mode reduction ranging from an explicit solvable pedagogical example with three modes to a prototype atmospheric general circulation model with a thousand degrees of freedom where an effective reduced stochastic model with only ten low frequency modes captures the statistical dynamical behavior. A controversial topic in the recent climate modeling literature is the metastable low-frequency regimes in the atmosphere occur despite nearly Gaussian statistics for these planetary waves. A simple 57-mode paradigm model for such metastable atmospheric regime behavior is introduced and analyzed through hidden Markov model (HMM) analysis of the time series of suitable low-frequency planetary waves. The analysis of this paradigm model elucidates how statistically significant metastable regime transitions between blocked and zonal statistical states occur despite nearly Gaussian behavior in the associated probability distribution function and without a significant role for the low-order truncated nonlinear dynamics alone; turbulent backscatter onto the three-dimensional subspace of low-frequency modes is responsible for these effects.

Tutorial: Concrete problems of chaotic and clustering time-series analysis

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Target audience: graduate

I. Chaotic time-series analysis:

1. Spectral discrimination between chaotic and stochastic (turbulent) time-series
    1.1 Exponential and power-law broad-band spectra
    1.2 Time-series related to low dimensional dynamic systems
    1.3 Time-series related to infinite dimensional dynamic system
    1.4 Singularities at complex times and the exponential spectra
2. Hidden periods of chaotic time series
    2.1 Chaotic dynamics of atmospheric CO_2 and glaciation cycles
    2.2 Global temperature anomaly at millennial timescales
    2.3 Chaotic Sun.

II. Cluster analysis of turbulent (stochastic) time-series:

1. Telegraph approximation of turbulent signals
2. Clustering and scaling: cluster-exponent
3. Clustering and intermittency
4. Clustering and spectral simulations: Gaussian stochastic signal
5. Clustering in sunspots number and in interplanetary magnetic field: modulation by Photospheric convection
6. Isotherms clustering in cosmic microwave background and primordial turbulence.

Tutorial: Fractional kinetics

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Target audience: graduate and professional

The tutorial will start with the description of the famous St. Petersburg paradox demonstrating unusual properties of a random distribution with a diverging mathematical expectation, and the formulation of “Levy flights”. Next, the continuous time random walk is considered. It is shown that slow decay of the waiting time and step length distributions may lead to unusual, fractional, kinetics and anomalous diffusion processes, governed by equations containing fractional partial derivatives.

In the second part of the tutorial, we discuss the applications of the fractional kinetics to the turbulence theory, and present some other applications of that approach in physics, chemistry and biology. In conclusion, we discuss the extensions of the theory, specifically the phenomenon of strong anomalous diffusion and its relation to multifractality. The tutorial would foster the application of innovative approaches for tackling the fundamental aspects of the problem, which is formulated as one of the objectives of the TMB.

ADVANCED NUMERICAL SIMULATIONS

On modeling of Saffman-Taylor instability with regularization

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We consider a low viscosity fluid with the permeability $k = k_0 = const > 0$ is injected into a more viscous one with $k = k_1 = 5k_0$, in a porous medium, $\rho_t + \nabla \cdot \rho \mathrm{u} = \nabla \cdot lc \nabla \rho / 2$, $k\mathrm{u} = \nabla p - \rho g \mathrm{k}$, $\rho - \rho_0 = \beta(p - p_0)$, with holes and constant gravitational acceleration g and atmospheric density ρ_0 and pressure p_0. Here, l and c are characteristic scale and velocity for a porous medium that form the proper *regularization* in the right-hand side of the mass balance equality, β is the volume expansion coefficient [1]. When based on some earlier constructions [2], we obtain the required instability.

[1] P. G. Saffman and G. I. Taylor, The penetration of a fluid into a porous medium or Hele-Shaw cell containing a more viscous fluid, Proc. Royal Society, 1958, V. 245, P. 312-329; [2] M. S. Belotserkovskaya, Modeling of filtering with nested grids, Candidate's Dissertation in Mathematics and Physics, Lomonosov State University, Moscow, 2007.

Transition to chaos: numerical experiment

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Numerous investigations of flows at high Reynolds number show *distinctly* the Large Ordered Structures (LOS) that contain stochastic cores of the Small Turbulence (ST). This approach can also be used for description of "residual" coherent structures of bifurcation origin (dynamic structures). Numerical simulations of that phenomena give rise to a very complex problem to provide the full resolution of turbulent cores from maximum to minimum scales even with the help of the modern super computers.

Our approaches is based on the weak dependence of the LOS on the Reynolds number and consists mainly in the Direct Numerical Simulation (DNS) of the main mixing nonlinearity that is covered basically by the hydrodynamics of an ideal fluid where the account is paid for the dissipation produced with ST.

The lecture provides an original approach in the research of structural analysis of free shear compressible turbulence developed through the instabilities at high Reynolds numbers on the base of DNS and related mechanism of dissipation (FLUX dissipative monotone "upwind" difference schemes). It *does not use any explicit sub-grid approximation and semi-empirical models of turbulence*.

As this takes place the convective mixing is considered to be a principal part of conservation laws. Appropriate hydrodynamic instabilities (free developed shear turbulence) are investigated from a unified point of view. The point is based on the concept of large ordered structures with stochastic core of small scale developed turbulence ("turbulent spot"). The decay of the "turbulent spot" is simulated by the Monte Carlo method.

We try to analyze some of the scenarios of the transition to chaos while employing such *realistic* and *complete models* as the Kolmogorov flow, the wind-induced ocean flows, the stratified flows (S. O. Belotserkovskii) and evolutions of the Rayleigh-Taylor, Richtmyer-Meshkov or Kelvin-Helmholtz instabilities in the real time.

During the conducting of numerical experiments a special attention had been paid for the topology of the contact boundary, the problem of the increased depth of mixing and other questions coming into existence in the modeling of the nuclear reaction processes where the turbulent mixing zone play usually main part and demands the use of small scale grid and cells of different forms.

Results of calculations would have been used as well in modeling of such phenomena as catastrophes including tornado and forest fare. The related codes had been produced directly by A. M. Oparin, L. M. Kraginskii, A. V. Konukhov and S. V. Fortova. They could be used in understanding of the main nuts and bolts of such a complex phenomenon as turbulence [1, 2].

[1] O. M. Belotserkovskii, A. M. Oparin and V. M. Chechetkin. *Turbulence: New approaches,* CISP, Cambridge Int. Science Publishing Ltd, 2005; [2] O. M. Belotserkovskii, *Constructive Modeling of structural turbulence and hydrodynamic instabilities*, Singapore: World scientific Publishing, 2008.

Lag modeling of subgrid-scale dissipation in Large Eddy Simulation

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Modeling the dissipation terms in transport equations for subgrid-scale (SGS) energy or SGS scalar variance is of high importance in LES of non-homogeneous flows, such as atmospheric flows or combustion. We propose a new approach to model these terms, based on averaging of source terms along Lagrangian trajectories. This approach results in addition of two transport equations to the system. A-priori tests show good prediction of the SGS energy dissipation rate. Work in progress is the extension of the approach to modeling of the SGS dissipation of a scalar variance. Results of a posteriori tests for various non-equilibrium flow conditions will be shown.

Simulations and model of the nonlinear Richtmyer-Meshkov instability

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The nonlinear evolution of the Richtmyer-Meshkov (RM) instability is investigated using numerical simulations with the FLASH code in two-dimensions (2D). The purpose of the simulations is to develop a nonlinear model of the RM instability that is accurate to the regime of inertial confinement fusion (ICF) and ejecta formation, namely, at large Atwood number A and initial amplitude kh_0 of the perturbation (k is the wave-number). The FLASH code is first validated by obtaining excellent agreement with RM experiments well into the nonlinear regime. The results are then compared with a variety of nonlinear models that are based on potential flow. We find that the models agree with simulations for moderate values of A and kh_0, but not for the values characteristic of ICF and ejecta formation. As a result, a new nonlinear model is developed that captures the simulation results consistent with potential flow and for a broader range of A and kh_0.

On vortex cascades in shear flow instabilities

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In this poster we present new results obtained in numerical modeling of the vortex cascade phenomenon in an unstable shear flow [1,2]. We have discovered that the cascade *comes into existence* in case that the following conditions are met:

(1) The width (Z) of the channel is more that $\pi/2$;

(2) The length (Y) of the channel is more than $7\pi/4$;

(3) The amplitude of initial disturbances is more than 2% of the shear velocity U.

