Turbulent Mixing and Beyond

International Conference

ABSTRACTS

August 18-26, 2007

The Abdus Salam International Centre

for Theoretical Physics

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TABLE of CONTENTS

Preface

The goals of the Conference are to expose the generic problem of Turbulence and Turbulent Mixing in Unsteady Flows 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 provides the opportunity to bring together scientists from the areas, which include but are not limited to high energy density physics, plasmas, fluid dynamics, turbulence, combustion, material science, geophysics, astrophysics, optics and telecommunications, applied mathematics, probability and statistics, and to have their attention focused on the long-standing formidable task.

The Turbulent Mixing and Turbulence in Unsteady Flows, including multiphase flows, plays a key role in a wide variety of phenomena, ranging from astrophysical to nano-scales, under either high or low energy density conditions. Inertial confinement and magnetic fusion, light-matter interaction and non-equilibrium heat transfer, properties of materials under high strain rates, strong shocks, explosions, blast waves, supernovae and accretion disks, stellar non-Boussinesq and magneto-convection, planetary interiors and mantle-lithosphere tectonics, premixed and non-premixed combustion, oceanography, atmospheric flows, unsteady boundary layers, hypersonic and supersonic flows, are a few examples to list. A grip on unsteady turbulent processes is crucial for cutting-edge technology such as laser-micromachining and free-space optical telecommunications, and for industrial applications such as aeronautics.

Unsteady Turbulent Processes are anisotropic, non-local and multi-scale, and their fundamental scaling, spectral and invariant properties differ from those of classical Kolmogorov turbulence. The singular aspects and similarity of the mixing dynamics are interplayed with fundamental properties of the Euler and compressible Navier-Stokes equations, with the problem sensitivity to the boundary conditions at the discontinuities and the initial conditions, and with its stochastic description. The state-of-the-art numerical simulations of the multi-phase non-equilibrium dynamics suggest new methods for capturing discontinuities and singularities and shock-interface interaction, for predictive modeling of the multi-scale dynamics in fluids and plasmas, for error estimate and uncertainty quantification as well as for novel data assimilation techniques.

The Organizing Committee hopes the TMBW will serve to advance the state-of-the-art in understanding of fundamental physical properties of turbulent mixing and turbulence in unsteady flows and will have an impact on predictive modeling capabilities, physical description and, ultimately, control of these complex processes.

The Book of Abstracts includes all accepted contributions: 150 lectures, talks, tutorials and posters, in a broad variety of Themes, sorted alphabetically within each theme. You are invited to take a look at this book for information on the frontiers of theoretical, numerical and experimental research and technology.

TURBULENCE

Percolation scalings and turbulent transport in the presence of flow topology reconstruction

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Often several different types of anomalous transport are present simultaneously in turbulent diffusion. A variety of forms requires not only special description methods, but also an analysis of general mechanisms for different turbulence types. One such mechanism is the percolation transport [1]. Its description is based on the idea of long-range correlations, borrowed from the theory of phase transitions and critical phenomena. These long-range correlations are responsible for the anomalous transport. It was suggested that we could explain anomalous transport in two-dimensional cases in terms of the percolation threshold. In the present paper we consider the influence of drift flow and time-dependence effects on the passive scalar behavior in the presence of both flow topology reconstruction and stochastic instability. The renormalization method of a small parameter is reviewed in continuum percolation models [2-4]. It is suggested to modify the renormalization condition of the small parameter of the percolation model in accordance with additional external influences superimposed on the system. This approach makes it possible to consider simultaneously both parameters: the characteristic drift velocity U_d and the characteristic perturbation frequency w. The effective diffusion coefficient D is proportional to $w^{1/7}$ that satisfactory describes the low-frequency region w, where the long-range correlation effects play a significant role. The character of the dependence of D_{eff} on the drift flow amplitude U_d in different regimes is analyzed [4-6]. This scaling agrees well with analogous expressions that describe low frequency regimes of transport.

[1] Isichenko M B 1992 Rev. Mod. Phys. 64 961. [2] Bakunin O G 2004 Reports on Progress in Physics 67 965. [3] Bakunin O G 2005 Physica A 345 1; [4] Bakunin O G 2006 J. Plasma Physics 72 647. [5] Bakunin O G 2005 Chaos Solitons & Fractals 23 1703. [6] Bakunin O G 2005 Plasma Physics Control. Nucl. Fusion, 47 1857.

Lagrangian velocity structure functions in Bolgiano turbulence

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The object of study is single-particle dispersion in the Bolgiano-Obukhov regime of two-dimensional turbulent convection. Unlike dispersion in a flow displaying the classical K41 phenomenology, here, the leading contribution to the Lagrangian velocity fluctuations is given by the largest eddies. This implies a linear behavior in time for a typical velocity fluctuation in the time interval τ. The contribution to the Lagrangian velocity fluctuations of local eddies (i.e. with a characteristic time of order τ), whose space/time scalings are ruled by the Bolgiano-Obukhov theory, is thus not detectable by standard Lagrangian statistical observables. To disentangle contributions arising from the large eddies from those of local eddies, a strategy based on exit-time statistics has successfully been exploited.

The result is a bifractal prediction for the moments of the exit-times of Lagrangian velocity increments, with low-order moments dominated by large eddies and high-order ones dominated by the local contribution, which is cleanly observed in our DNS simulation. Lagrangian velocity increments in Bolgiano convection thus provide a physically relevant example of a signal with more than smooth fluctuations.

Fluctuations of the energy flux and intermittency in wave turbulence

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We report an experimental study of gravity and capillary wave turbulence. Power-law spectra are found in both regimes and compared to theoretical predictions. The shape of the probability density function of the local slope increments of the surface waves strongly changes across the time scales. The related structure functions and the flatness are found to be power laws of the time scale on more than one decade. The exponents of these power laws increase nonlinearly with the order of the structure function. All these observations show the intermittent nature of the increments of the local slope in wave turbulence. Finally, strong fluctuations of the energy flux are observed and their implication on the energy cascade is discussed.

E. Falcon, C. Laroche and S. Fauve, Phys. Rev. Lett. 98, 094503 (2007); E. Falcon, and S. Fauve and C. Laroche, Phys. Rev. Lett. 98, 154501 (2007)

Large-Scale Simulation of Weakly-Compressible Turbulence

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We present the results of a large-scale simulation of weakly-compressible homogeneous, isotropic turbulence with Lagrangian tracer particles performed by the DOE ASC Flash Center on the Lawrence Livermore National Laboratory IBM BG/L. In this talk, we will focus on two sets of questions. The first, relevant to the numerical modeling of turbulent flows, is how well a MILES-based approach constructed on the Euler equations can capture the full physics of the Navier-Stokes equations in a turbulent flow. To address this question, we will present extensive results on the

Eulerian and Lagrangian scaling properties of our simulation, and compare these against both theory and previous simulation. The second set of questions deal with the more fundamental topic of how weakly-compressible turbulence differs from the incompressible limit. We will present results on the scaling of density structure functions, showing the presence of high-intermittency signatures.

Spectra of turbulence generated by singularities

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The problem of turbulence spectra generated by the singularities located on lines and planes is considered. It is shown that the frequency spectrum for water waves due to white caps (linear singularities) has the same scaling as the weak-turbulent Zakharov-Filonenko spectrum. The corresponding k spectrum may be highly anisotropic with the same decrease in a maximum like for the Phillips spectrum. However, in the isotropic case the spectrum is very different from the Phillips spectrum.

For two-dimensional hydrodynamic turbulence we study the appearance of sharp vorticity gradients and their influence on the turbulent spectra. We have developed the analog of the vortex line representation as a transformation to the curvilinear system of coordinates moving together with the divorticity lines. Compressibility of this mapping can be considered as the main reason for the formation of the sharp vorticity gradients at high Reynolds numbers. In the case of strong anisotropy the sharp vorticity gradients can generate spectra which fall off as k^{-3} at large k resembling the Kraichnan spectrum for the enstrophy cascade. For weak anisotropy the spectrum due to the sharp gradients coincides with the Saffman spectrum: $E(k) \sim k^{-4}$. We have compared the analytical predictions with direct numerical solutions of the two-dimensional Euler equation for decaying turbulence. We observe that the di-vorticity is reaching very high values and is distributed locally in space along piecewise straight lines. Thus, indicating strong anisotropy and accordingly we find a spectrum close to the k^{-3}-spectrum.

Finally we discuss the spectra for the acoustic type turbulence, when shocks play the role of singularities. We show that the isotropic spectrum has the same behavior as the Kadomtsev-Petviashvili spectrum: $E_\omega(k) \sim \omega^{-2}$.

Recent Progress in Prediction of Complex Turbulent Flows Using a Cubic Non-linear Eddy-Viscosity Model

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An economical way to capture turbulence anisotropy is through the use of non-linear turbulence models. In this approach two transport equations for turbulence parameters are solved and the stress-strain relation of the linear eddy-viscosity models is extended, by including non-linear products of strains and vorticities. These non-linear stress-strain relations have the ability to produce differences between the normal stresses and thus can extend the model's applicability, by allowing it to predict flows in which the anisotropy of turbulence is important, such as flows involving turbulence-driven secondary motions. Craft et al. (1996) developed the non-linear eddy-viscosity model (NLEVM1), including low-Reynolds-number effects. Moreover, they demonstrated that, in order to exhibit the correct sensitivity to streamline curvature, such a non-linear model must retain cubic terms in the stress-strain relationship, whereas the majority of alternative proposals only include quadratic terms. This model was then used to predict a range of applications including flow in curved channels, through a rotating pipe, transitional flow over a flat plate, impinging jet flow and flow around a turbine blade. In each case, it resulted in significant predictive improvements in comparison to what a linear low-Reynolds-number k-e model is able to produce. However, parallel application of this model in the computation of heat and fluid flow through two-dimensional and axi-symmetric ribbed passages by Raisee (1999) showed that the Craft et al (1996) non-linear model exhibited severe problems of numerical stability and also of predictive accuracy in relation to the thermal behavior in the computation of separated flows over sharp corners (ribs and expansions). Following from the recommendations of Raisee (1999), Craft et al (1999) proposed an alternative formulation for the variation of the turbulent viscosity parameter, cmu , with strain rates. The modified model (NLEVM2) not only improved the heat transfer predictions in both an abrupt pipe flow and the axi-symmetric impinging jet, but also removed the numerical instability and the need to prescribe the wall-distance explicitly. The proposed paper is further assess the capabilities of the modified cubic low-Reynolds number two equation model, (NLEVM2), in predicting a number complex turbulent flows including turbulent flow in curved ducts, turbulent flow through rotating cavities, unsteady turbulent flow around square cylinders, turbulent heat transfer in two- and three-dimensional ribbed passages, turbulent heat transfer in passages with sudden expansion or contraction. The paper will clearly demonstrate that marked improvements in flow and thermal predictions of above complex flows can be achieved using NLEVM2 in comparison to the original version of non-linear EVM (NLEVM1) and also the linear EVM.

Craft, T. J., Launder, B. E. and Suga, K., 1996, "Development and Application of a Cubic Eddy Viscosity Model of Turbulence", International Journal of Heat and Fluid Flow, Vol. 17, pp. 108-115; Craft, T. J., Iacovides, H. and Yoon, J. H., 1999, "Progress in the Use of Non-Linear Two-Equation Models in the Computation of Convective Heat Transfer in Impinging and Separated Flows", Flow, Turbulence and Combustion, Vol. 63, pp. 59-80; Raisee, M., 1999, "Computation of Flow and Heat Transfer through Two- and Three-Dimensional Rib-Roughened Passages", Ph.D. thesis, Department of Mechanical Engineering, UMIST.

Spatio-temporal investigation of the scalar gradients in correlation to the local topology of a turbulent flow

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For a sufficiently high ratio of solvent viscosity to passive scalar diffusion, Schmidt number, the turbulent transport of passive scalar generates large gradients of concentration distributed in sheet-like structures. Recent research shows that such gradients are formed in the biaxial extensional flows, implying that this particular flow topology has a significant impact on mixing at high Schmidt number. First, we discuss the relation between vortices and biaxial extensional flows. The intensity of the latter is measured by, sigma_max, the maximum magnitude of the eigenvalues of the velocity gradient tensor. Then, we study the formation of large gradients as a function of time and relative position to vortices. Conditional analysis is performed to study the evolution of sigma_max and the second and third invariants of the velocity gradient tensor. Finally, possible relations between vortices' scales and mixing scales will be discussed. The flow consists of a highly-resolved direct numerical simulation of a turbulent Kolmogorov flow at low Reynolds numbers. The resolution of the flow allows for the simulation of Schmidt numbers larger than unity.