In subsequent experiments we plan to make a thorough investigation of general conditions that result in formation of vortex cascades. We will analyze the influence on the shear flow provided by various initial conditions, dimensions of the integration domain, and many other parameters.

[1] O. Belotserkovskii, S. Fortova, A. Oparin, et al., The turbulence in free shear flows and in accretion disks, in “Investigations of Hydrodynamical Instability and Turbulence in Fundamental and Technological Problems by Means of Mathematical Modeling with Supercomputers”, Final report of RFBR/JSPS Collaborative Research Program, ed. By O. Belotserkovskii, Y. Kaneda and I. Menshov, Nagoya University, Nagoya, Japan, 2007, p. 229-241; [2] S. V. Fortova, The Cascade mechanism in free shear flows, 24^{th} International Conference on Interaction of Intense Energy Fluxes with Matter, March 1-6, 2009, Elbrus, Russia.

Numerical simulation of reacting flows using spectral deferred corrections

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Numerical simulations of turbulent mixing in reacting flows frequently require capturing advection, diffusion, and reaction processes, which can have time scales that differ widely. Traditional approaches all have shortcomings that can lead to excessive computational costs in many cases of interest. Fully implicit methods require the simultaneous solution of (typically nonlinear) equations that couple each term in the system, and the computational cost of solving these equations can be prohibitively large. Fully explicit methods, where the time step is controlled by the fastest process, can require too many time steps. Operator slitting methods allow for the use of a mix of implicit and explicit methods; however the splitting errors can be so large that prohibitively small time steps are still needed.

An alternative to operator splitting is a class of methods called Spectral Deferred Corrections (SDC). The basic idea of SDC methods is to represent temporal evolution as an integral in time and develop algorithms that iteratively couple different physical processes, thus reducing the splitting error. This work explores the use of SDC methodology in two-dimensional simulations of reacting flows. The results from simulations using SDC are presented and their performance is compared with that of Strang splitting.

Turbulent mixing, transport and subgrid models

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We propose a departure from conventional methods of computational modeling. More precisely, we combine two distinct themes and add additional ideas. The result will allow accurate simulation of macroscopic mixing variables as well as microscopic or molecular level mixing, with feasible grid resolution, well short of full DNS resolution.

We combine the dynamic subgrid models proposed by Moin and coworkers with the high resolution methods favored by the capturing community, and to this we add our front tracking approach, which carries the high resolution further. We improve the front tracking, to allow non zero mass diffusion across an interface, but only as given by the physical transport parameters, without numerical diffusion.

These ideas have been verified in an extensive 2D numerical study of a Richtmyer-Meshkov instability including reshock. For the Richtmyer-Meshkov problem, the macroscopic variables such as the mixing zone edges, are shown to be insensitive to physical and numerical modeling of laminar and turbulent transport, but the molecular level mixing observables such as the joint PDF of temperature and concentration, or the chemical reaction rate of temperature sensitive process is very sensitive to these effects. For the problem considered, the chemical reaction rate is subject to statistical fluctuations even after a spatial average, a fact which obscures and interferes with a mesh convergence study.

At least in a form without the subgrid models, these ideas have been validated by the simulation of 3D Rayleigh-Taylor instabilities, in agreement with experiment. In this case both the micro and the macro observables (including the famous mixing rate parameter alpha) are sensitive to laminar and turbulent physical and numerical modeling issues.

We are pleased to acknowledge the joint efforts of a team of collaborators from Stony Brook University, Los Alamos National Laboratory, and Brookhaven National Laboratory, and especially of many very talented students who carried out much of the reported work.

A turbulent mixing Reynolds stress model fitted to match linear interaction: analysis predictions

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In order to predict the evolution of turbulent mixing zones developing in shock tube experiments with different gases, a turbulence model must be able to reliably evaluate the production due the shock/turbulence interaction. In the limit of homogeneous weak turbulence, the “linear interaction analysis” (LIA) can be applied. This theory relies on Kovasznay's decomposition and allows the computation of the waves transmitted or produced at the shock front. With assumptions about the composition of the upstream turbulent mixture, one can connect the second-order moments downstream from the shock front to those upstream through a transfer matrix depending on the shock strength.

The purpose of our work is to provide a turbulence model that matches LIA results for the shock/turbulent mixture interaction. Reynolds Stress Models (RSM) with additional equations for the density-velocity correlation and the density variance are considered here. The turbulent states upstream of and downstream from the shock front calculated with these models can also be related through a transfer matrix provided that the numerical implementation is based on a pseudo-pressure formulation. Then, the RSM should be modified in such a way that its transfer matrix matches the LIA one. Using the pseudo-pressure to introduce ad hoc production terms, we are able to get a quite close agreement between LIA and RSM matrices for any shock strength and thus improve the capabilities of the RSM.

On implicit Large Eddy Simulation of material turbulent mixing

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In the large eddy simulation (LES) approach the large energy containing structures of turbulent flows are resolved whereas the smaller, presumably more isotropic, structures are filtered out and their unresolved subgrid scale (SGS) effects are modeled. The construction of SGS models for LES is pragmatic and based primarily on empirical information. Implicit LES [1] (ILES, MILES) proposes to effectively rely on the use of SGS modeling and filtering provided implicitly by physics capturing numerics. Extensive work has demonstrated that predictive unresolved simulations of turbulent velocity fields are possible using a class of high resolution, non-oscillatory finite-volume (NFV) numerical algorithms. Popular NFV methods such as flux-corrected transport, the piecewise parabolic method, total variation diminishing, and hybrid algorithms are being used for ILES. Truncation terms associated with NFV methods implicitly provide SGS models capable of emulating the physical dynamics of the unresolved turbulent velocity fluctuations by themselves; the connection of these truncation terms to the physical theory of inviscid dissipation and ultimately to irreversible thermodynamics has been demonstrated. The extension of the ILES approach to the substantially more difficult problem of material mixing by an unresolved velocity field has not yet been investigated numerically, nor are there any theories as to when the methodology may be expected to be successful. Progress in addressing these issues in studies of shock-driven scalar mixing driven by Richtmyer-Meshkov instabilities will be reported in the context of ongoing simulations of AWE's inverse chevron and LANL's gas-curtain shock-tube laboratory experiments.

[1] F. F. Grinstein, L. G. Margolin, and W. J. Rider 2007, Eds., Implicit Large Eddy Simulation: Computing Turbulent Flow Dynamics, Cambridge.

Comparison of different approaches to shock-capturing turbulent flow simulations

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On the basis of simulations of a number of experiments, strengths and weaknesses of two approaches to turbulent flow simulations are discussed: direct numerical simulations that use difference solution of Euler equations, and statistical modeling that uses a finite number of first moments of the joint probability distribution function for turbulent velocity and density fluctuations. Direct 3D numerical simulations were carried out by 3D TREK code [1]. Statistic modeling is performed using the k-ε [2] and the Nikiforov-Kozlov [3] models that belong to RANS models (Reynolds Averaged Navier-Stokes equations).

[1] A. L. Stadnik, A. A. Shanin, and Yu. V. Yanilkin, The Eulerian Technique TREK for Simulation of 3D Hydrodynamic Multimaterial Fluid Flows; VANT. Ser.: Math. Model. Phys. Process. 1994. Issue 4, pp. 71-78; [2] A. R. Guzhova, A. S. Pavlunin, and V. P. Statsenko, Specification of k-ε constants for the turbulence model basing on the direct numerical simulation of the simplest turbulent flows and measurements results; VANT, Ser.: Theor. and Appl. Physics, Issue 3, 2005, pp. 37-48; [3] V. I. Kozlov, Simulations of SW turbulence interaction; Proceedings of the 10 International Workshop on The Physics of Compressible Turbulent Mixing, Paris, 17-21 July 2006, France.

Two validation cases for BHR

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BHR is a RANS model for variable density turbulence which was developed and is under continuous development at the Los Alamos National Laboratory. The model has been tested extensively for the unstable turbulent Rayleigh-Taylor layer, and the model reduces to the well-validated k-epsilon model for the case of the simple shear layer. Here we present results for two other validation cases which are important for applications such as inertial confinement fusion (ICF). The first is shear combined with density gradient in the absence of a body-force (i.e., no buoyancy). This would be encountered, for example, on the sides of a jet which forms due to the ablation of a slug of material in an ICF capsule. The second is the change in the state of the turbulence across a normal shock in isotropic turbulence. Although the shocks encounter in ICF applications will in general have more complex shapes, this flow is the basic building block for any shocked turbulence problem. Careful comparison to experimental and DNS data will be made. Since the available data for validation is quite limited, the talk will conclude with some comments about the outstanding issues to be addressed for future model validation and development.

Implementation of turbulence models in an unstructured hybrid mesh finite volume CFD code and its application for study of a forward facing step

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Most of the practical CFD problems can be solved only when an unstructured grid can be employed. To solve turbulent problems appropriately, fine grids are needed near the no-slip boundaries. Usage of structured grid near the walls enables more accurate discretization of the conservation equations as compared to unstructured grids. This requirement can be achieved by using hybrid grid. Computationally viable scheme for modeling turbulence in industrial applications is the usage of RANS, which divides the instantaneous velocity into a mean velocity and a fluctuating component. In this numerical developmental work, high Reynolds number models and low Reynolds' number models are implemented. The low Reynolds number models do need a very fine grid near wall to capture the gradient. Two of the high Reynolds number models that also have been incorporated are standard *k-ε* model and the standard *k-ω* model, both require wall function treatment and hence coarse grid near the wall. Since the standard model *k-ε* was found to under predict the results, RNG *k-ε* model was also incorporated into the CFD code, which gives good results for the separated flows. The Shear Stress Transport model proposed by Menter utilizes the original *k-ω* model in the inner regions of the boundary layer and switches to the standard *k-ε* model in the bulk flow zone and in free shear regions, taking into account of the both models.

The equations of conservation (mass, momentum and energy) was modified to incorporate the RANS the equations. The set of equations were discretized using Finite Volume Scheme. A good number of benchmark cases were solved and the code has been validated. The code is used to analyze conjugate heat transfer in a forward facing step geometry under turbulent flow conditions. Influence of various parameters such as thermal conductivity ratio, Reynolds number, Prandtl number on the hydrodynamics and heat transfer is analyzed and reported.

On the assessment of Large Eddy Simulation of particle-pair statistics in turbulence

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Subgrid scale (SGS) turbulent motion affects particle-pair statistics of inertial particles in Large Eddy Simulation (LES) of turbulent particle-laden flows. The discrepancies of the statistics of particle motions in LES from those in Direct Numerical Simulation (DNS) are due to a combination of the filtering operation and the SGS model error. The former leads to the missing of SGS velocity and eddies and the latter usually results in a lower prediction of enstrophy spectrum near the cutoff wavenumber and a much smoother vorticity field as compared with that from DNS. The magnitude and extension of the two errors on various particle statistics have not been compared and assessed simultaneously with DNS, filtered DNS and LES in previous studies. The objective of this paper is to quantitatively compare and assess the effects of the two errors on particle-pair statistics in a wide range of particle Stokes numbers using *a priori* and *a posteriori* methods. The results obtained suggest that particle SGS model considering the effects of SGS fluid flow on particle motion should be constructed for particles with small and intermediate Stokes numbers.

BHR-2 simulations of shock-driven instability experiments

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Description of number compressible mixing flows remains a formidable experimental, theoretical, and computational challenge. In this study, we use the BHR-2 (Besnard-Harlow-Rauenzahn) model to simulate a series of experiments of the Richtmyer-Meshkov instability at various Mach numbers. The BHR-2 model is a single-point, multiple-species, compressible turbulence model that uses Reynolds- and Favre-decompositions for fluctuating quantities to describe the flow behavior. The transport equations for second order correlations are reduced, through diffusion-approximation closures and other modeling assumptions, to a set of evolution equations for a restricted set of variables. These additional equations describe the dynamics of the turbulent kinetic energy k, a turbulent length scale S (defined as $k^{3/2}/\varepsilon$, where ε is the dissipation rate of turbulent kinetic energy), the mass flux (drift) velocity a, the density self-correlation b, and the mass fractions of the various species. These equations are integrated numerically as part of the finite-volume-based compressible flow algorithm in the RAGE hydrocode. The RAGE-BHR-2 code has been used to simulate Kelvin-Helmholtz, Rayleigh-Taylor and Richtmyer-Meshkov instabilities in the low Mach number regime. Here, we extend the use of this approach to simulate certain experiments conducted with different gases at several, higher Mach numbers. We examine the BHR-2 model results at both intermediate (Ma ~ 1.5) and higher (Ma > 2) Mach numbers by evaluating the time-dependent growth of the total mixing zone width associated with the various experimental configurations as an integral metric. Based on these results, we speculate on the relative effect of different model input parameters.

Numerical investigation of the turbulent mixing in a converging shock tube

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In this study, we are concerned with physics aspects of three-dimensional Richtmyer-Meshkov instability (RMI) and resulting turbulent mixing phenomena in a convergent geometry. Three layer of two fluids, a heavy gas (sulfur hexafluoride, SF_6) enclosed with a light gas (Helium, He), are initially separated by two surfaces. A feature is imposed at one of these randomly-perturbed interfaces to enunciate the presence of a macroscopic perturbation.

TURMOIL3D, an AWE MILES (Monotonic Integrated Large Eddy Simulations) code, is utilized to numerically investigate the detail of the RMI mechanism in the presence of the feature. Cases with various shock strength are simulated to better understand the RMI physics, turbulent mixing, and to validate turbulent mixing model parameters. In particular, this multi-scale modeling allows the detail of the two-fluid flow to be determined (which may not be easily available from experimental measurements) for the detailed analysis of the He/SF_6/He mixing process based on the simulated results.

In the full paper, we will present simulation results and insights into RMI phenomena in the proposed convergent geometry and in the presence of the feature. The density, mass fraction, vorticity and simulated density Schlieren fields are provided to qualitatively describe the typical mixing process. A comprehensive interrogation of local and global mixing evolution is then performed. Modal characteristics in the mixing layer are further quantified with the spectra of the fluctuating density and kinetic energy, the variances of the density and mass fraction. The perturbed transmitted shock front strongly amplifies the mixing process at the second interface. It is concluded that the discrete feature, in conjunction with the random perturbation, significantly influences the Richtmyer-Meshkov instability and turbulent mixing characteristics.

Turbulence modeling and Large Eddy Simulations for shock-induced instability and transition to turbulence

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Modeling of shock-induced instabilities is pertinent to several engineering and physics problems, including inertial confinement fusion, supersonic combustion and supernova explosion. The authors are involved in the development and application of Large Eddy Simulation (LES) methods and engineering turbulence models for such flows. The present study focuses on the Richtmyer-Meshkov instability (RMI), transition and turbulent mixing, occurring when the interface between two fluids is impulsively accelerated by a shock wave. The aim of this work is to study the applicability of an eddy-viscosity, two-equation (K-L) turbulence model to RMI problems by comparing the results against high-resolution LES data.

High-resolution implicit LES have been conducted for the planar RMI problem with up to 15 million computational cells. The development of the RMI is presented, illustrating the growth of the interface perturbations and enhancement of mixing. The turbulence model employs two differential equations, for the turbulence kinetic energy (K) and the eddy length scale (L). The choice of L as variable for defining the second turbulence transport equation is motivated by the fact that the evolution of RMI is self-similar with the eddy size. In the present case, the mixing is defined by the integral length of the mixing zone (H).

The integral length of the mixing zone obtained by the turbulence model is in good agreement with the ILES results. Results for a range of density ratios for the two fluids, from 3:1 to 20:1, will be presented. More complex situations where multiple shocks pass through the interface will also be considered. Turbulent mixing due to RMI is dependent on the initial conditions. The treatment of initial conditions in the turbulence model is also discussed.

Geometric structure and subgrid-scale modeling in turbulence

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A methodology for the study of the multi-scale, non-local geometry of structures in turbulence will be described. The starting point is a three-dimensional field of any scalar quantity. The approach described consists of three main steps: extraction, characterization and classification of structures defined as scalar isosurfaces. The curvelet transform, which produces a multi-scale decomposition, is used to perform the extraction stage. The characterization and classification steps utilize differential-geometry properties of scale-dependent isosurfaces and their representation in a "feature-space" defined by a set of three reduced geometrical parameters. Several applications will be described that include fields of enstrophy, dissipation and Lagrangian structure obtained from direct-numerical simulation of box turbulence. The Eulerian fields all show a similar transition, with decreasing scale, from blob-like shapes at forced scales, to tube-like and sheet-like structures in the inertial range and finally pancake/sheet geometry at dissipation scales. The observations support a vortex-based, small-scale model of turbulence that can form the basis of a subgrid-scale model suitable for large-eddy simulation. This model will be described and some applications to LES of turbulent channel flow at extremely large Reynolds numbers and to buoyancy-driven mixing flows will be discussed. This LES has a multi-scale character in that it enables extension to subgrid scales of some second-order statistics.