Group-theoretical model of developed turbulence and renormalization of the Navier-Stokes equation

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We propose [1] to associate the phenomena of stationary turbulence with the special self-similar solutions of the Euler equation – they represent the linear superposition of eigenfields of the symmetry subgroup generators corresponding to the pure imaginary eigenvalues. The self-similar solution implies its dependence on time through the parameter of the space symmetry transformation only. From this model it follows that for stationary homogeneous turbulence, the change of the scale of averaging is equivalent to the composition of scaling, rotation, and translation transformations. We call this property a renormalization-group invariance of averaged turbulent fields. Assuming that on the small length scale (inner threshold of the turbulence), the turbulent velocity field can be approximated as the sum of a smooth velocity field and a random isotropic field, we averaged the Navier-Stokes equation over this small scale by making use of our averaging formula. Because the Navier-Stokes equation is invariant under translations and rotations, the renormalization-group invariance provides an opportunity to transform the averaged Navier-Stokes equation over a small scale to any scale by simple scaling. From methodological point of view, it is important to stress that we have shown that the turbulent viscosity appeared not as a result of averaging of the nonlinear term in the Navier-Stokes equation, but from the molecular viscosity term with the help of renormalization-group transformation.

[1] V.L. Saveliev and M.A. Gorokhovski, Group-theoretical model of developed turbulence and renormalization of the Navier-Stokes equation, Phys. Rev.E 72, 016302 (2005)

Resolution effects in direct numerical simulations of turbulence

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This talk will examine the adequacy of grid-resolution that is traditionally employed in direct numerical simulations of turbulence. It will draw a broad set of conclusions on the basis of recent theory (with V. Yakhot) and superfine simulations (with J. Schumacher, P.K. Yeung and D. Donzis). The primary conclusion is that, at high Reynolds numbers, the needed resolution varies as Re^{-1} rather than $\mathrm{Re}^{-4/3}$ as traditionally believed. Here, Re is the large-scale Reynolds number. The talk will also attempt a few remarks on continually accelerating flows such as the Rayleigh-Taylor flow.

Batchelor decay regime of mixing

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By using high molecular weight fluorescent passive tracers with different diffusion coefficients and by changing the fluid velocity we study the dependence of a characteristic mixing length on the Peclet number, Pe, which controls the mixing efficiency. The mixing length is found to be related to Pe by a power law, $L_{mix} \propto Pr^{0.26\pm0.01}$, and increases faster than expected for an unbounded chaotic flow. The role of the boundaries in the mixing length abnormal growth is clarified. By measuring velocity field particularly near the walls in the same channel we are able also to get the coefficient in the above relation that agrees well with recent theoretical predictions.

Dissipation element analysis of turbulence

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There have been many attempts to define the geometrical elements that one intuitively believe to represent 'eddies' of different size in turbulent flows. However this lack of relevant work is probably due to the difficulty of clearly defining shapes and length scales. The work to be presented is about a totally new method to analyze turbulent flows, dissipation element theory. Starting from each material point in flow field in ascending and descending directions along scalar gradients, each trajectory will inevitably reach the maximum and minimum ending points. The ensemble of material points sharing the same pair of maximum and minimum points cover a spatial region which is named a dissipation element. This decomposition is space-filling and exact without any arbitrariness, which could serve as an natural way to mark 'units' in turbulence. Each dissipation element can be parameterized with two most important characteristic parameters, the scalar difference at two extreme points and the linear distance between the points.

A number of classical conceptions for turbulence can be well interpreted with the dissipation element analysis. For example, the conditional mean of the scalar difference, a counterpart of the classical auto-structure function, assumes a more extended inertial range. Intermittency, which is usually characterized with the non-Gaussianity, can be newly reconsidered from the joint PDF of these two characteristic parameters. A theoretical modeling of the joint PDF can generally agree well with the DNS results in different dimensional spaces.

Developments in large numerical simulations of turbulence: resolution, intermittency, and Schmidt number scaling

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Tremendous advances in computing power in the 21st Century are enabling the conduct of very large-scale numerical simulations of turbulence and turbulence mixing, where the general emphasis is to contribute to physical understanding in canonical flow problems that involve an ever-wider range of scales. At the same time, there is significant concern that in most simulations the smallest scales in velocity and scalar fields may not be resolved sufficiently well to ensure accuracy in high-order statistics which are important descriptors of intermittency. The most direct test of such resolution effects is to compare results from simulations at nominally the same Reynolds number but different degrees of resolution at the small scales. In this talk we review recent results on velocity fields, and consider similar issues for passive scalar fields which generally possess greater high-wavenumber content than the velocity field, especially at high Schmidt numbers (Sc) where the smallest scale that must be resolved is smaller than the Kolmogorov scale and decreases with Sc . We will also discuss the possibility that the extreme tails of the probability density function of scalar dissipation fluctuations may scale similarly over a range of Schmidt numbers, in a manner that is consistent with a saturation of intermittency observed in the numerical simulations at low Reynolds number. A close comparison will also be made of the degrees of intermittency of scalar dissipation versus energy dissipation and enstrophy.

TURBULENT MIXING

Turbulent Mixing and Beyond

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Turbulent mixing and turbulence in unsteady flows, including multiphase flows, plays a key role in a wide variety of physical phenomena ranging from astrophysical to micro scales. Explosions of supernovae, stellar and planetary convection, magnetic and inertial confinement fusion, non-equilibrium heat transfer induced by ultra-fast laser pulses, Z-pinches of extreme ultra-violet sources for semi-conductors, impact dynamics of liquids and solids, are a few examples to list. Based on the new theoretical concept, the rate of momentum loss, we develop a phenomenological model, which accounts for the highly anisotropic and non-local character of the mixing dynamics and describes the transports of momentum and energy in the turbulent flow. It is shown that the invariant, spectral, scaling and statistical properties of the accelerated turbulent mixing differ substantially from those in isotropic Kolmogorov turbulence. The rate of momentum loss is the basic quantity of the unsteady flow, similarly to the rate of energy dissipation in Kolmogorov turbulence. The velocity scales as square root of length scale and the spectrum of kinetic energy is proportional to k^{-2} in RT flow, compared to the power 1/3 for the velocity scale and $k^{-5/3}$ for velocity spectrum in the classical case. We describe the random character of the dissipation process in the unsteady turbulent flow and show that the ratio between the rates of momentum loss and momentum gain is the statistic invariant and a robust parameter to diagnose for either sustained or time-dependent acceleration, with or without turbulent diffusion accounted for.

Atomistic Simulation of the Rayleigh-Taylor Instability

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The DSMC (direct simulation Monte Carlo) method was able to simulate the Rayleigh-Taylor instability in a comparable amount of computer time as the Navier-Stokes approach for a comparable period of the mixing process, using about ten billion particles so as to avoid boundary effects. The short time behavior of the evolution is shown to be quantitatively given by linear stability analysis of the hydrodynamic equations, starting from a flat interface roughened only by the naturally occurring fluctuations. Subsequently, the merging of the mushrooms that develop at the ends of the spikes leads to a quadratic time dependence for the advance of the mixing zone, with a coefficient in agreement with experiment, while continuum calculation disagree by about a factor of two. Following that regime, a slowing down to a linear in time or constant velocity zone advance is observed, as drops break off from the stems of the mushrooms, indicating that viscosity effects dominate at long times and Stokes' law applies. Magnetic levitation experiments, which have good control over the initial conditions, confirm these finding quantitatively, thus showing that these results can be scaled over many orders of magnitude in time, size and gravitational field. The failure of the continuum calculations to find the drop formation is likely due to the absence of fluctuations in their model and that is in the process of being confirmed by adding them to the Navier-Stokes equations. Finally, adding to the initial conditions a large amplitude perturbation compared to the amplitude of the fluctuations, both experimentally and numerically, leads to the conclusion that after about ten exponential initial growth times, their memory is lost and thus a asymptotically valid solution can be established, independent of initial conditions.

This work was carried out with the collaborators listed in the publication: PNAS (2007) Kai Kadau, Charles Rosenblatt, John Barber, Timothy Germann, Zhibin Huang, and Pierre Carles

The third-order Eulerian structure function in free surface turbulence

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Results of the classical Kolmogorov theory of turbulence (K41) should not be applicable to turbulence in a free surface on top of a turbulent bulk flow since such flow is not divergence free. We determine the third-order Eulerian velocity structure function experimentally in such two-dimensional flow by tracers that cannot sink into the bulk. Nevertheless, the third order structure function is found to agree well with the classical fourfth law in K41. Our findings are supported by direct numerical simulations that approximate the free surface well. In addition, the probability density function (PDF) of the instantaneous energy flux across scales is determined. The non-zero velocity divergence at the surface being a random variable, one can conduct a spatial decomposition of the velocity field into regions of positive and negative divergence. This allows calculation of the energy flux at the free-surface conditional upon the sign of the velocity divergence. It is perhaps not surprising that their r-dependence is very different. The measurements suggest that the direct cascade and the related scaling and sign of the third-order velocity increment moment might be established in a more general context than that of incompressible three-dimensional turbulence for which these relations can be derived rigorously from the equations of motion.

The effect of acceleration on turbulent entrainment

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A new class of self-similar turbulent flows is proposed, which exhibit dramatically reduced entrainment rates. Under strong acceleration, the rotation period of the large-scale vortices is forced to decrease linearly in time. In ordinary, unforced turbulence, the rotation period always increases linearly with time. However, by imposing an exponential acceleration on the flow, the vortex rotation period is forced to become the e-folding time scale of the acceleration. If the e-folding time scale itself decreases linearly in time, the forcing is "super-exponential", characterized by an acceleration parameter a. Based on dimensional and heuristic arguments, a model suggests that the dissipation rate is an exponential function of a and the dimensions of the conserved quantity of the flow. Acceleration decreases the dissipation and entrainment rates in all canonical laboratory flows except for Rayleigh-Taylor. Experiments of exponential jets and super-exponential transverse jets are in accord with the model. As noted by Johari, acceleration is the only known means of affecting the entrainment rate of the far-field jet. Numerical simulations of Rayleigh-Taylor flow by Cook and Greenough are also consistent. In the limit of large acceleration, vortices do not move far before their rotation period changes substantially. In this sense, extreme acceleration corresponds to stationary vortices.

Turbulence models for the Rayleigh-Taylor and Richtmyer-Meshkov instabilities

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Turbulence models are used to describe the self-similar growth of the Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities at high Reynolds number. This paper will describe a variety of such models including simple buoyancy-drag, turbulent diffusion and multi-phase flow models. It will also describe analytical solutions for simple flows and a systematic validation procedure using experiments and high resolution simulations to calibrate the phenomenological constants.

Multi-scale measures of mixing for steady scalar sources

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We study the evolution of passive scalar fields maintained by steady but spatially inhomogeneous sources and sinks stirred by an incompressible flow. The effectiveness of a flow field to enhance mixing over molecular diffusion is measured by the suppression of the space-time averaged scalar variance, the gradient variance (stressing small scales), and the inverse gradient variance (focusing on large scale fluctuations). Ratios of these variances without stirring to the corresponding variances with stirring provide non-dimensional measures of the "mixing efficiency" of the flow on various length scales. In this work we derive rigorous estimates on these multi-scale mixing efficiencies for a variety of source-sink distributions stirred by statistically homogeneous and isotropic velocity fields, and compare them with direct numerical simulations and exact calculations for sample problems. We find that the mathematical bounds on the efficiencies may be saturated in some cases, and that the mixing efficiency for any flow is ultimately be limited by the structure of the sources and sinks. This is joint work with Jean-Luc Thiffeault (Imperial College) and Tiffany Shaw (University of Toronto).

Experimental study of mixing at the external boundary of a submerged turbulent jet

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We study mixing at the external boundary of a submerged turbulent jet using Particle Image Velocimetry (PIV) to determine the jet velocity field and its statistical characteristics. In the experiments an air jet is seeded with the incense smoke particles which are characterized by large Schmidt number and small Stokes number. The obtained spatial distribution of the intensity of scattered light allows us to determine the spatial distribution of the jet fluid with a high concentration of the particles and spatial distribution of the surrounding fluid with a low concentration of the tracer particles. Every image was normalized by a light intensity measured at the jet exit into the chamber in order to eliminate effects associated with a change of concentration of the incense smoke.

In the analysis we use the approach suggested by Hazak et al. (Phys. Rev. E 73, 047303, 2006) which is based on the measured phase function for the study of the mixed state of two fluids induced by Rayleigh-Taylor instability. In their study Hazak et al. found that PDF of the phase function can be described by Gamma distribution.

Our experiments demonstrated that PDF of phase function in turbulent jet mixing can be also described by Gamma distribution. The observed behavior of the PDF of phase function in our experiments is similar to that during mixing induced by Rayleigh-Taylor instability. However, there is a difference in the parameters of Gamma distribution for mixing induced by Rayleigh-Taylor instability and for mixing at the external boundary of a turbulent jet. The difference is caused by the different physical mechanisms of mixing in these two systems. In particular, the structure functions of the multi-scaled turbulent velocity field and the flow field induced by Rayleigh-Taylor instability are different.

Mixing and segregation in two-phase flows

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I shall review the analytic theory of the statistics of inertial particles in random flows. Short-correlated and telegraph models are two exactly solvable limits that allow qualitative understanding and (in some cases) quantitative description of the statistics of the particle concentration and velocities, including phase transitions. I briefly describe applications to cloud physics and unsolved problems.

Distribution functions in the statistical theory of mixing due to Rayleigh-Taylor instability.

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In incompressible fluids, the pressure is not a thermodynamic variable but rather a functional of density and velocity fields. This functional plays a central role in the theory of turbulence[1]. In the present work, the expression is derived for this functional for incompressible fluids with large spatial variations in the density. The expression indicates that the average pressure induced by a "test eddy" immersed in a “sea” of spatial density fluctuations decays exponentially, with the density correlation length as the decay length. As a consequence, the self consistent force is mainly due to an uncorrelated sum of the long range effects of density and velocity fields. In the presence of gravitation, this “mean field” reflects the buoyancy and drag effects and the known t-square evolution of the mixing zone. The correlated part, which is effective only at short distance acts as a collisional randomizing effect, which determines the strength of the drag. The above picture serves as a guide for the derivation of the statistical equations of the RTI mixing. Specifically, the hierarchy of coupled equations for the time evolution of the two-component N-point probability density functions, f_N (PDF's), is rigorously derived. The new expression for the pressure determines the flux of momentum in these equations. The "mean field" approximation of the one-point (N=1) equation displays the expected form of the buoyancy and drag forces. Closure is obtained by incorporating the corrections due to correlations into a Fokker-Planck collision term [1]. In the talk, the closed form of the effective Fokker-Planck equation, with a mean force which is specific to the RTI mixing will be derived. Simple solutions will be presented and compared to existing results. The program for further utilizing this theoretical framework in the problem of RTI mixing will be discussed.

[1] Stephen B. Pope "Turbulent flows" (Cambridge University press, 2000).

Coherent structures and turbulent mixing

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Large-scale shear flows (such as differential rotation, zonal flows, etc) are common features in many physical systems and play a crucial role in mixing and transport of quantities like chemical impurities, momentum, etc. In particular, they may reduce turbulent transport locally, forming the so-called transport barrier. Additionally, the small-scale turbulence also affects the large-scale structures. This feedback between large and small scales leads to the possibility of self-regulation, exhibiting time-transient behavior. Here, I will discuss turbulence regulation by shear flow, formation of transport barriers, self-organization, and then some of the important implications for the mixing and transport in laboratory and astrophysical plasmas. I will further discuss the effects of rotation, stable stratification, and magnetic fields on turbulent mixing.

Vanishing viscosity limit for 2D flows in an unsteadily rotating circle

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We consider 2D viscous incompressible flows in a disk with rotating boundary. We assume that the angular velocity is only Bounded Variation in time, which includes impulsively started and stopped rotations. We study the vanishing viscosity limit and prove that for circularly symmetric initial data the solution of the Navier-Stokes equations converges strongly in the energy norm uniformly in time to the corresponding stationary solution of the Euler equations. This result generalizes work of Matsui, Bona and Wu, and is related to work of Wang. We also discuss the behavior of vorticity in the limit and the appearance of a vortex sheet at the boundary. This is joint work with Milton Lopes and Helena Nussenzveig Lopes.

Features of thermal turbulent convection at very high Rayleigh numbers

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This talk will address features of turbulent convection at very high Rayleigh (Ra) numbers, obtained using cryogenic helium gas as a working fluid. The experiments have taken place in various aspect ratio cylindrical cells, all at high Ra:

aspect ratio ½, used to obtain the highest Rayleigh numbers (up to 10^{17}); aspect ratio unity, in which a mean wind is robust and can exhibit unusual reversal behavior when observed at a single point; aspect ratio 4, in which the influence of sidewalls is reduced, as well as the strength of the mean wind. Here, scaling of the heat transfer is observed to be consistent with the long-time correlation of the circulating wind. A novel method of directly measuring the effective thermal diffusion of turbulent convection - applied in aspect ratios 1 and 4 - will be presented as well as the plausibility of empirically estimating the position of a core/boundary-region interface at very high Ra.

Turbulent mixing phenomena in liquid metal cooled reactors

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In the United States there is renewed interest in fast neutron ("recycle") reactors as part of the solution to a closed nuclear fuel cycle. GNEP (Global Nuclear Energy Partnership) includes support for an advanced simulation program intended to apply high-fidelity modeling to aid in optimizing design and certifying the safety of fast reactors. A major focus is an understanding of the detailed temperature distribution within the reactor that results from various design choices. Much of this depends on the turbulent mixing properties of the low-Pr coolant both in rod bundle geometries and in the upper plenum region where jets with strong thermal gradients exit the core. This talk will discuss a number of key simulation challenges in this area, the relevant fundamental physics, and some very early results of applying LES to multi-pin wire-wrapped rod bundle geometries.

HIGH-ENERGY DENSITY PHYSICS

Classical and Ablative Richtmyer-Meshkov and Rayleigh-Taylor Instabilities and Other ICF-Relevant Plasma Flows Diagnosed with Monochromatic X-Ray Imaging

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In inertial confinement fusion (ICF) and high-energy density physics (HEDP), the most important manifestations of the hydrodynamic instabilities and other mixing processes involve lateral motion of the accelerated plasmas. In order to understand the experimental observations and to advance the numerical simulation codes to the point of predictive capability, it is critically important to accurately diagnose the motion of the dense plasma mass. The most advanced diagnostic technique recently developed for this purpose is the monochromatic x-ray imaging. This technique combined with streak camera (for continuous time resolution) and framing camera (for 2D snapshots) was applied for single mode planar experiments on the NRL Nike laser [1]. Its application made it possible for the experimentalists to observe for the first time important hydrodynamic effects that trigger compressible turbulent mixing in laser targets, such as ablative Richtmyer-Meshkov (RM) instability, feedout, interaction of a RM-unstable interface with rarefaction waves [2-5]. It also helped to substantially improve the accuracy of diagnosing many other important plasma flows, ranging from laser-produced jets [6] to electromagnetically driven wires in a Z-pinch. We will review the results obtained with the aid of this technique in ICF-HEDP studies and the prospects of its future applications.

[1] Y. Aglitskiy et al., “High-resolution monochromatic x-ray imaging system based on spherically bent crystals,” Applied Optics 37, 5253-5261 (1998). [2] Y. Aglitskiy et al., “Direct Observation of Mass Oscillations Due to Ablative Richtmyer-Meshkov Instability in Plastic Targets,” Phys. Rev. Lett. 87, 265001 (2001). [3] Y. Aglitskiy et al., “Direct Observation of Feedout-Related Mass Oscillations in Plastic Targets,” Phys. Rev. Lett. 87, 265002 (2001). [4] Y. Aglitskiy et al. “Direct Observation of Oscillations Due to Ablative Richtmyer-Meshkov Instability and Feedout in Planar Plastic Targets,” Phys. Plasmas 9, 2264-2276 (2002). [5] Y. Aglitskiy et al., “Perturbation evolution started by Richtmyer-Meshkov instability in planar laser targets,” Phys. Plasmas 13, 080703 (2006). [6] B. Loupias et al., “Plasma Jet Experiments Using LULI 2000 Laser Facility,” Astrophys. Space Sci. 307, 103 (2007).

From Physics Understanding of the Ablative Rayleigh-Taylor Instability to Impact Fast Ignition

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Our work on the ablative Rayleigh-Taylor (RT) instability extends from physics understanding through the suppression of the instability until validation of a new ignition scheme, impact fast-ignition.

The first focus on understanding of the instability was to demonstrate measurements of all the parameters in the Takabe-Bodner formula in order to validate the predicted coefficient characterizing the effect of ablation. While the Rayleigh-Taylor instability has been studied at length, this work represents a significant advance in that it presents a first quantitative measurement [1] of the ablation effect in the Takabe-Bodner formula.

Based on the rigorous test of the understanding, we have found two suppression schemes of the RT instability. 1 "Double Ablation" The first scheme is to generate double ablation structure in high-Z doped plastic targets. In addition to the electron ablation surface, a new ablation surface is created by x-ray radiation from the high-Z ions. Contrary to the previous thought, the electron ablation surface is almost completely stabilized by extremely high flow velocity. At the same time, the RT instability on the radiative ablation surface is significantly moderated. 2. "Cocktail Color Irradiation" The second is to enhance the nonlocal nature of the electron heat transport by illuminating the target with long wavelength laser light, whereas the high ablation pressure is generated by irradiating short wavelength laser light.

The sufficient suppression of the RT instability not only increases compressed density, but it also make the impact fast-ignition [4] feasible: Here we employ a new approach that totally eliminates ultra-intense laser-plasma interaction problem while keeping the advantage of the compactness of the fast ignition; we accelerate a small portion of the fuel to high enough velocity (impactor) to collide with a pre-compressed plasma (main fuel). We have achieved two orders-of-magnitude increase of neutron yield at a right timing of impact collision, providing another pathway to compact and reliable fusion energy production.

[1] H. Azechi et al., Phys. Rev. Lett. 98, 045002 (2007). [2] S. Fujioka et al., Phys. Rev. Lett. 92, 195001 (2004). [3] K. Ohtani, submitted to Phys. Plasmas; An abstract/summary can be found in K. Shigemori et al., Bull. Am. Phys. Soc. 46, 286 (2001) and H. Azechi et al., Plasma Physics and Controlled Fusion 46, B245 (2004). [4] M. Murakami et al., Nucl. Fusion 46, 99 (2006).

Instabilities and nonlinear patterns of thermal fronts: gaseous flames, detonations, ablation fronts in ICF …

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In this lecture we present a survey of theoretical analyses on the dynamics of thermal fronts, including gaseous flames, detonations, and ablation fronts encountered in inertial confinement fusion. The first part of the lecture is devoted to the structure and the linear stability of planar fronts. We will consider the intrinsic instabilities of freely propagating fronts and also the case of Rayleigh-Taylor unstable situations. Similarities and differences between these fronts will be pointed out. A particular attention will be played to the stabilization mechanisms at small wavelengths that control the marginally stable wavelength. The second part of the lecture concerns analytical studies of the nonlinear patterns appearing on unstable fronts. The attention will be focused on the limiting cases for which an analytical approach may be carried out yielding results that are relevant to the real situations. Eventual formation of singularities at finite time will be discussed, especially for the case of Rayleigh-Taylor unstable ablation fronts in ICF conditions. The effect of a small external noise upon the nonlinear patterns will be presented in the case of flames. The flame to detonation transition will also be briefly discussed.

Approaches to Turbulence in High-Energy-Density Experiments

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In high-energy-density (HED) experiments, some energy source creates pressure above 1 Mbar (0.1 TPascal) to initiate some dynamics of interest. In the experiments discussed here, the source is a laser and the pressure is created by laser ablation. Using such a source, one can in principle devise experiments in which shocks, decelerations, shear flows, or some combination of these amplify initial modulations in the system and cause it to evolve toward a turbulent state. I will show examples involving shock-wave-driven and blast-wave-driven interfaces, jets, and shear flows. The attractive aspects to these experiments are that they naturally produce high-Mach-number flows, that they typically involve ionized media having comparatively simple equations of state, and that they offer the potential for producing a gradual and diagnosable transition to turbulence. As you will see, diagnostic techniques have advanced substantially and show promise of further advances, even though they do not approach the resolution and precision found in experiments with gasses or liquids using laser sheets and microparticles. I will show data (and sometimes simulations) and discuss the status of the four types of experiments mentioned above. Because of the transitory nature of the energy source, none of these experiments can reach a steady state. This introduces the temporal problem of the onset of turbulence. Some considerations relating to the onset of turbulence will be discussed, along with the prospects for observing this onset in present and future experiments.