Compressibility effects on single-mode Rayleigh-Taylor instability

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The single-mode compressible Rayleigh-Taylor instability is investigated using numerical simulations on an adaptive mesh, performed with the Adaptive Wavelet Collocation Method (AWCM). Due to the physics-based adaptivity and direct error control of the method, AWCM is ideal for resolving the wide range of scales present in the development of the instability. The problem is initialized consistent to the solutions to the linear stability theory. Of interest are the departure

time from the linear growth, the onset of strong non-linear interactions, and the late-time behavior of the fluid structures. The late time bubble/spike velocities are computed and compared to those obtained in the incompressible case.

Numerical simulations of turbulent flow through a fine screen

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A 3-D numerical model of the turbulent incompressible flow through fine screens (50×25 mesh per inch) was developed. Several turbulence models from the commercial package FLUENT for computational fluid dynamics (CFD) were tested: the standard RNG and realizable k-ε models, the standard and transient SST k-ω models, and the Reynolds stress model (RSM). Numerical results were compared with well documented experimental results for turbulent flow through screens in wind tunnels. The decay of turbulence was predicted well by the SST k-ω model. Numerical modeling of the screen with a SST k-ω model enabled us to draw some conclusions that we used in the numerical model of the screen and in applying a standard k-ε turbulent model to examine the mixing of external, internal and screen flows. Simulation results (pressure loss, tangential force, and production of the turbulent kinetic energy) are incorporated into the numerical model, which is capable of modeling a screen as a virtual screen with source that exerts a drag on the flow and accordingly creates a pressure loss and changes the velocity components. Reduction of velocity components and flow turning were simulated by inputting a force into the momentum equation. The effects of turbulence generation were reproduced by fixing kinetic energy production at the virtual screen. The numerical results yielded by simulation of the screen as a virtual screen agreed well with those of a full numerical model of the screen.

High-order WENO simulation of shock vortex interactions

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In this talk we will first describe algorithm formulation and a few recent developments of finite difference and finite volume weighted essentially non-oscillatory (WENO) schemes for solving hyperbolic conservation law systems. These schemes can provide formal high order accuracy and non-oscillatory shock transitions. They are especially suitable for problems containing both discontinuities and complex smooth structures in the solution, such as shock vortex interactions to be described in this talk, and direct numerical simulation of compressible turbulence.

We will then move on to describe our recent work in applying high order WENO finite difference schemes for simulating shock interaction with vortices.

The interaction between shock waves and vortices is an important phenomenon in aerodynamics and aeroacoustics. When a shock wave meets a vortex or vortices, disturbance is generated, which propagates along the shock wave and results in its deformation. Behind the deformed shock wave, the flow field is compressed and rarefied locally and forms acoustic waves. These interesting phenomena are closely related to the shock-turbulence interaction which is one of the major sources of aerodynamic noise and has attracted a lot of attention in the literature. Our simulation is performed on two and three dimensional compressible Navier Stokes equations with high Reynolds numbers. We will start from the description of shock interaction with a single vortex, and present the multi-stage feature of this interaction. We will then move on to the description of the interaction of a shock wave with an oblique vortex pair, and present the shock dynamics and mechanism of sound generation in this scenario. Next, we will give a more detailed study of shock interaction with a vortex pair, and demonstrate the existence of a linear regime and a nonlinear one. Finally, using three dimensional simulation, we will study the topological structure of shock induced vortex breakdown for the interaction of shock waves with a longitudinal vortex.

Different parts of this work were jointly performed with (a different subset of) the following collaborators: Shufen Jiang, Hanxin Zhang, Shuhai Zhang and Yong-Tao Zhang.

Numerical simulations of the development of regular local perturbations and turbulent mixing behind a shock wave for various shock wave strengths

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The development of turbulent mixing and regular local perturbations (LP) at the air/SF_6 interface behind the front of a shock wave with Mach numbers varying from 1.7 to 9.1 is studied with the 2D EGAK code [1] and the 3D TREK code [2]. Computations were carried out by direct 2D and 3D numerical simulation using no turbulence models. The paper considers cases of 2D LPs of various shapes on the interface of interest, namely: a groove with triangular cross-section (“groove”) and a half-cylinder. Small-size random initial perturbations on the interface were also specified. Results of computations are compared with the known data of experiments by Nevmerzhitsky, et al. [3]. The turbulence parameters are analyzed along with the scheme effects occurring during the numerical simulation.

[1] Yanilkin Yu. V., Belyaev S. P., Gorodnichev A. V., et al. EGAK++ code system for simulation using an adaptable refined computational grid; Voprosy Atomnoi Nauki I Tekhniki (VANT), Ser.: Math. Model. Phys. Process. 2003. Issue1. pp.20-28; [2] Stadnik A. L., Shanin A. A., Yanilkin Yu. V., The Eulerian Technique TREK for Simulation of 3D Hydrodynamic Multimaterial Fuid Flows; VANT. Ser.: Math. Model. Phys. Process. 1994. Issue 4, pp. 71-78; [3] Nevmerzhitsky N. V., Razin A. N., Sotskov E. A. et al., Studying the Development of Turbulent Mixing and Perturbation Growth in Gases of Higher

Compressibility with Mach Numbers 2 to 9 of Shock Waves; Presentation at conference "Zababakhin's Scientific Readings", 10-14 September, 2007, Snezhinsk.

New models to capture evolution of molecular mix and demix in variable-density flows

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Variable-density flows are ubiquitous in nature and can be encountered on a larger scale in astrophysical, geophysical, atmospheric and ocean flows, as well as at smaller scales such as in inertial confinement fusion, combustion in engines, and even in your morning cup of coffee and creamer. Our goal was to capture turbulence physics in variable-density flows previously not modeled or simulated. More specifically, the evolution of density fluctuations and, consequently, the evolution of the molecular mix between fluids, has been incorporated as part of a second generation BHR turbulence model and implemented into the RAGE hydrocode. Results for various types of flows with Atwood numbers ranging from 0.04 to 0.67 are used to demonstrate the improvements in modeling variable-density flows. Additionally, a new model for the species equation has been developed to capture demix between fluids. Initial results from this model also will be presented.

Direct numerical simulation of scalar transfer in regular and fractal grid turbulence

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Turbulent mixing of passive scalar in grid-generated turbulence is investigated by means of the direct numerical simulation (DNS). A turbulence-generating grid was numerically constructed using the immersed boundary method at the entrance to the computational domain, which is 64 M in length 8M × 8M (for regular grid) and 16M × 16M (for fractal grid) in cross section, where M is the effective mesh size of the grids. Two types of grids were simulated: the first one is a regular grid consisting of square-rod, square-mesh and biplane constructions, and the other one is a fractal grid [1,2]. Both grids have the same solidity of 0.36. The Reynolds number based on the mesh size, $Re_M = UM/\nu$, is 2,500 in both flows, where U is the mean velocity and ν is the kinematic viscosity. The scalar mixing layers with an initial step profile develop downstream of the grids. The Prandtl number is 0.71 considering a turbulent diffusion of heat in an air flow. The governing equations are the continuity equation, forced incompressible Navier-Stokes equations and the transport equation for scalar.

To solve the governing equations, we constructed a numerical code based on fully conservative high order accurate finite difference schemes for full staggered grid systems, high order Runge-Kutta scheme for time advancement and Fast Fourier Transform for the Poisson equation of pressure. The results show that turbulent mixing in the fractal grid turbulence is strongly enhanced compared with that in the regular grid turbulence at the same mesh Reynolds number. The budgets of transport equation for scalar variance and turbulent heat flux are computed and compared for two types of scalar mixing in grid turbulence.

[1] Hurst, D., and Vassilicos, J. C., 2007, Scalings and Decay of Fractal-Generated Turbulence, Physics of Fluids, Vol. 19, 035103; [2] Seoud, R. E., and Vassilicos, J. C., 2007, Dissipation and Decay of Fractal-Generated Turbulence, Physics of Fluids, Vol. 19, 105108.

Entropy stable approximations of Navier-Stokes equations with no artificial numerical viscosity

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Entropy plays an important role in the dynamics of nonlinear systems of conservation laws and related convection-diffusion equations. What about the corresponding numerical framework? We present a general theory of entropy stability for difference approximations of such nonlinear equations. Our approach is based on comparing numerical viscosities relative to certain entropy conservative schemes. It yields precise characterizations of entropy stability which is enforced in rarefactions while keeping sharp resolution of shocks.