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Simulations of the DD fusion reaction

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Predominant future primary power source will be the nuclear power. It is the only way to cover increasing energy consumption, it is not the source of the greenhouse gases and the fuel will last for billions of years. Presented paper is engaged in research of the Z-pinch discharge and its relation to the fusion experiments. Perturbation analysis of the beam-target interaction for DD reaction in frame of the MHD theory is presented in the paper. Linear analysis of the problem was performed and dispersion relation found. The stable and unstable regions of the dispersion relation were calculated numerically and determined such plasma parameters, for which the most efficient thermalization during beam-target interaction occurs. Numerical PIC-MC simulation of the beam-target interaction in the unstable region of the parameters was performed. For the calculations current 3D PIC program package supplemented with Monte Carlo simulations of the collisions with known effective cross sections was used. For field calculations both FFT and multigrid solvers were used. The particle motion was treated via Boris-Buneman and Canonical differential schemes. For the visualization of fields the method LIC (Line Integral Convolution) was used.

The results are compared with nowadays z-pinch experiments realized in the Czech Technical University in Prague (Czech Republic) and Institute of Plasma Physics and Laser Microfusion at Warsaw (Poland)

Experimental study of supersonic plasma jets

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We will present results of high energy density laboratory experiments which explore the evolution of collimated outflows and jets driven by a toroidal magnetic field. The experiments are scalable to astrophysical flows in that critical dimensionless numbers such as the plasma collisionality, the plasma beta and the magnetic Reynolds number are all in the astrophysically appropriate ranges. Our experiments use the MAGPIE pulsed power machine (1MA, 250ns) and allow us to explore the role of magnetic pressure in creating and collimating the outflow as well as showing the creation of a central jet within the broader outflow cavity [1,2]. The experimental configuration allows generation of several episodes of the magnetically driven jet eruptions. The subsequent ~Smagnetic bubbles~T have higher propagation velocities and are catching up the previously ejected, producing shocks. These experiments suggest that periodic formation of magnetic tower jets in the astrophysical situations could be responsible for some of the variability of the astrophysical jets. Modifications of the experimental configuration allowing addition of the poloidal magnetic field and angular momentum to the jet will be also discussed. The experimental results will be compared with computer simulations performed with laboratory plasma codes and with astrophysical codes.

[1] S.V. Lebedev et al., Mon. Not. R. Astron. Soc., 361 97 (2005). [2] A. Ciardi et al., Physics of Plasmas, 14, 056501 (2007)

Rogue Waves Generated in Laser-Matter Interaction

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In a series of experiments in which nanosecond laser pulse irradiates a thin metal target we have generated Rayleigh-Taylor and Richtmyer-Meskhov environments with the nonlinear and nonequilibrium phenomena evolution, like breaking waves (1) and a variety of complex vortex structures (2). In the present experiment we confine the region above the planar target with a parallel transparent quartz plate (a semi-confined configuration, SCC). The laser power density that was varied from 10^7 to 10^8 (or 10^9) W/cm^2, caused vaporization of indium into the channel-like trap. The ablated vapor moves vertically, strikes the cover plate and reflects back. The downward reflected vapor front "snowplows" the melted layer to the left and right and gives rise to a horizontal plasma "vapor-wind" ~10^5 -10^6 cm/s, which enhances the excitation of surface waves. These waves are similar to the giant sea waves, formed by a wind over the surface where a plasma vapor wind is the analog of the air wind. In comparing measured wave profiles with numerical simulation profiles, indicates that the laser induced giant wave evolves from the random fluid surface of melted indium analogous to the "random sea surface", exposed to the amplitude and the phase modulation. The amplitude wave modulation is dominant at low and high energies, while the phase modulation is dominant at medium laser energies. The scenario for the low and high laser energy (62 and 95mJ) is based on the appearance of a single giant wave associated with a deep hole (without side waves). In contrast, for medium energies of 75 and 85 mJ, giant wave appears from the center of the wave packet, similar to a giant sea wave. Different wave profiles in various domains are due to the plasma-wind inhomogeneity and variation of the phase modulation over the spot.

[1] S. Lugomer and N.J. Zabusky, Appl. Phys. Lett, 87 204101 (2005). [2] S. Lugomer, Y. Fukumoto, B. Farkas, T. Szorenyi and A. Toth, Phys. Rev E, (submitted).

Studies of High Energy Density States in Matter Using Intense Heavy Ion Beams: the HED-ge-HOB Collaboration

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The subject of High Energy Density (HED) states in matter is of considerable importance to many branches of basic and applied physics. In addition to that, it has great potential for lucrative industrial applications. This talk presents an overview of theoretical work that includes two- and three-dimensional hydrodynamic simulations and analytic modeling that has recently been done to assess the potential of intense heavy ion beams to study this important field of research. It is to be noted that this work has been carried out in connection with the Future Facility for Antiprotons and Ion Research (FAIR) that is being built at Darmstadt. It has been found that two very different schemes, namely, HIHEX and LAPLAS can be employed for such studies. The former scheme involves isochoric and uniform heating of matter by an ion beam that is followed by isentropic expansion of the heated material. Using this technique, one can access the entire phase diagram including those regions which can not be accessed by traditional methods of shock waves. The second scheme considers a multiple shock reflection technique that allows one to achieve a low-entropy compression of a test material like hydrogen or water which generates physical conditions that are expected to exist in the interior of giant planets. Interesting physical problems like Rayleigh-Taylor and Richtmyer-Meshkov instabilities have also been investigated in detail. This work has provided the necessary basis for the HEDgeHOB scientific proposal.

2-D PIC simulation of the heating in the plasma fiber

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One of the possible ways to gain energy from thermonuclear reactions in plasma is the dense Z-pinch. The critical parameters of plasma designed for mentioned purpose are the temperature, density and the time during it the required temperature and density are maintained. In various pinch experiments (plasma focus, implosions of wire and others) come to the heating by various ways e.g. by thermalisation of the ion kinetic energy or by electric current. In presented numerical model the possible ways how the energy can be thermalised are studied, weather for two opposite beams or for plasma fiber with strong electric current. The used model is 2-dim PIC in cylindrical geometry with azimuthal symmetry. Thus the particle density depends only on radial and axial coordinates. However the nonzero azimuthal component of both particle velocity and magnetic field are admitted respectively. This makes possible to test more complex configurations such as helical structure of

magnetic field and current lines. The typical plasma parameters used in tested configurations are (similar as in many laboratory pinch experiments) following: the density is 10^19 particles per cubic centimeter, the total current in fiber is about 1 MA and the mean ion energy is 1 keV.

New perspectives on similarity scaling criteria and mixing transition for studying astrophysics using high energy density laboratory experiments or numerical simulations

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Advances in laboratory scale experimental techniques such as use of modern high energy intensive pulsed laser beams have achieved capabilities which can produce energy densities in submillimeter-scale volumes that otherwise are only manifest in actual astrophysical events. This is tantamount to creation of experimental testbeds where theory and modeling can be quantitatively tested against astrophysical observations (so called laboratory astrophysics). Naturally, concern emerges as to whether this is of sufficient magnitude to investigate the physics of actual astrophysical events. In effect legitimate questions may be anticipated about the degree of confidence with which once can apply the laboratory results to interpretation of astrophysical phenomena. In this talk, recent efforts in an attempt to address this question will be reviewed. A new approach, based on additional insight gained from review of Navier-Stokes turbulence theory, will be discussed. It allows for revelations about the distinctive spectral scale dynamics associated with high Reynolds number astrophysical flows. From this perspective, the energy containing range of the turbulent flow measured in a laboratory setting must not be unintentionally contaminated in such a way that the interactive influences of this spectral scale range in the corresponding astrophysical situation cannot be faithfully represented. In this talk the concept of a minimum state is introduced as the lowest Reynolds number turbulent flow that a time-dependent mixing transition must achieve to fulfill this objective. The Reynolds number of the minimum state is determined as 1.6X10^5. The temporal criterion for the minimum state is also obtained. The efforts here can be viewed as a unification and extension of the concepts of both similarity scaling and transient mixing transition concepts. At the last the implications of our approach in planning future intensive laser experiments or massively parallel numerical simulations are discussed.

PLASMAS

Excitation and Diagnosis of Langmuir Wave Turbulence in Ionospheric Plasmas at Gakona, Alaska

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Preliminary ionospheric plasma heating experiments were conducted at Gakona, Alaska to investigate HF heater-excited Langmuir wave turbulence diagnosed by the newly constructed Modular UHF Ionospheric Radar (MUIR). In spite that parametric decay instability has been investigated theoretically and experimentally for many years, it is still not clear how Langmuir waves could be spatially excited and distributed in the ionosphere above the heater. The recent work of Kuo and Lee [JGR, vol. 110, A01309, 2005] was intended to advance the theory of parametric decay instability. According to the theoretical results of Kuo and Lee, the concerned process involves the decay of a Langmuir pump wave into a Langmuir sideband and an ion acoustic wave via "resonant and non-resonant cascading". Because ion acoustic waves are heavily damped by ion Landau damping, the following expectation needs to be verified in our Gakona experiments. The non-resonant cascade of Langmuir waves proceeds at the same location and is severely hampered by frequency mismatch effect, because the decay wave is a driven ion mode oscillating at considerably lower frequency than that of the ion acoustic wave. In contrast, the resonant cascade, which takes place at different resonant locations to minimize the frequency mismatch effect, has to overcome the propagation loss of the mother Langmuir wave in each cascade step. It is known, in general, that the resonant cascade process requires lower thresholds than those of the non-resonant cascade process. It is then expected that the losses caused by downward propagation in the resonant cascade process are less than those from ion Landau damping in the non-resonant cascade process. Although the resonant cascade has a lower threshold, the cascade lines spread over a range of altitude. Our plasma line measurements made with MUIR have showed good qualitative agreement with the theoretical predictions.

Diagnoses of Large Plasma Sheets Excited by HF Heater via Thermal Filamentation Instability at Gakona, Alaska

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In the past two years we have been conducting experiments to investigate the thermal filamentation instability above Gakona, Alaska at a high-latitude location using a HF heater and diagnostic instruments: digisonde, riometer, and the newly constructed Modular UHF Ionospheric Radar (MUIR). This work was motivated by our earlier mid- latitude ionospheric heating experiments at Arecibo, Puerto Rico. Large-scale sheet-like ionospheric density irregularities were excited above Arecibo by vertically injected O-mode and X-mode heater waves, as expected from the theory of thermal filamentation instability [Lee et al., GRL, vol. 25, pp. 3067-3070, 1998]. The generation of large ionospheric plasma sheets has been inferred from our Gakona experiments. During vertical ionospheric heating, ionosonde signals had no problem to be totally reflected and appear in ionograms in the presence of O-mode generated plasma sheets which are parallel to the meridional plane. In contrast, because X-mode heater waves induce orthogonal plasma sheets, ionosonde signals transmitted near the zenith will be guided to propagate away. They, thus, cannot be reflected to appear in the ionograms. However, when plasma blobs are present, the ionosonde signals transmitted at a large angle may still be bounced back from the remote plasma blobs. In addition, the missing of traces on ionograms near the heater frequency indicates anomalous absorptions of ionosonde signals that may include two processes: (1) the scattering of ionosonde signals into electrostatic (e.s.) wave modes by heater-induced short-scale ionospheric density striations, and/or (2) the Bragg scattering of ionosonde signals by heater-induced medium-scale ionospheric irregularities. This prominent ionospheric effect caused by HF heater was confirmed in skymaps. In short, skymap signal decreased after the O-mode heater was turned on. A correlation of skymap signal intensity with heater operation was clearly found.

Interplay of the Turbulence and Strong Coulomb's Coupling in the Formation of the Anomalous Plasma Resistance

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The anomalous electric resistance of plasmas can manifest itself both in the natural astrophysical phenomena and laboratory experiments. Of particular importance is it in the artificial plasma bunches released from the rockets and satellites to the Earth's ionosphere and magnetosphere. For a long time, the main mechanism of the anomalous resistance was assumed to be only the plasma turbulence. The resent studies suggest that an important role in this phenomenon is played also by the effects of strong Coulomb's coupling, which can develop in the course of sharp plasma expansion. The aim of the present report is (1) to discuss the interplay between the two above-mentioned mechanisms and (2) to present an efficient method for calculation of the effective distribution function of charged particles in the regime of strong Coulomb's coupling. This function is well suitable for the description of quasi-localization of electrons in the vicinity of nearby ions and the resulting suppression of the electric conductivity.