We demonstrate this approach with a host of first- and second-order accurate schemes ranging from scalar examples to Euler, Navier-Stokes and the shallow-water equations. In particular, we construct a new family of entropy stable schemes which retain the precise entropy decay of the Navier-Stokes equations. They contain no artificial numerical viscosity. Numerical experiments provide a remarkable evidence for the different roles of viscosity and heat conduction in forming sharp monotone profiles in the immediate neighborhoods of shocks and contacts.

The three-dimensional multimode Richtmyer-Meshkov instability

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Previous simulations have shown a late time dependence of the growth rate of a shock-induced turbulent mixing layer on the form of the initial perturbation [1]. This paper presents recent results gained for the Implicit Large Eddy Simulation (ILES) of the Richtmyer Meshkov (RM) instability using narrowband and broadband initial perturbations. Results are gained using two different numerical methods, the third order semi-Lagrangian algorithm “TURMOIL3D” [2] and the fifth-order Godunov method “CNS3D” [3], with grid sizes from 96×64×64 through to 720×2048×2048.

For the narrow band case at A = 0.9 the growth rate exponents are shown to be only marginally higher than that at A = 0.5. Anisotropy persists until late times, however principally in the energy containing large scales. The small scales become isotropic, as demonstrated by the kinetic energy spectra taken in slices in the centre of the mixing layer. The molecular mixing fraction shows that the higher Atwood case has reduced mix efficiency, asymptoting to 0.7 compared to 0.84 for the low Atwood case. The high Atwood case presented is more sensitive to the chosen turbulence modeling approach and multicomponent model.

The broadband simulations are dominated by the superimposed linear growth of the 'just saturated' mode, tending to a power law growth exponent of 2/3 as resolution increases, which is in agreement with the analysis of Youngs [1]. Importantly, the convergence to this growth rate is slow, requiring a wide range of length scales in the initial perturbation to allow self-similar growth for a reasonable length of time. The molecular mix parameter is significantly less than for the narrowband case, asymptoting towards 0.35.

[1] Youngs, D. L., Presented at the IWPCTM 9, 2004; [2] Youngs, D. L., Phys. Fluids A, 3(5):1312/2261320, 1991; [3] Thornber, B., Mosedale, A. , Drikakis, D., Youngs, D., Williams, R., J. Comput. Phys., 227, 4873-4894, 2008.

Rayleigh-Taylor instability with localized perturbations

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The growth of Rayleigh-Taylor instability is determined by initial perturbations to the material surface. Numerous studies have characterized the effect of different perturbation spectra on the growth rate of the RT mixing layers. In this work, high resolution large eddy simulations will be used to study the combined effect of broadband spectral perturbations and localized macroscopic features on RT mixing layer growth. We characterize the lateral spread of the influence of the perturbations, and differences in structure across the surface. The results are compared to both plane RT growth and the evolution of buoyant thermals.

Tutorial: Transport in hydromagnetic turbulence and dynamos

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Target audience: graduate

The goal of the tutorials is to train the students in high-order numerical schemes that are used to simulate turbulence, to determine turbulent transport coefficients, and to compare direct numerical simulations with mean-field models. The course begins with an introduction to high order numerical schemes, the use of the Pencil Code, advection tests, Burgers shock and nonlinear sound waves, energy conservation, Brunt-Väisälä oscillations in a stratified atmosphere, the Roberts flow dynamo, and the turbulent helical dynamo.

Tutorial: An introduction to uncertainty quantification

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Target audience: graduate and professional

Uncertainty Quantification (UQ) is a very young and rapidly emerging field in numerics and should become a valuable tool for studying turbulent flows. It is the next step beyond verification and validation. Many inputs to numerical simulations have errors and uncertainties. These can be related, for example, to parameters of an experiment being simulated, quantities such as equations of state or opacities, grid resolution, or tunable parameters within the numerical code, such as adjustable constants in turbulence models. All of these uncertainties propagate through the simulation to provide uncertainties in the results. The goal is to provide a formal framework for the quantification of errors and uncertainties in numerical simulations. Instead of obtaining a single answer to a calculation, one ends up with a probability distribution for each quantity of interest. Thus each computed value has an associated error bar. If a laboratory experiment is being simulated, the observed values can be compared to the results of the simulation to provide constraints on the uncertainties of the input values.

The first part of the tutorial will present an overview of the basic ideas of uncertainty quantification. This will be followed by details of UQ theory, including the framework of Bayesian statistics. The cost of performing a detailed UQ analysis can be prohibitive unless some care is taken. A number of techniques for reducing the computational cost will be discussed, including the use of emulators and dimension reduction techniques. The number of dimensions in a typical simulation, i.e. the number of uncertain input parameters, can be huge, especially if one considers each value in equation of state tables or opacity tables to be an independent variable, each with its own uncertainty. The cost of the analysis depends on a high power of the number of input parameters, so any reduction in the dimensionality of the problem can provide enormous savings. Since a complete analysis involves a very large number of numerical simulations, each with different values of the input parameters, it is also important to employ methods to intelligently sample the input space. The final section of the tutorial will show an example of the use of UQ taken from the CRASH center at the University of Michigan. The simulations will be of a laser experiment performed on Omega of the formation and propagation of a radiative shock.

This research was supported by the DoE NNSA under the Predictive Science Academic Alliance Program by grant DEFC52-08NA28616.

Tutorial: Implicit Large Eddy Simulation methods

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Target audience: graduate and professional

Methods to simulate turbulent mixing are of crucial relevance to many applications in engineering, geophysics and astrophysics. The extreme flow complexity in typical applications will always require achieving accurate and dependable large scale predictions of highly nonlinear processes with under-resolved computer simulations. Extensive work by Grinstein and collaborators has demonstrated that predictive under-resolved simulations of turbulent velocity fields are possible using any of the class of nonoscillatory finite-volume (NFV) numerical algorithms. This is a new area of research undergoing rapid evolution. Scientific understanding and theory explaining the success of these methods have been proposed and demonstrated: truncation terms associated with NFV methods implicitly provide subgrid scale models capable by themselves of emulating the physical dynamics of the under-resolved turbulent velocity fluctuations. This strategy is called implicit large eddy simulation (ILES).

Tutorial: Concepts and methodology of Large-Eddy Simulation

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Target audience: graduate and professional

This tutorial will consist of a short introduction to the concepts of large-eddy simulation (LES) for the computation of complex fluid-dynamical flows. The presentation will be at a graduate level and will assume a knowledge of both fluid mechanics and the idea of computational fluid dynamics. We will begin by summarizing present-day direct-numerical-simulation (DNS) technology and its limitations both presently and in the foreseeable future. The conceptual basis for LES will then be discussed including ideas underpinning algebraic subgrid-scale (SGS) modeling. Some present-day modeling LES/SGS approaches will then be summarized followed by an outline of their implementation in complex fluid-dynamics codes.

Topics covered will include filtering, resolved and DNS-filtered fields the problem of closure, fluid-dynamical processes for which the dynamics of small scales may be important, the explicit representation of subgrid scales, numerical requirements, testing with canonical flows, LES/SGS of both passive and active mixing, the interaction and coupling of SGS models with numerical algorithms, open problems, the limitations of LES and future prospects.

Tutorial: A short introduction to WENO finite difference, WENO finite volume and discontinuous Galerkin methods and their comparisons

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Target audience: graduate

In this tutorial we will give a short introduction to the algorithm formulation, properties, implementations and applications of three classes of high order accurate schemes suitable for compressible flow calculations: finite difference weighted essentially-oscillatory (WENO) schemes, finite volume WENO schemes, and discontinuous Galerkin finite element method. These are all high order schemes suitable for simulations of convection dominated problems such as compressible flow, including turbulent mixing problems. We will emphasize the practical aspects of these algorithms: their basic formulation, their main mathematical properties, their implementation in different dimensions and meshes, and their relative advantages and disadvantages when comparing among themselves and with other methods.

EXPERIMENTAL DIAGNOSTICS

Dynamics of laser-driven shock waves in solid targets observed with monochromatic X-ray imaging

Y. Aglitskiy (1), M. Karasik (2), A. L. Velikovich (2), V. Serlin (2), J. Weaver (2), A. J. Schmitt (2), S. P. Obenschain (2), J. Grun (2), N. Metzler (3), S. T. Zalesak (4), J. H. Gardner (4), J. Oh (5), and E. C. Harding (6)

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Accurate shock timing is a key issue of both indirect- and direct-drive approaches to laser fusion. The recent experiments on the Nike laser at NRL presented here were made possible by improving the imaging capability of our monochromatic X-ray diagnostics based on Bragg reflection from spherically curved crystals. Side-on imaging implemented on Nike makes it possible to observe dynamics of the shock wave and ablation front in laser-driven solid targets. Recording the images with either frame or streak camera, we can choose to observe a sequence of 2D images or a continuous time evolution of an image resolved in one spatial dimension.