Lower Hybrid Wave Turbulence and Meter-scale Plasma Density Irregularities Produced by Whistler Wave Interactions with Ionospheric Plasmas

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Experimental investigation of whistler wave interactions with ionospheric plasmas can be ideally conducted at Arecibo Observatory. A Naval transmitter code-named NAU is located nearby, emitting radio waves at a power and frequency of 100 kW and 40.75 kHz, respectively. The Arecibo 430 MHz radar can be used to diagnose ionospheric plasma turbulence due to NAU transmission-excited plasma instabilities. A small fraction of NAU transmitted power could be coupled into the ionosphere via refraction and mode conversion in the presence of naturally occurring ionospheric density irregularities. In this case field-aligned ionospheric irregularities act as waveguides to guide NAU signal to propagate along geomagnetic field lines and facilitate the linear mode conversion of NAU signals into whistler mode waves. The electric field amplitudes of NAU-generated 40.75 kHz whistler-mode waves are estimated to reach 1 mV/m in the ionospheric F region. Such intense whistler waves can parametrically excite lower hybrid waves and meter-scale zero-frequency field-aligned density irregularities in ionospheric plasmas within a second. Based on these expectations we conducted a series of Arecibo experiments between 20:00 and 24:00 local time (LT) during 20-27 December, 2004 to investigate ionospheric plasma interactions with NAU-generated 40.75 kHz whistler waves in the F region. It was found that NAU was responsible for causing the enhanced plasma lines, detected by the Arecibo 430 MHz radar in the nighttime ionosphere F region. The lower hybrid waves, generated in a broad range of altitudes at the wake of 40.75 kHz whistler waves, have a single frequency of 40.75 kHz but with a spectrum of wavelengths. They can effectively accelerate electrons continuously along the Earth's magnetic field to energies ranging from a fraction of 1 eV to 10 eV. These energetic streaming electrons, when detected by the Arecibo 430 MHz radar, give rise to enhanced plasma lines with a frequency spectrum of ~ 3.25 – 4.75 MHz.

Ionospheric Plasma Turbulence Triggered over Puerto Rico via Rayleigh-Taylor Instability by Tsunami-launched Acoustic Gravity Waves on December 26, 2004

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Experiments were conducted at Arecibo Observatory, Puerto Rico during December 19-27, 2004, using Arecibo 430 MHz incoherent scatter radar (ISR), two ionosondes, Global Positioning System (GPS) satellites, and MIT All Sky Imaging System (ASIS) to investigate ionospheric plasma turbulence. We report on measurements of large-scale plasma turbulence carried out between 20:00 and 24:00 local time (LT) on December 26, 2004, about one day after the occurrence of deadly tsunamis associated with the Mw = 9.2 earthquake in Samatra, Indonesia. Intense ionospheric plasma turbulence excited by Rayleigh-Taylor instability was triggered by tsunami-launched gravity waves, noticed in two sequential events of traveling ionospheric disturbances (TIDs): (1) the bottomside ionosphere rose by ~50 km, inducing intense large-scale plasma turbulence and spread F echoes on ionograms, and (2) alternating cycles of bottom-side plasma rising and falling persisted subsequently through the remainder of the experiments. These two marked events are consistent with the following two scenarios supported by GPS satellite measurements. Scenario (1): tsunami-induced gravity waves were launched close to the seismic epicenter and propagated along the great circle path between Sumatra (95.78^o E, 3.3^o N) and Puerto Rico (66^{o}W, 18.5^o N), triggering solitary-type of TIDs observed at Arecibo. Scenario (2): gravity waves responsible for later observed train of TIDs at Arecibo were generated relatively close to Puerto Rico as tsunami waves propagated from Indian Ocean toward South Atlantic Ocean. These two scenarios also agree with computer simulations [Occhipinti et al., GRL, 2006] and numerical modeling using combined tide-gauge and satellite-altimetry data [Titov et al., Science, 2005]. The wind-velocity field of these gravity waves caused local ionospheric plasma to rise, seeding bottomside irregularities via the Rayleigh-Taylor instability to generate intense large-scale plasma turbulence, as detected by multi-diagnostic instruments at Arecibo.

Generation of Multi-scale Ionospheric Plasma Turbulence by Injected High-Power Radio Waves at Arecibo, Puerto Rico

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Large-scale ionospheric turbulence in the forms of plasma sheets and rising plasma bubbles was created in our 1997 ionospheric HF (high-frequency) plasma heating experiments at Arecibo, Puerto Rico. These large plasma sheets were produced within the meridional planes by injected O-mode HF heater waves via the thermal filamentation instability. When these plasma sheets experienced E x B drifts, they were detected by the Arecibo 430 MHz radar and seen as slanted stripes in the range-time-intensity (RTI) plots [M.C. Lee et al., GRL, 1998(a)]. In contrast, CW O-mode heating of the ionosphere yielded large plasma depletion along the geomagnetic field due to thermal expansion and chemical reactions (i.e., charge exchange and dissociative recombination processes). Under the g x B drifts the depleted magnetic flux tubes moved upward and northward as rising plasma bubbles [M.C. Lee et al., GRL. 1998(b)]. Sharp plasma density gradients across the depleted magnetic flux tubes provided the source of free energy to enhance Rayleigh-Taylor instability, leading to augmented spread F echoes on ionograms [M.C. Lee et al., GRL, 1999]. Our laboratory simulation experiments at MIT had successfully reproduced some Arecibo results [M.C. Lee et al., GRL, 1997]. It has been demonstrated that 28.5 kHz waves emitted by the nearby Naval transmitter (code named NAU) can be favorably guided by HF heater-generated plasma sheets (acting as parallel-plate waveguides), to propagate from Puerto Rico coherently all the way to the Arecibo geomagnetic conjugate point now near Puerto Madryn, Argentina, in the form of ducted whistler waves (M.J. Starks and M.C. Lee, Radio Sci., 2000; M.J. Starks et al., JGR, 2001). As shown in our recent Arecibo experiments, such conjugate experiments provide extremely effective probes of ionospheric plasmas [A. Labno et al., JGR, 2007] and magnetospheric plasmas in inner radiation belts [R. Pradipta et al., GRL, 2007], and yield crucial information on wave-plasma and wave-particle interactions.

Ionospheric Plasma Turbulence Caused by Electron Precipitation from the Inner Radiation Belt

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A 100 kW and 40.75 kHz transmitter code-named NAU is operated by the United States Navy at Aguada, Puerto Rico, about 52 km to the west of the Arecibo Observatory. Most of NAU's emitted power propagates in the Earth-ionosphere waveguide. However, in the presence of ionospheric turbulence appearing in the form of plasma density irregularities, some fraction of the NAU carrier signal scatters into the ionosphere and magnetosphere where it propagates along magnetic field lines in the whistler mode. Although the NAU transmitter operates exclusively for Naval communications, its proximity to the Arecibo Observatory offers occasional opportunities to observe ionospheric plasma turbulence due to whistler-wave coupling. Arecibo is located at ~30^o N magnetic latitude where it is magnetically conjugate to the inner radiation belt at L = 1.35. We examine the possible correlations between occurrences of nighttime ionospheric E-region plasma line (PL) enhancements (i.e., episodic bursts of electron precipitation) and NAU emissions. On the night of January 1 – 2, 2006, the experiments were conducted from 22:00 local time (LT) to 6:00 LT. The NAU transmitter was turned off from the beginning of our experiments until 01:45 LT when continuous operations resumed for the remainder of the experiments. Enhanced PL events lasting < 10s had central frequencies and bandwidths of about 2.5 and 1.5 MHz, respectively. The PL center frequency and bandwidth indicate that Arecibo radar detected 2.3 to 8.5 eV suprathermal electrons streaming along the Earth's magnetic field. The rate of PL event detections increased by a factor of 2.8 after NAU turn-on. We suggest that 40.75 kHz radiation sporadically leaked though local ionosphere, abetted by field-aligned plasma density irregularities. Within the magnetosphere the radiation propagated in the whistler mode through the inner radiation belt along the L = 1.35 field line where gyroresonant interactions with trapped 390 keV electrons increased the rate of precipitation.

ASTROPHYSICS

Turbulent Flames in Type Ia Supernovae

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Type Ia supernovae (SNe Ia) are the biggest thermonuclear explosions in the universe. They are thought to arise when a white dwarf star gradually accretes matter from its companion red giant star, and grows to approximately 1.4 solar masses. At this point, the carbon/oxygen core of the star begins to undergo rapid thermonuclear burning resulting in the explosion of the star. Simulations of SNe Ia are not able to model the full range of scales needed to simulate thermonuclear burning from first principles. Numerical models for Type Ia supernovae require the specification of the turbulent burning speed. Laminar burning velocities for thermonuclear flames are extremely small relative to the sound speed in the star, making detailed studies of turbulence flame interactions intractable using compressible flow simulations. Consequently, current approaches typically incorporate some type of phenomenological model for the turbulent flame speed.

This paper uses a low Mach number model to study the detailed evolution of planar flame sheets propagating through a three-dimensional turbulent background. In particular, the simulations focus on the detailed microphysics of turbulence / flame interactions. The use of a low Mach number adaptive algorithm allows us to accurately resolve the thermal structure of the flame and capture the inviscid energy cascade, while implicitly incorporating energy dissipation at the grid-scale. Conditions for the simulations are based on estimates for the background convective turbulence within the star. The simulations span a range of conditions from the flame-let regime to the distributed burning regime, achieved by varying the density of unburned gas, which controls the laminar flame speed. The local response of the flame to wrinkling induced by turbulence is explored, along with the global effect on overall flame speed. The implications of the simulations for the development of turbulent flame speed models will also be discussed.

Shock Wave Revival and Turbulent Mixing in Supernovae Explosions

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One of the outstanding problems with supernovae is how they explode. It is generally accepted that neutrinos play a part in heating the dense plasma reviving a stalled shock wave that is responsible for exploding the star. In this paper we describe how neutrino plasma instabilities can result in restarting and breaking up of the shock wave forming turbulent structures that propagate out through the star creating nonspherical explosions. The inhomogeneous density structures created are responsible for modulating the neutrinos through the MSW matter effect, also described. More sensitive neutrino detectors may be used as a probe for the early phase of supernovae dynamics.

The Origin of Magnetic Fields in the Universe and the Turbulent Dynamo

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Magnetic fields are observed very early in the evolution of structure of the universe. It is not known how or when these fields were created. I will discuss the various theories of the field origin and the fluid mechanical issues that arise. Small scale fields of observable amplitudes are relatively easy to create on short time- scales by turbulent flows or compact objects. The central issue is the creation of the observed long scale coherence in the field. I will discuss the generation of such long-scale coherence in mixing turbulent flows.

SN Evolution in Massive Star Winds, and Associated Hydrodynamic Instabilities

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Core-Collapse supernovae (SNe) arise from massive stars, (> 8 solar masses). As these stars evolve along the main sequence and beyond, they tend to lose a large amount of mass through winds and outbursts. This material accumulates around the star, forming circumstellar (CS) wind-blown bubbles. The wind properties (mass-loss rate and wind velocity) will also evolve during the various phases of the star's evolution, giving rise to a complicated CS structure, accompanied by the formation and growth of various hydrodynamical instabilities, and the onset of turbulence. When the star ends its life in a SN explosion, the resulting shock wave will interact with this altered medium, modifying the evolution of the remnant from that in the ISM, and giving rise to further instabilities.

Using analytic models and high-resolution numerical simulations, we first discuss the evolution of the medium around a massive star. The slowly changing position of the wind termination shock gives rise to pressure variations and the deposition of vorticity into the medium. This vorticity is carried out along with the

shocked wind, giving rise to a highly turbulent structure and large azimuthal velocities. In later stages we see the rise of various instabilities, especially Rayleigh-Taylor instabilities in the post-main-sequence phases. We then discuss the evolution of the SN shock wave within this medium, and show how the turbulent medium causes the SN shock wave to be corrugated, with loss of spherical symmetry. The shock interacts with the surrounding shell in a piecewise manner, a phenomenon seen recently in SN 1987A.

Spin evolution in young low mass stars

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The usual explanation for the low rotation rates observed in young low mass stars is based on disk locking theory whereby angular momentum is transferred from the star to a surrounding accretion disk. However, recent considerations suggest that the magnetic interaction is indeed, not enough for the braking required by observations. If the star and disk are assumed as perfect conductors, high values of differential rotation between star and disk lead to a progressive inflation and eventually opening of the poloidal component of the magnetic field. In order to quantify the effect of the opening on the stellar rotation rate, we construct a parameterized, time-dependent model for spin evolution of a young solar type star including the effect of the opening through only one parameter and at the approximation in which the magnetic diffusivity is of the order of magnitude of the disk's effective viscosity. Solutions were compared with those obtained with a classical model without opening. Results confirm that the spin-down torque is less efficient than predicted by the classical disk locking scenario. We therefore conclude that another loss angular momentum mechanism must be active during the first stages of the stellar formation, possibly through a stellar wind along the open field lines.

Turbulent Mixing in the Interstellar Medium - an application for Lagrangian Tracer Particles

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Turbulent mixing of chemical species in the Interstellar Medium (ISM) has profound consequences on the morphology, chemistry, cooling and shielding of Molecular Clouds (MCs). MCs are known to be the formation site of young stars. It is therefore a prerequisite in a successful theory of star formation to explain the physical and chemical environment in which stars are born. It is well established that MCs show supersonic turbulent motion on parsec length scales. The compressions that are

created by the formation of strong shocks thereby facilitate the formation of molecular hydrogen H2. Observations of MCs detect CO as a tracer for H2 which is, however, found to be ubiquitous throughout the cloud and not only in regions of high density. An explanation for the relative homogeneity of H2 in this respect, can be turbulent transport to lower density regions. We adopt 3-dimensional numerical simulations of self-gravitating turbulent gas in combination with Lagrangian Tracer Particles to investigate the mixing process of H2 in MCs. Tracer Particles are used to represent dense gas which is associated with H2. We initially place them in regions of a density contrast larger than 10 times the mean density of the gas. We then follow their trajectories and find an upper limit for the mixing timescale for H2 of the order of $10^5\,\text{yr}$. This is significantly smaller than the lifetime of MCs which demonstrates the importance of turbulent H2-mixing as preliminary stage to star formation.

Turbulent mixing in natural fluids

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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. Fossil turbulence is defined as a perturbation in any hydrophysical field produced by turbulence that persists after the fluid is no longer turbulent at the scale of the perturbation. Turbulence always cascades from small scales to large because vorticity is produced at the Kolmogorov scale by viscous stresses extracting kinetic energy from the non-turbulent irrotational flow. Adjacent eddies with the same spin are forced to merge by vxw forces, driving the cascade to large scales where eddies and microstructure are fossilized by buoyancy or Coriolis forces, or by the exponential inflation of space beyond the scale of causal connection in the case of big bang turbulence and the first turbulent combustion (Gibson 2005) giving the first fossil turbulence (Gibson 2004). Patterns of cosmic microwave background temperature anisotropies (Bershadskii and Sreenivasan 2002 and Bershadskii 2006) preserve information about big bang turbulence and confirm its Reynolds number of order 10^5. Self gravitational fragmentation of the plasma at 30,000 years begins at protosupercluster scales as shown by the small scale of the acoustic peak, and ends with the formation of protogalaxies with density preserved at the Nomura scale 10^20 meters and with the morphology of small scale turbulence (Nomura and Post 1998), as shown by the Hubble Space Telescope ultra deep field (Gibson and Schild 2007). In the ocean, atmosphere, and the interior of stars, vertical and radial transport occurs by a complex but generic interaction of turbulence, fossil turbulence and small scale nonlinear internal waves termed beamed zombie turbulence maser action mixing chimneys.

See http://www-acs.ucsd.edu/~ir118 for details and references.

Turbulent Entrainment in Stellar Interiors

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We describe the results of three-dimensional (3D) numerical simulations of turbulent oxygen shell burning and hydrogen core burning in a 23 solar mass stellar model. A detailed study is made of the heat and composition transport in the stratified, turbulent flow, including a detailed comparison to mixing length theory (MLT) for shell convection. We find that the extents of mixed regions are better predicted using a dynamic boundary condition based on the bulk Richardson number than by purely local, static criteria like Schwarzschild or Ledoux. Convective "overshooting" is better described as an elastic response by the convective boundary, rather than ballistic penetration of the stable layers by turbulent eddies. The boundaries of the turbulent layer are rife with internal and interfacial wave motions, and a variety of instabilities arise which induce mixing through a process best described as turbulent entrainment. We find that the rate at which boundary layer mixing proceeds is consistent with analogous laboratory experiments as well as simulation and observation of terrestrial atmospheric mixing. In particular, the normalized entrainment rate E=u_E/sigmaH, is well described by a power law dependence on the bulk Richardson number Ri_B = \Delta b L/sigmaH**2 for the conditions studied, 20 < Ri_B < 420. We find E = A Ri_B**{-n}, with best fit values, log A = 0.027 +/- 0.38, and n = 1.05 +/- 0.21. We discuss the processes underlying the boundary layer mixing and the applicability of these results to stellar evolution calculations.

Radiation-Gasdynamical Simulations of Star Formation

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We study the coupling of radiation and hydrodynamics and its impact on star formation. We are especially interested in the effects of radiative feedback on the formation of massive and low-mass stars. Can radiation prevent further accretion on a massive star? Does a massive star in the neighborhood of a molecular cloud prevent or trigger the formation of stars in the cloud? Is this a way how low-mass stars are formed? These questions are studied with 3D AMR simulations using the FLASH code.

Peta-scale computing in astrophysics

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On the Evolution of Thermonuclear Flames on Large Scales

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The thermonuclear explosion of a massive white dwarf in a Type Ia supernova explosion is characterized by vastly disparate spatial and temporal scales. The extreme dynamic range inherent to the problem prevents the use of direct numerical simulation and forces modelers to resort to subgrid models to describe physical processes taking place on unresolved scales. We consider the evolution of a model thermonuclear flame in a constant gravitational field on a periodic domain. The gravitational acceleration is aligned with the overall direction of the flame propagation, making the flame surface subject to the Rayleigh-Taylor instability. The flame evolution is followed through an extended initial transient phase well into the steady-state regime. The properties of the evolution of flame surface are examined. We confirm the form of the governing equation of the flame surface evolution suggested by Khokhlov (1995). A new flame surface enhancement subgrid-scale model is developed based on this governing equation.

MAGNETO-HYDRODYNAMICS

Chaotic dynamos generated by turbulent flows

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We first report the observation of a magnetic field generated by a turbulent von Karman flow of liquid sodium (VKS dynamo experiment). Small changes of the flow driving parameters generate different dynamical regimes of the magnetic field: oscillations, intermittent bursts and field reversals. In a second part, we discuss the effect of turbulence on the nature of the dynamo bifurcation, on the geometry of the generated magnetic field and on scaling laws for the magnetic energy density. We finally compare the reversals observed in the VKS experiment with recordings of the reversals of the Earth magnetic field and discuss theoretical models.

Saturation of the Magneto-rotational Instability: Asymptotically Exact Theory

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The magnetorotational instability is of fundamental importance in astrophysics, and is increasingly the subject of laboratory experiments. An analytical, asymptotically exact theory has been developed that describes the process of nonlinear saturation of this instability under conditions relevant in astrophysics [1]. In this regime the instability saturates by extracting energy from the shear, and modifying the shear responsible for it. The essence of the approach is captured by the shearing sheet approximation with arbitrary (but linear) shear flow, but the theory can be extended to both cylindrical and spherical domains, and to describe the approach from small amplitude perturbations to the final strongly nonlinear saturated state. This talk will describe the theory and will present preliminary comparisons of the theoretical predictions with the results of direct numerical integration of the MHD equations.

[1] E. Knobloch and K. Julien, Phys. Fluids 17, 094106 (2005)

The effects of rotation and magnetic fields on turbulence

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Turbulence occurs in the Earth's atmosphere and outer core, in the atmospheres of the other planets, in the convective zones of stars including our sun, and most astrophysical situations. We probe aspects of the dynamics of these flows using experiments in liquid sodium, helium, nitrogen, and water. The goal of these numerous experimental devices is to explore how turbulence interacts with rotation, magnetic fields or both. As both add some measure of elasticity to the flows, several types of oscillatory behavior are observed in the experiments depending on the force balance involved. Ordering the Coriolis, Lorentz, and inertial forces is key to understanding the complicated states observed. While these experiments are undertaken in part to understand the geodynamo, they have led to a number of different first observations, including the magnetorotational instability, inertial waves in spherical Couette flow and inertial waves in decaying rotating turbulence in cryogenic fluids. These latter experiments have led to our directly observing superfluid vortices in He4. We will also report on our recent exploration of cylindrical Couette flow (Taylor-Couette flow) in sodium with magnetic fields.

MHD Turbulence and Turbulent Mixing in Astrophysical Flows

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Understanding of turbulence within magnetized gas is essential for understanding of many astrophysical processes, including dynamics of molecular clouds, cooling of gas, as well as to star formation. In dealing with the problem we adopted an approach that includes, first of all, a quest for scaling relations for compressible MHD turbulence; second, studies of astrophysical turbulence from Doppler-shifted spectral lines; third, simulating effects of turbulence mixing on astrophysical gas at different temperatures. On the first topic I shall report on (a) a density modification of velocities that restores the Kolmogorov scalings for the modified quantities for magnetized turbulence with the sonic Mach number up to 10, (b) the degree of coupling between the fundamental MHD modes and their dependence on sonic and Alfven Mach numbers. On the second topic, I shall report on two new techniques to study astrophysical turbulence and results on turbulence spectra obtained with the techniques for galactic HI and CO data. On the third topic, I shall report on results on the MHD simulations of the turbulent mixing layers for high latitude galactic gas.

Structure and growth rates of magnetic fields in helical turbulence

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We investigate the amplification of magnetic fields by a turbulent velocity field with nonzero helicity, in the framework of the kinematic Kazantsev-Kraichnan model. We present the full numerical solution of the model for the Kolmogorov distribution of velocity fluctuations, with large Reynolds and magnetic Reynolds numbers. We found that in contrast with the nonhelical case where a growing magnetic field is described by a few bound eigenmodes concentrated inside the inertial interval of the velocity field. In the helical case the number of bound eigenmodes considerably increases, moreover, new unbound eigenmodes appear. Both bound and unbound eigenmodes contribute to the large-scale magnetic field. This implies a limited applicability of the conventional alpha-model of a large-scale dynamo action.

The authors are the members of the Center for Magnetic Self-Organization (CMSO).

Magneto-rotational instability, turbulence and dynamo.

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It is commonly believed that angular momentum transport in astrophysical accretion disks is due to turbulence that arises in the non-linear development of the magneto-rotational instability (MRI). The MRI occurs in Rayleigh-stable rotating systems destabilized by the presence of a weak external magnetic field and finite conductivity. It has been studied intensively in the local approximation and more recently, in entire disk simulations to capture full complexity of accretion processes. Here we report the first realization of fully developed magneto-rotational turbulence in the idealized geometry between two concentric co-rotating cylinders inspired by the MRI liquid metal experiment in Princeton. The purpose of our three-dimensional incompressible magneto-hydrodynamical (MHD) computations is to study the magneto-rotational turbulence and angular momentum transport in the simplest manifestation. Our results for Reynolds number Re=62,000 (magnetic Reynolds numbers Rm=31,000) show that MRI saturates both due to the enhanced viscous and ohmic dissipation and basic flow modification from the initial Couette flow toward solid body rotation. The observed strong correlation between radial and azimuthal fluctuations of magnetic field in this regime increases the angular momentum transport by a factor of 20 compared to the initial Couette flow. Finally, at this high magnetic Reynolds number the magneto-rotational turbulence becomes an efficient dynamo capable of sustaining the magnetic field and therefore, the effective angular momentum transport even in the absence of the externally imposed magnetic field.

Computer Modeling of the Accretion Disk Corona

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Accretion disks are unique objects in astrophysics. The physics of accretion disks is closely related to gamma ray bursts and plasma jets associated with stars. The formation and dynamics of a star can not be described without a proper accretion disk model. Angular momentum transport in the disks is a key in understanding of accretion mechanisms. Conservation of angular momentum prevents the accretion. The microscopic resistivity and viscosity are too small to explain the accretion rate inferred from observations. The turbulence dissipation has been considered as a possible mechanism of removal of angular momentum in accretion disk. However, there are no sufficient evidences of developed turbulence in many disks such as disks around young stars and disks in binary systems. Possible mechanisms of angular momentum transport in accretion disks are discussed in this report. Evolution of a magnetic loop in an accretion disk corona is studied by using the resistive MHD code MAB. We test an idea that the evolution of coronal magnetic fields might make differential rotation flows in the disk to be unstable by leading to the development of coronal magneto-rotational instability (MRI) and enhancement of angular momentum transport in the disk. The MHD equations for the accretion disk and its corona are modeled separately. The poloidal component of magnetic field and the velocity field in the disk are used as a boundary condition to advance the coronal flows. The toroidal and radial components of magnetic field are computed in the corona simulation and their boundary values are used in turn to advance the accretion disk flows. This provides a feedback loop between the MHD flows in the accretion disk and its corona. In this report, the evolution of a single coronal magnetic loop and the corresponding angular momentum transport in the disk are considered.