Sequence of snapshots reveals propagation of a shock wave in a 0.5 mm thick solid plastic target driven by a 8 ns long Nike pulse. The frames have been taken using vanadium backlighter at 5.2 keV, with 300 ps exposure time. The shape of the shock wave reflects the intensity distribution in the Nike beam (FWHM Ø750 μm, uniform irradiation in the central area Ø400 μm). The streak records with continuous time resolution have been taken using silicon backlighter at 1.85 keV. One of the records shows the *x*-*t* trajectory of a laser-driven shock wave in a 10% solid density DVB foam. Another record illustrates laser acceleration of a 30 μm thick CH foil across a vacuum gap to collide with a 10% solid density foam layer. Shock compression, acceleration, and shock deceleration of the CH foil plasma after the collision are clearly observed.

This work was supported by the U.S. Department of Energy and U.S. Defense Programs.

Two-dimensional mixing of fluid's surface

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Magnetic microparticles suspended at the water-air interface and subjected to AC external driving self-assemble into dynamic structures (magnetic snakes). The snakes are accompanied by four large hydrodynamic vortices. At high enough frequencies and amplitudes of driving the snakes transform into self-propelled swimmers. Increased particle density results in formation of numerous snakes in the system. Moving erratically, these swimmers mix the surface of fluid at a very high rate. We performed detailed experimental studies of such self-organized mixing. We studied space and time correlation and diffusion process in such systems.

Experimental investigation of a twice-shocked spherical density inhomogeneity

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Results are presented from a series of experiments investigating the behavior of a twice-shocked spherical density inhomogeneity. After initial shock, the spherical inhomogeneity develops into a vortex ring with a velocity different than the shocked particle velocity. This relative velocity is dependent on the vorticity deposited during the initial shock-bubble interaction, which in turn, is dependent on the shock strength and Atwood number of the inhomogeneity.

The incident shock wave reflects off the tube end wall interacts with the translating vortex ring (reshock), resulting in vorticity deposition in the opposite sense to that of the initial vorticity deposition. This lowers the overall circulation of the vortex ring. After reshock, the ambient particle velocity is nearly zero and the subsequent translational motion of the vortex ring is due entirely to the net circulation present and relative translational velocities at the time of reshock. Two Atwood numbers (A = 0.68, 0.17), and three initial Mach number strength (M = 1.35, 2.00, 2.33) are investigated. Experiments are performed in a 9 m-long vertical shock tube with a square internal cross-section of 25.4×25.4 cm^2, equipped with a pneumatically driven retracting bubble injector. High speed cameras operating at 10,000 fps are used to observe the development of the vortex ring after reshock. An understanding of the shock-induced compression and vortex generation is vital to our program's objective of studying combustion initiated by shock focusing phenomena.

Shock tube investigations of the instability of a two-gas interface accelerated by a shock wave

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This lecture sets out the main results of shock tube experiments for investigating the instability of an interface between two gases with different densities accelerated by a shock wave:

1. regularities of the development of initial perturbation of an unstable interface;
2. peculiarities of the discontinuity break-up arising when a shock wave is passing through a perturbed interface of two gases having different densities;
3. development of the instability mechanisms;
4. peculiarities of the development of turbulent mixing of gases at an unstable interface;
5. peculiarities of the instability development when the interface is being accelerated by steady and unsteady shock waves.

The lecture is based on the results of the experiments conducted by and with a direct participation of the author.

The dispersion of lines written in a turbulent jet flow

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We write patterns, such as dots, lines and crosses, in a strongly turbulent air flow by fusing N_2 and O_2 molecules to NO, which is then used as a tracer. This photosynthesis is done in the focus of a strong UV laser (ArF excimer, Lambda Physik, LPX 150). A while (tens of μs) later, the written patterns are made visible through inducing fluorescence with a second (UV) laser. The deformed and dispersed pattern of NO molecules is photographed in the UV using a fast intensified camera. This technique allows us to create tracer patterns at will and with sizes comparable to the smallest length scale in turbulence. This would have been very hard using seeded particles, such as in particle tracking velocimetry. The initial width of our tracer pattern is $\sigma = 50$ μm.

The turbulent flow emanates from a jet, and the turbulent velocity u is varied by varying its plenum pressure. In this manner, the Kolmogorov scale η is varied from η = 50 μm at the smallest turbulent velocity to η = 17 μm at the largest u. Thus; at the smallest u our lines embrace one small eddy, and a few Kolmogorov lengths at the largest *u*. Our written patterns wrinkle and blur due to molecular diffusion and turbulent dispersion. The key question about this combined effect is what we are going to discuss in our presentation: will molecular diffusion enhance or diminish the effect of turbulent dispersion?

High Schmidt number scalar transfer in regular and fractal grid turbulence

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Turbulent mixing of high-Schmidt-number passive scalar in grid-generated turbulence is experimentally investigated by means of the particle image velocimetry (PIV) and the planar laser induced fluorescence (PLIF) technique. A turbulence-generating grid was installed at the entrance to the test section, which is 1.5 m in length and 0.1 m × 0.1 m in cross section. Two types of grids were used: the first one is a regular grid consisting of square-rod, square-mesh and biplane constructions, and the other one is a fractal grid [1-2]. Both grids have the same solidity of 0.36. The Reynolds number based on the mesh size, $Re_M = UM/\nu$, is 2,500 in both flows, where U is the mean velocity, M is the effective mesh size and ν is the kinematic viscosity. Rhodamine B was homogeneously premixed only in the lower stream, and therefore, the scalar mixing layers with an initial step profile develop downstream of the grids. The Schmidt number of the dye (Rhodamine B) is about 1,000. The dye diffusing in the flow was illuminated by a 5 W laser sheet and captured by a digital camera. The pixel number of the camera was 4256 × 2832 and the typical resolution was 4.7 μm/pixel. The results show that turbulent mixing in the fractal grid turbulence is strongly enhanced compared with that in the regular grid turbulence at the same mesh Reynolds number. The spatial spectra of scalar fluctuations show the -1 power decay region, which suggests the Batchelor spectrum.

[1] Hurst, D. and Vassilicos, J. C., 2007, Scalings and Decay of Fractal-Generated Turbulence, Physics of Fluids, Vol.19, 035103; [2] Seoud, R. E. and Vassilicos, J. C., 2007, Dissipation and Decay of Fractal-Generated Turbulence, Physics of Fluids, Vol.19, 105108.

Dispersion of liquid drops under effect of an air shock wave with intensity from 0.2 atm to upto 42 atm

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The authors present results of experiments with study of dispersion of drops of liquid tributylphosphate having diameter ∅ 2 mm under the effect of an air shock wave with intensity from 0.2 atm to upto 42 atm. Experiments were performed with the use of an air shock tube. Shock wave was created by an explosion of a mixture of C_2H_2 + 2.5 O_2, compressed air, or compressed helium.

Registration of the dispersion process was held with the use of high-velocity macro- and microfilming (the Schlieren method and ordinary filming). Macroregistration allowed to register integral picture of the process of drop dispersion and to determine the time of drops evaporation. Microregistration allowed to resolve fragments of liquid with the sizes of ≥ 2 μm and to obtain distribution of spectrum of drop fragments, which is necessary for calibration of the analytical models.

The influence of the Mach number of a shock wave on turbulent mixing growth at the interface

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The authors present results of experimental study of turbulent mixing occurring due to the Richtmyer -Meshkov instability in gases at Mach number's of the shock wave ranging from ≈ 1.4 to ≈ 9.

Experiments were performed with the use of an air shock tube with the channel crossection of 40 × 40 mm. The shock wave passed from "light" to "heavy" gas. Air was used as "light" gas, while Xe, CO_2, SF_6 were used as "heavy" gases. Gases were initially separated by a thin (≈ 1 μm) polymer film, which was destroyed after the shock wave passing. The registration of the flow was accomplished by the Schlieren method using a high-speed camera.

It was found that the width of the mixing zone and the speed of its growth increase with the growth of the Mach number of the shock wave.