Magnetic reconnection and chaotic behavior in plasmas

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The theory of magnetic reconnection in plasmas will be reviewed. Special attention will be given to recent results pertaining to the behavior of plasmas in weakly collisional regimes, where electron inertia rather than collisional dissipation allows for the violation of the frozen-in-law that couples magnetic field lines to the plasma motion. In the two-dimensional approximation, we show that the flows associated with the reconnection process can be subjected to Rayleigh-Taylor instabilities. Three-dimensional effects will give rise to chaoticity of the magnetic field lines, described in terms of trajectories of an Hamiltonian system. Consequences on the turbulent transport of particles and energy and its relevance to experimental observations from tokamak fusion plasmas will be pointed out. Open problems will be discussed.

GEOPHYSICS

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 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. 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 impinge on an interface located in a two-layer stably stratified environment. The entrainment rate is quantified for each flow using Laser-Induced Fluorescence. 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

Turbulence in gravity-driven stratified layers: Understanding oceanic overflows using laboratory experiments

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Oceanic overflows are important elements of the earth's global thermo-haline circulation but the mixing and entrainment that occur for such overflows is poorly understood. In particular, as the overflow water moves down an incline, it accelerates and generates a stratified gravity current. The stability of this current is governed by the competition between stratification, which stabilizes the flow, and vertical shear, which tends to destabilize the flow. We measure the properties of a laboratory experiment designed to mimic oceanic overflows to the degree possible on laboratory-accessible length scales. The flow exits a nozzle and flows along an inclined plane such that there is a gravitational forcing of the flowing gravity current. We inject velocity fluctuations into the fluid prior to its exit from the nozzle, thereby generating a turbulent boundary layer condition at the plane boundary. The Taylor Reynolds number of the flow coming out of the nozzle is about 100. We simultaneously measure velocity fields using particle different approaches and directly measure the gradient Richardson Number for the flow as a function of spatial position. We simultaneously measure velocity fields using particle image velocimetry and density fields using planar laser induced fluorescence. We will present characterization of the gravity current including mean and fluctuating parts of the velocity and density fields as a function of distance from the inclined plate and the distance downstream. We also measure the local momentum and buoyancy stresses and related them to vertical gradients in the mean velocity and density, respectively. Further, we compute the entrainment rate using several different approaches and directly measure the gradient Richardson Number for the flow as a function of spatial position. Finally, we compare our results with in-situ measurements of oceanic overflows.

Experimental study of mixing, coherent structures and hysteresis phenomenon in turbulent convection

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Coherent large-scale circulations of turbulent thermal convection in air have been studied experimentally in a rectangular box heated from below and cooled from above using Particle Image Velocimetry. The hysteresis phenomenon in turbulent convection was found by varying the temperature difference between the bottom and the top walls of the chamber (the Rayleigh number was changed within the range of $10^7 - 10^8$). The hysteresis loop comprises the one-cell and two-cells flow patterns while the aspect ratio is kept constant (A = 2 - 2.23). This study demonstrates that the anisotropy of turbulent velocity field plays a crucial role in the hysteresis phenomenon. The observed transition from the two-cell to one-cell flow patterns causes a drastic change of the degree of anisotropy of the turbulent velocity field from negative to positive values [1]. The developed theory of coherent structures in turbulent convection [2-4] is in agreement with the experimental observations. The redistribution of the turbulent heat flux plays a crucial role in the formation of coherent large-scale circulations in turbulent convection. Two competitive effects, namely redistribution of the vertical turbulent heat flux due to convergence or divergence of the horizontal mean flows, and production of the horizontal component of the turbulent heat flux due to the interaction of the mean vorticity with the vertical component of the turbulent heat flux, cause the large-scale instability and formation of the large-scale coherent structures in turbulent convection. The obtained results may be important in atmospheric turbulent convection and laboratory turbulent flows.

[1]. A. Eidelman, T. Elperin, N. Kleeorin, A. Markovich, I. Rogachevskii, *Experiments in Fluids* **40**, 723 (2006); [2]. T. Elperin, N. Kleeorin, I. Rogachevskii, S. Zilitinkevich, *Phys. Rev. E* **66**, 066305 (2002); [3]. T. Elperin, N. Kleeorin, I. Rogachevskii, S. Zilitinkevich, *Boundary-Layer Meteorology* **119**, 449 (2006); [4]. T. Elperin, I. Golubev, N. Kleeorin, I. Rogachevskii, *Phys. Fluids* **18**, 126601 (2006).

Experimental study of large-scale mixing of particles in stably and unstably stratified turbulent flows

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The main goal of this communication is to review our recent experimental studies of mixing of inertial particles and formation of large-scale structures in spatial distribution of particles. In particularly, we discuss a new phenomenon of turbulent thermal diffusion which was predicted theoretically in [1]. The essence of this phenomenon is the appearance of a nondiffusive mean flux of particles in the direction of the mean heat flux. This phenomenon causes formation of large-scale inhomogeneities in the spatial distribution of particles that accumulate in the regions of minimum mean temperature of the surrounding fluid. Turbulent thermal diffusion is a fundamental phenomenon which should be studied for different types of turbulence and different experimental set-ups. The effect of turbulent thermal diffusion has been detected experimentally in air flow in two experimental apparatuses: oscillating grids turbulence generator and multi-fan turbulence generator. These devices are capable of producing a confined homogeneous turbulent flow with a small mean velocity. We use Particle Image Velocimetry to determine the turbulent velocity field, a specially designed temperature probe with twelve sensitive thermocouples to measure the temperature field, and an Image Processing Technique based on an analysis of the intensity of Mie scattering to determine the spatial distribution of particles. We performed experiments with two directions of the mean temperature gradient, for stably stratified fluid flow (the cooled bottom and heated top walls of the chamber) and for unstably stratified fluid flow (see, e.g., [2-5]). It has been found in our experiments that in an unstably stratified flow particles accumulate in the vicinity of the top wall of the test chamber (in the vicinity of the minimum mean temperature). In a stably stratified flow particles accumulate in the vicinity of the bottom wall of the test chamber. We demonstrated that independently of the method of turbulence generation and even in strongly inhomogeneous temperature fields, particles accumulate at the regions with minimum of mean temperature of surrounding fluids due to the phenomenon of turbulent thermal diffusion. The phenomenon of turbulent thermal diffusion can cause formation of the large-scale aerosol layers in the atmospheric turbulence with temperature inversions.

[1]. Elperin T., Kleeorin N. and Rogachevskii I., *Phys. Rev. Lett.* **76**, 224-227 (1996); [2]. Eidelman, A., Elperin, T., Kleeorin, N., Krein A., Rogachevskii I., Buchholz J., and Grünefeld, G., *Nonlinear Processes in Geophysics* **11**, 343-350 (2004); [3]. Buchholz, J., Eidelman, A., Elperin, T., Grünefeld, G., Kleeorin, N., Krein, A., and Rogachevskii, I., *Experiments in Fluids* **36**, 879-887 (2004); [4]. Eidelman, A., Elperin, T., Kleeorin, N., Markovich, A., and Rogachevskii, I. *Nonlinear Processes in Geophysics* **13**, 109-117 (2006); [5]. Eidelman, A., Elperin, T., Kleeorin, N., Rogachevskii, I., and Sapir-Katiraie, I. *Experiments in Fluids* **40**, 744-752 (2006).

Zonostrophic Turbulence

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Zonostrophic turbulence is a subset of geostrophic turbulence and is a regime of anisotropic large-scale circulation often established in the terrestrial and planetary environments. Zonostrophic turbulence develops in flows with a small Burger number and owes its existence to a small-scale convective and/or baroclinic instability and anisotropic inverse energy cascade in the barotropic mode. Details of the dynamics and dispersion processes will be presented via numerical experimentation using forced-dissipative barotropic vorticity equation on the surface of a rotating sphere. Zonostrophic turbulence is distinguished by a strongly anisotropic energy spectrum the zonal component of which follows a steep n^{-5} distribution while its nonzonal counterpart retains the classical $n^{-5/3}$ slope, n being the total wavenumber in spherical harmonics decomposition. We shall discuss relevant scaling parameters, non-dimensional numbers, and circulation regimes characteristic of different parameter ranges. We shall analyze the spectral energy transfer and show that anisotropization and zonation (generation of a set of alternating zonal jets) are intrinsic in zonostrophic turbulence. The analysis of the energy and enstrophy spectra and corresponding spectral transfers sheds light on many aspects of this complicated flow regime. Using spectral analysis in the frequency domain, we shall elaborate upon waves inherent in zonostrophic turbulence, their interactions amongst themselves and with turbulence. We shall show that this interaction produces a new class of nonlinear waves, or zonons, which can be described neither within a theory of weakly anisotropic nor wave turbulence. Zonostrophic turbulence is most profound on solar giant planets where it manifests itself in systems of powerful, slowly-varying, alternating zonal jets. In the terrestrial oceans, zonostrophic turbulence is revealed in narrow subsurface zonal jets appearing in high-resolution simulations and tracer dispersion patterns. Recently, the regime of zonostrophic turbulence has been reproduced in the Grenoble experiment conducted in the Coriolis turntable.

Mixing-induced global modes in open reactive flows

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We address the problem of mixing in reaction-advection-diffusion systems in open regular and chaotic flows and focus on a competition of absolute and convective instabilities. We consider a laminar mean through flow with a localized mixing region, e.g., in an open flow through a pipe. The flow is active, i.e., some substance in the flow (plankton or a chemical) grows. We fix the mean velocity in such a way that

in case of no mixing all the plankton is moved away sooner or later; this picture corresponds to the convective instability. In the presence of mixing, the situation can change towards the absolute instability, when a nontrivial concentration pattern, the so called global mode, is born. Based on a generalized Kolmogorov-Petrovsky-Piskunov-Fischer model, we develop a theory for such a transition, considering three qulitatively different mechanisms of nonuniformity in the flow: (i) the mixing "spot" of nonuniform activity, (ii) the spot of nonuniform diffusivity, (iii) the mixing region due to a regular or chaotic vortex. We demonstrate that the transitions in cases (ii) and (iii) are in many ways equivalent, which is in agreement with the effective-diffusion formalism, whereas case (i) reveals qualitatively different features. Our systematic approach includes analytical and numerical treatment of the linear and nonlinear problems in one- and two-dimensional geometries. The effects predicted are generic and are expected to be valid for different systems and at different scales: from the dynamics of biological species in geophysical flows to chemical reactions in microfluidic devices.

Anisotropic Turbulence and Internal Waves in Stably Stratified Flows (QNSE Theory)

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Vertical-horizontal anisotropy and turbulence-internal wave interaction are among the most fundamental problems one encounters in modeling of turbulent flows with stable stratification. Governed by strong nonlinearity, these two phenomena have been beyond reach for analytical theories. Here, we present a self-consistent theory capable of dealing with host of complicated factors introduced by nonlinearity and stable stratification within a framework of a second-moment spectral closure – Quasi-Normal Scale Elimination (QNSE) theory. Treating turbulence and waves as one entity, the QNSE theory offers a solid mathematical foundation for analytical handling of difficult problems related to anisotropic turbulence with waves. Among these problems are the threshold criterion for generation of internal waves, internal wave frequency shift due to turbulence, and the modification of the wave's dispersion relation by turbulence. The QNSE theory indicates that there is no a single-valued critical Richardson number, Ri, at which turbulence is fully suppressed by stable stratification, in agreement with large amount of atmospheric, oceanic and laboratory data. Instead, there exists a range of Ri, between, approximately, 0.1 and 1, in which turbulence undergoes remarkable anisotropization: the vertical mixing becomes suppressed while the horizontal mixing is enhanced;. The theory also yields analytical expressions for various 1D and 3D kinetic and potential energy spectra that reflect the effects of waves and anisotropy. The transition from the Kolmogorov to the stable

stratification dominated N^2k^{-3} spectrum is obtained on scales of the order of the Ozmidov scale. The model's results are suitable for immediate use in practical applications. We shall present results of the tests of the QNSE-based model with a state-of-the-art numerical weather prediction system and demonstrate that our model substantially improves the system's prediction skills.