Understanding experimental diagnostics and results for code and model validation

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High-resolution experimental measurements of Richtmyer-Meshkov mixing are invaluable for understanding the physics of shock-driven flows, as well as for validating models and simulations. At the gas shock tube facility at Los Alamos National Laboratory, we operate a unique simultaneous Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) diagnostic to measure the velocity and density fields of shocked unstable flows, enabling the calculation of the Favre averaged Reynolds stress tensor in 2D. The current experiments involve the study of a dense curtain of SF6 suspended in air, under single shock and reshock conditions. In order to understand how this flow evolves in time, we take time-series measurements of the density and velocity fields. The experimental data is used to initialize simulations to study the impact of initial conditions on turbulence transition. The turbulence statistics obtained from the experiments (including the density self-correlation) are compared with results from simulations. I will discuss our latest measurements, the physical insights they lend to these flows, and discuss how simulations assist us in our understanding of the experiment and future designs. I will emphasize that consistent collaboration is required to simulate experiments with strong initial condition dependence, but this collaboration is mutually beneficial. The role of 2-D versus 3-D measurements and simulations will be discussed in the context of our latest work.

ICF-related Richtmyer-Meshkov instability: Mach 10 experiments

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Results are presented from experiments performed at the LANSCE Proton Radiography Facility studying the interaction of a planar shock wave of strength M = 10 with a gaseous interface between xenon and helium (Atwood number of 0.94). Because of a large initial density difference between the gases, and the high impact strength of shock wave, these experiments are applicable to Inertial Confinement Fusion (ICF) environments where small capsules containing deuterium-tritium (DT) fuel are compressed by laser-generated shock waves to initiate a very rapid thermonuclear burn. Due to manufacturing limitations, there are small perturbations on the interface between an ablator and the solid DT fuel, and on the interface between solid DT fuel and gaseous DT fuel for ICF. In our experiments, we use an aluminized mylar film of thickness 25 microns and an aluminum mesh (different sizes, e.g. 10 × 10 wires per inch, 0.635 mm wire, with approximately 2 mm gaps) to separate xenon from helium. The mesh serves to seed a prescribed initial perturbation between the gases. We use high explosive (HE) to drive a projectile, which hits the KAPTON wall (approximately 6 microns thick) on the xenon side and generates a planar shock wave that traverses though the xenon toward the mylar membrane. When the shock wave crosses the density interface it drives the formation of Richtmyer-Meshkov instabilities. The subsequent evolving flow field is imaged with proton radiography to measure the instability growth rate and turbulent mixing. The facility is capable of acquiring twenty one high resolution images per shot, that allows us to study the growth of the instability. This is an on-going research program, and so we shall describe the experimental setup in detail and the recent results obtained from our latest experimental efforts.

Experimental techniques for measuring the Rayleigh-Taylor instability in inertial confinement fusion

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In inertial confinement fusion (ICF), a spherical shell is irradiated either directly by a large number of overlapping laser beams (direct drive) or by x rays produced in a high-Z “hohlraum” (indirect drive). During the laser-driven acceleration phase of an implosion, the target compresses while it converges, then decelerates to peak compression as the core is heated to high temperatures, causing a thermonuclear burn within its fuel. Rayleigh-Taylor (RT) instability is one of the major concerns in ICF because target modulations grow in both acceleration and deceleration phases of implosion, which leads to shell disruption and performance degradation of imploding targets. Laser-driven experiments were conducted on the 60-beam OMEGA laser to study the linear, nonlinear, and turbulent mixing regimes of the RT growth. The experiments were performed in planar and spherical, convergent geometries. The linear regime of the instability has been studied by measuring growth of pre-imposed 2-D target modulations below nonlinear saturation levels using X-ray radiography. The nonlinear regime was measured using 3-D modulations with broadband spectra near nonlinear saturation levels. The turbulent mixing regime has been studied using X-ray spectroscopic and nuclear techniques. In this talk, the experimental methods and techniques for measuring RT growth and mix will be reviewed with the emphasis on capabilities of X-ray, neutron, and particle diagnostics. The characteristics of the imaging systems such as noise, sensitivity, and spatial resolution will be discussed. The imaging techniques to determine and separate signal from noise will be described.

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Experimental study of compressible turbulent mixing

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Paper reports summary of experimental studies of compressible turbulent mixing performed for the past two decades at the Interdisciplinary Shock Wave Research Division, institute of Fluid Science, Tohoku University.

Firstly, we will describe shock wave interaction with various gaseous interfaces which were carried out in a 60 mm × 150 mm shock tube equipped with a double exposure holographic interferometry. A highlight of visualization is that instability of a cylindrical helium soap bubble impinged by a planar shock wave in the shock tube. We saw clearly that the experimental setup being two-dimensional, the interfacial instability typically exhibited three-dimensional features.

Secondly, we will explain instability of converging cylindrical shock wave by using an annular coaxial vertical shock tube equipped with double exposure holographic interferometry and its result extended to the shock interaction with cylindrically shaped foreign gas interfaces.

To verify experimentally the effect of the presence of a solid boundary on the interfacial instability mode, we designed and manufactured a spherical test chamber in which a spherical shock wave was generated by explosion of 10 mg of silver azide, was reflected from spherical wall and imploded toward its center. The spherical test chamber having an aspherical outer shape, we could quantitatively visualize, by using a collimated object beam, process of imploding spherical shock wave and its interaction with detonation product gas. Lastly, the preliminary result will be described.

A DNS based Tomo-PIV accuracy assessment

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PIV accuracy depends on a large number of factors (Raffel 1998) and is highly dependent on the flow conditions and experimental setup, making quantification through comparison with previous experiments difficult. Furthermore, there have been relatively few Tomo-PIV accuracy studies and although useful, these often make use of simple ideal flow fields (Elsinga et al 2006, Worth and Nickels 2008). Therefore, to obtain a more representative experimental uncertainty estimate for the flow in the Cambridge large mixing tank facility a set of DPIV and Tomo-PIV simulations have been conducted, using high Reynolds number DNS data as the ideal flow field.

The effects of experimental resolution and noise are examined through the uncertainty in local and global measurements of velocity, vorticity and dissipation, in addition to energy spectra and flow topology comparisons. Both DPIV and Tomo-PIV are found to perform well at high resolution, with a resolution of at least 3 Kolmogorov microscales required for accurate assessment of quantities such as the dissipation rate, and identification of high vorticity magnitude flow structures. The effect of PIV spatial averaging is demonstrated, supporting the dissipation rate corrections proposed by Lavoie et al (2007).

Velocity and concentration fields in turbulent buoyant mixing inside a tilted tube

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Mass and momentum transport in buoyancy driven turbulent mixing of miscible fluids of different densities in a long tilted tube close to vertical has been studied experimentally. Concentration and velocity measurements using LIF and PIV techniques in a vertical diametric plane are reported. Linear profile of the mean concentration and axial velocity are observed in the central part of the tube section together with a non-zero transverse mean flow component suggesting the presence of recirculation cells parallel to the tube axis. Convective momentum transport by turbulent fluctuations is large in the central part of the tube with a maximum on the axis while viscous momentum transport increases and becomes dominant near the walls. The inertial region corresponds to a nearly constant mixing length which allows to reproduce well the corresponding velocity profile by a simple 2D model. The dependence on these flow characteristics of the density contrast and the tilt angle is discussed.

Tutorial: Holographic optical diagnostics of fluid flows

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Target audience: graduate and professional

Holography is an optical imaging method that captures both amplitude and phase information of an optical field by interfering with a known reference field. The resulting intensity pattern, known as a "hologram" or "interferogram," is captured onto an optoelectronic transducer array (e.g., CCD camera) and digitally processed to extract features of interest. In the case of fluid flow diagnostics, relevant information typically includes the velocity of seed particles, obtained by correlation between successive frames. Holography can map the positions of the particles in a three-dimensional (3D) space from the interferogram captured from a single camera frame; whereas in traditional particle image velocimetry, sheet illumination and scanning must be used to resolve 3D positions. The ability to capture a volumetric flow in a single shot is paramount for understanding complex flows and matching measurements to theoretical simulations.

The tutorial is intended to be divided in two one-hour-long sessions. In the first session, we will cover the basics of holography, including the underlying physics and mathematical description. We will discuss typical experimental arrangements, present experimental results from the MIT group and from other groups published in the literature, and discuss certain technological limitations. In the second session, we will establish a connection between optics and fluid mechanics. As a unified theoretical tool, we will introduce the Wigner Distribution Function (WDF), which provides a convenient geometrical way of visualizing optical propagation and understanding sampling and space-bandwidth limitations. We will use the WDF to discuss concepts such as axial and lateral spatial resolution, field of view, and space-bandwidth product in the context of sampling a turbulent flow. We will also discuss the issue of seed particle size and density vis-á-vis accuracy. These last topics are being actively investigated by our research group at present and, hence, many remain open ended; it is hoped that by raising them to an audience of experts in both theoretical and experimental aspects of fluid mechanics, further collaborations and progress will be spawned in this critical field.

Tutorial: A laboratory experiment on colliding plasmas

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Target audience: graduate and professional

Twenty years ago it was inconceivable that one could do laboratory experiments that had any bearing on astrophysical processes. The development of large, quiescent, highly magnetized plasma sources capable of providing interesting background plasmas, coupled with the availability of pulsed commercial lasers with appropriate energy changed all that. Couple this with diagnostics that allow measurement of relevant quantities with great detail in space and time and laboratory experiments that have piqued the interest of some astrophysicists have been done. Carefully planned experiments can have features similar to those in space although the scaling can never be exact. However, there is something to be gained; measurements of quantities such as local magnetic fields can be done in the lab but not for events many parsecs away. When processes that occur closer to Earth are modeled they can be compared with satellite and rocket data. Results can stimulate examination of concepts in a new light. Here we present an experiment in which two plasmas, initially far denser than a background magnetoplasma, collide as they move across a magnetic field. In the course of the interaction many basic plasma processes and waves occur which are underlined and will serve as a springboard for tutorials in the spirit of this summer school. The dense plasmas are formed when laser beams, nearly orthogonal to the background magnetic field strike two targets. The initial high beta plasmas expel the background magnetic fields and create diamagnetic bubbles. Fast Alfvén waves are observed to race across the bubbles and radiate into the background plasma. Electromagnetic turbulence occurs when the bubbles collide. The merging plasmas are observed to shed electrons aligned along the background magnetic field. This spawns the generation of intense lower hybrid waves and solitons and whistler waves in the background plasma. Initial bursts of fast particles evolve into complex, fully three-dimensional, current systems, where the return current is supplied by the background plasma. Magnetic field line reconnection events, magnetic flux forced together by the motion of the currents, occur at many locations throughout the plasma volume and electric fields are induced. The currents in the magnetoplasma are those of Alfvén waves and the physics of these waves plays a great role in the interaction. The magnetic fields and currents derived from them were measured at tens of thousands of spatial locations and as a function of time. They will be displayed in detailed images and movies. The moving dense plasmas churn up the background plasma and generate ion acoustic waves and effect the plasma they move through. The relation of this experiment to several phenomena in astrophysical and space plasmas will be discussed. As a tutorial when observations made in this experiment are presented (diamagnetic bubbles, drift wave turbulence, whistler waves, Alfvén waves, Cherenkov radiation) we will pause to present the basic physics of these phenomena and use previous experiments in which the phenomena were observed as examples.

Tutorial: Cryogenic techniques applied to fluid turbulence

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Target audience: graduate and professional

Fluid turbulence is a paradigm for nonlinear systems with many degrees of freedom and important in numerous applications. Because the analytical understanding of the equations of motion is poor, experiments and, lately, direct numerical simulations of the equations of motion, have been fundamental to making progress. In this vein, a concerted experimental effort has been made to take advantage of the unique properties of liquid and gaseous helium at low temperatures near or below the critical point. Here we discuss the promise and impact of results from recent helium experiments and some interesting new possibilities for studying classical and quantum flows at low temperatures.

The outline of the tutorial:

A. Introduction
- a. Fluid equations and non-dimensional parameters
- b. Low temperature helium as a test fluid
- c. Tunability and scaling
- d. Material properties
- e. Table-top experiments

B. Major results in Helium flows
- a. Hydrodynamic turbulence
  - i. Karman flows
  - ii. Free jets
- b. Thermal turbulence
  - i. Rayleigh-Benard convection
- c. Superfluid flows
  - i. Grid flows
  - ii. Superfluid Karman flows

C. New developments in measurement techniques
- a. Optical techniques
  - i. Visualization of reconnecting vortices
  - ii. Possibilities for LIF approaches
  - iii. Laser tweezers?

D. Other prospects and future directions

Tutorial: New technologies for fluid dynamics experiments and advanced optical diagnostics

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Target audience: graduate and professional

Modern technologies offer new opportunities for the experimentalists in a broad variety of research areas including hydrodynamics. A significant improvements in accuracy, precision, reproducibility, control, data acquisition rate, and information capacity of the experimental data sets over the current state-of-the-art are envisaged using the new technical approaches and techniques. Application of the new technologies in experimental diagnostics can bridge the current resolution gap between the experiments and the large-scale simulations of computational fluid dynamics allowing the direct and unambiguous comparison of the data and the modeling results.

One of the new technologies which will be described in the tutorial is the modern digital holographic data storage. The state-of-the-art digital motion control and electro-mechanics allow for realization of different turbulent flows with very high Reynolds number ($> 10^7$) in a relatively small, laboratory-scale form-factor, while the holographic optical imaging can provide quantification of their properties with extremely high 3-dimensional spatial resolution and temporal bandwidth. The digital in-line holographic technology is capable of providing complete three-dimensional mapping of the flow velocity and density fields at high-data rates (over 1,000 frames-per-second) over large spatial area, with high spatial (1 to 10 microns) and temporal (better than few ns) resolutions and, thus, can provide extremely accurate quantitative description of the fluid flows, including multiphase and unsteady conditions. These unique experimental and metrological capabilities can enable the studies of spatial and temporal properties of the transports of momentum, angular momentum, and energy and the identification of scalings, invariants, and statistical properties of the complex multiphase and unsteady turbulent flows. These new technologies can be applied for the investigations of a large variety of hydrodynamic problems including the fundamental properties of non-Kolmogorov unsteady turbulence, particle-flow interactions, accelerating and rotating flows, boundary layer turbulence, Rayleigh-Taylor and Richtmyer-Meshkov instabilities, and turbulent mixing.

HIGH-PERFORMANCE COMPUTING and CYBER-INFRASTRUCTURE

Visualizing petascale data sets with VisIt

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Visualization and analysis plays a crucial role for scientific simulations as an enabling technology: exploring data, confirming hypotheses, and communicating results. But analyzing the extremely large data sets produced by massively parallel simulations is difficult. The dedicated tools that serve this purpose must be specially designed to support the size of the data in all phases of processing.

This talk will discuss VisIt, an open source visualization and analysis tool for massive data. VisIt won an R&D 100 award in 2005; has been downloaded over 100,000 times, is being used to study “hero” runs on 6 of the world's top 8 supercomputers, and developed by a large community, including developers supported by the US Department of Energy's Office of Science, National Nuclear Security Agency, and Office of Nuclear Energy. The tool is intended for more than just visualization and is built around five primary use cases: data exploration, quantitative analysis, comparative analysis, visual debugging, and communication of results. VisIt has a client-server design for remote visualization, with the server operating in a fully data parallel way and in a distributed memory setting. In addition, multi-resolution, streaming, and in situ visualization are approaches being actively pursued within the tool, to prepare for the peta- and exa- scale futures.

Using and abusing computational fluid dynamics

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I will discuss the use of numerical simulations in furthering our understanding of fluid dynamics, focusing in particular on the role that validation plays in establishing the credibility of such work.

Tutorial: GLOSS: Collaborative tagging for scientific data

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Target audience: graduate and professional

GLOSS (Generalized Labels Over Scientific data Source) is a collaborative tagging platform designed specifically for online scientific resources. Tagging of web-pages, photos and videos has become ubiquitous. It is featured in both standalone social-bookmarking applications such as Del.icio.us and StumbleUpon, and social media sites such as Facebook and Flickr. Several science-oriented sites such as myexperiment, Connotea, and CiteULike, have already incorporated this general form of tagging.

Tagging in GLOSS differs in three important ways. Firstly, our system can operate on multiple levels of abstraction (variables, sets of variables, surveys, sections) whereas each of the general systems is focused on only one type of objects (workflow, web page, article). Secondly, our system engages both data producers and data users while current systems are predominantly user driven and do not allow for direct data producer participation. Thirdly, GLOSS is integrated and operates within the web pages of the online data sources, and thus is open to everyone who visits these sources. Typical online tagging systems require users to visit their own websites in order to discover and share tags.

In my tutorial, I will demonstrate the distinguishing features of GLOSS and explain how tagging with GLOSS can help the research process in the context of three online data repositories of chemical, economic, and news data.

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