PHYSICS of ATMOSPHERE

Vertical Turbulent Mixing Model for the Convective Boundary Layer

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Understanding of the atmospheric turbulent mixing, description of the planetary boundary layer characteristics and improvement of parametrization is important for air pollution transport and many other environmental models as well as for weather forecasting. Turbulent mixing in the atmosphere is commonly described by different types of local closure based on analogy with molecular diffusion. Local closure may fail in the convective boundary layer because the influence of large-scale transport is not accounted. This problem can be avoided if we use a non-local, advection-like concept. The non-local eddy diffusivity schemes and asymmetrical mixing models take place in the recent generation models. Assuming that large-size eddies transport fluid across finite distances and smaller eddies mix it simultaneously a simple non-local model was developed for simulation of vertical turbulent mixing in the convective boundary layer using time splitting procedure. The vertical mixing model was linked with a model for the mixing height determination (mixing height is one of the fundamental parameters to characterize the structure of the atmospheric boundary layer). Chemical materia can be emitted from sources at any point of the convective boundary layer, so top-down, bottom-up and mid-level plume numerical tests were done for passive and reactive pollutants. Parametrization of the mixing rates was based on turbulent velocity (function of surface turbulent kinetic energy). Results were compared with the numerical tests obtained for asymmetrical convective model.

Turbulent Mixing in the Environment and Impacts beyond Its Scale

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Stable stratification and turbulence are ubiquitous features in environmental flows, and the interaction between them leads to a myriad of phenomena such as internal waves, instabilities, flow meandering and turbulent mixing. In the oceans, turbulence in the upper mixed layer interacts with the stably stratified thermocline below, and mixing at the interface between the two determines how heat, mass and momentum transfer occurs in the upper ocean. The nocturnal atmospheric boundary layer is strongly stratified due to radiative cooling, and advection and dispersion therein is key to the development of nocturnal pollution episodes as well as air

pollution in the following morning. Predictions of nighttime temperature are also sensitively dependent on how heat and momentum transport in the nocturnal boundary layer is quantified. In predictive environmental flow models, many of the small-scale mixing phenomena cannot be resolved and hence need to be parameterized by using knowledge gained via fundamental studies. Recent attempts to understand and parameterize small-scale mixing processes in stable layers using theoretical, laboratory, numerical and field studies will be described in this presentation, paying particular attention to mixing across sheared and shear-free interfaces and turbulent convective flows bounded by inversion layers. The application of results, in combination with meso-scale numerical modeling, to predict oceanic and atmospheric flows will also be discussed. Of particular interest will be the demonstration of pervasive impacts of small scale mixing processes in determining the local weather, regional climate and air quality – the geophysical repercussions of turbulent mixing beyond its scale.

A comparison of statistical dynamical and ensemble prediction methods during the formation of large-scale coherent structures in the atmosphere

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In this paper we examine error growth using a family of inhomogeneous statistical closure models based on the quasi-diagonal direct interaction approximation (QDIA) and compare the results with those based on ensembles of direct numerical simulations using bred perturbations [1]. Our closure model includes contributions from non-Gaussian terms, is realizable and conserves kinetic energy and enstrophy. Further, unlike previous approximations such as those based on cumulant discard (CD) and quasi-normal (QN) hypotheses the QDIA closure is stable for long integration times and is valid for both strongly non-Gaussian and strongly inhomogeneous flows. We examine the performance of a number of variants of the closure model incorporating different approximations to the higher order cumulants. The roles of non-Gaussian initial perturbations and small scale noise in determining error growth are examined. We demonstrate the importance of the cumulative contribution of non-Gaussian terms to the evolved error tendency as well as the role of the off-diagonal covariances in the growth of errors. Cumulative and instantaneous errors are quantified using kinetic energy spectra and a small scale palinstrophy production measure respectively. As a severe test of our methodology we consider synoptic situations during a rapid regime transition associated with the formation of a block over the Gulf of Alaska. In general, the full QDIA closure results compare well with the statistics of DNS.

[1] O'Kane, T.J., & Frederiksen, J.S. (2007) A comparison of statistical dynamical and ensemble prediction during blocking. J. Atmos. Sci. (In Press)

Turbulent Mixing Scenario during Evening Flow Transition

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Thermally driven up and down-slope flows in complex terrain play an important role in local atmospheric circulation especially when they develop under weak synoptic forcing. Understanding of main turbulence characteristics of such flows is strictly relevant in dispersion modelling and in particular in studies tailored to the prediction of the fate of pollutants on enclosed valleys. Of particular interest is the period where up-slope flow occurring during the day transitions to down-slope flow. During this period, intense mixing is perceived to take place, wherein the up-slope flow stagnates and newly formed down-slope flow undercuts it forming a heavily vortical region with a high turbulence level. To study such processes, an evening transition experiment was conducted in the complex terrain of Phoenix, Arizona, dubbed the TRANSition FLow EXperiment (TRANSFLEX). In particular, the experimental design was guided by the theory of Hunt, Fernando, and Princevac (2003), which predicts a host of mixing processes driven by shear and convective instabilities. A suite of fast-response flow sensors, vertical-profiling tethered balloons and remote sensing instrumentation was employed together with particulate matter (PM) measurement devices. Wind speed and direction, temperature, velocity and temperature variances, and momentum and heat fluxes at or in the proximity of evening transition were analyzed to educe the dynamics of transition events. Multiple density current fronts were identified during transition events and their arrival was associated with turbulence episodes characterized by increases in velocity variances, momentum fluxes, and PM entrainment from the ground.

Hunt, J. C. R., Fernando, H. J. S., and Princevac, M.: 2003, 'Unsteady Thermally Driven Flows on Gentle Slopes', J. Atoms. Sci. 60, 2169-2182.

Atmospheric Turbulence Forecasting: Promising New Approaches Based on Bayesian Hierarchical Modeling and the High-Resolution Simulations and Observations Needed to Make them Work

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Meaningful high-altitude turbulence forecasts would be useful for many applications, ranging from aviation safety to laser-based communication. Nevertheless, numerical weather prediction models on which such forecasts are based lack the resolution needed to characterize the key dynamics, which include wind-shear instability, gravity-wave breaking, critical-level absorption, and the ensuring turbulence that results. As a result, current subgrid-scale (SGS) parameterizations in these models are applied at much larger length scales than are appropriate, and the key dynamical processes that give rise to turbulence are strongly damped. There are only two ways to address this problem: 1) increase model resolution or 2) employ a probabilistic approach. We are using both methods, and as such we have devised a Bayesian Hierarchical Model (BHM) for SGS parameterization in mesoscale forecast models that 1) estimates the local likelihood of key dynamical phenomena as a function of altitude from compiled balloon and aircraft data, 2) quantifies the dynamics using pre-computed high-resolution direct numerical simulations (DNS) of canonical processes, and 3) predicts probability density functions (PDFs) of desired SGS quantities. The beauty of the approach is that non-Kolmogorov statistics can be accurately described (even if they are not well understood) as long as the relevant processes are represented in the observations and the DNS. The feasibility of the approach is strongly encouraged by the observational data, whose PDFs exhibit non-trivial but universal forms that lend themselves to simple parameterization, and analysis of the PDFs gives the vertical resolution needed for deterministic forecast skill. Also, the high- resolution DNS of turbulent mixing layers we are using in the BHM demonstrate rich behavior that shows strong dependence on the Richardson number (Ri), making detailed comparisons with aircraft data and dynamical-event census feasible.

WALL-BOUNDED FLOWS

Baroclinic turbulence of dissociating gas as a reason for instability of bow shock wave

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Study of instability of bow shock wave and flow behind it in front of front of blunt body flowed around by dissociated polyatomic gas (the study started in 70 years of last century) [1] is urgent today yet, because there is needed to find a similar regimes for air. This investigation is looked to be perspective work for realization of economic flying apparatus. Because in spite of absence of energy deposition in front of shock wave it becomes destructed.

In this work some experimental data of spectral characteristics of turbulent flow of dissociating gaseous CF_2Cl_2 behind bow shock wave are presented. Found energy spectra of disturbances behind the body enable to measure one of main characteristic dimensions of turbulent flow. It is so called dimension of energy contained vortexes (0.3 мм), which occurred to be equal to mean dimension of disturbances on the front of bow shock wave and corresponds to the dissociation energy of CF_2Cl_2 (90.8kJ/kg). Other characteristic dimensions of investigated turbulence were found also. Comparison was made with the analogous dimensions for different mechanisms of arising turbulence: traditional viscous mechanism, mechanism depended only on the excitation of vibration states of molecules. Its result confirms the mechanism of molecules dissociation.

Theoretical analysis of equations for gas eddy flow together with analysis of the experimental data made it possible to find critical conditions at which effect of perturbation of bow shock wave is arising. These conditions take the place exactly at the flying regimes with bow shock wave perturbation and turbulent flow behind it at dissociation of CF_2Cl_2 in the compression region in front of body.

[1] Baryshnikov A.S., Bedin A.P., Maslennikov V.G., Mishin G.I. About instability of front of bow shock wave.//Pisma v GTF. 1979. V.5. N.5. P.281-284. in Russian.

On periodically excited turbulent mixing layer created downstream of a lane chevron partition

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The flow in a turbulent mixing layer resulting from two parallel, different velocity streams, that were brought together downstream of a jagged partition was investigated experimentally and numerically. A small flap hinged to the trailing edge of the partition had a triangular saw-tooth shape, and could also be forced to oscillate uniformly in a direction normal to the partition at a frequency that was prescribed at will.

The stationary saw-tooth trailing edge generated primary coherent vortices that were initially inclined to the flow in the direction of streaming but became also bent in the direction normal to the plane of the partition as a consequence of self-induction. This enhanced the streamwise vorticity component generated by the shape of the trailing edge and increased the mixing and turbulence levels observed in the flow. Periodic oscillation of the saw-tooth fliperon created large spanwise Kelvin Helmholtz (K-H) rolls that were locked in phase due to the uniformity of the oscillating solid boundary, but their circulation varied in a wavy fashion along the span, as a consequence of the triangular variation of the local chord of the fliperon. This motion inhibited the bending of the large eddies along the span while concomitantly forcing a local thickening (bulging) of these large eddies. Altering the amplitude of the imposed excitation alters the circulation in the spanwise rolls and thus alters the interaction between the streamwise and spanwise vortices in the mixing layer. This should allow one to control the mixing, the chemical reaction and the noise emitted by such flows and should provide a rational explanation for the effectiveness of a "Chevron Nozzle"

Analytic Model of the Universal Structure of Turbulent Boundary Layers

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Turbulent boundary layers exhibit a universal structure which nevertheless is rather complex, being composed of a viscous sub-layer, a buffer zone, and a turbulent log-law region. In this presentation we describe a simple analytic model of turbulent boundary layers which culminates in explicit formulae for the profiles of the mean velocity, the kinetic energy and the Reynolds stress as a function of the distance from the wall. The resulting profiles are in close quantitative agreement with measurements over the entire structure of the boundary layer, without any need of re-fitting in the different zones. Model also reveals functional dependencies of the von Karman constant and intercept parameter on Reynolds number or interpret mean velocity profile at finite Reynolds numbers as a power function.

Large Fundamentals of Wall Bounded Turbulence

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The goal of my lecture is to present physically transparent and as simple as possible but still adequate description of main statistical characteristics of wall-bounded turbulence, that accounts for basic physical processes and symmetries in classical examples of wall bounded turbulence: Large Re turbulent flows (Channel, Pipe and Couette flows, flow over incline plane in the gravity field (modeling river flows), atmospheric Turbulent Boundary Layer (TBL), etc; TBL with stable temperature stratification ,Time and spatial developing TBL, TBL with Stable temperature and heavy-particle Stratifications, etc.

Suggested "Minimal" models as a rule are versions of {algebraic Reynolds stress models}, designed to describe in {the plain geometry} the mean flow and} statistics of turbulence on the level of all relevant simultaneous, one-point second-order (cross)-correlation functions of velocity, temperature, particle concentrations, etc.

If required (for developing TBL, for the core of the channel flow, etc.) it includes nonlinear spatial fluxes of energy in differential approximations. The models are in good qualitative agreement with various Direct Numerical Simulations and experimental data.

High Reynolds Number Wall-Bounded Turbulence, the Approach to an Asymptotic State and International Consortium at CICLoPE

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Flat plate turbulent boundary layers under zero-pressure gradient at high Reynolds numbers are studied to reveal appropriate scale relations and asymptotic behavior. We find that many of the previously proposed empirical relations accurately describe the local Cf behavior when modified and underpinned by the same experimental data. The variation of the integral parameter H shows consistent agreement between experimental data and the relation from classical theory. In accordance with the classical theory, we also find that the ratio of Δ and δ asymptotes to a constant. Then, the usefulness of the ratio of appropriately defined mean and turbulent time scales to define and diagnose equilibrium flow is established. Next, the description of mean velocity profiles is revisited, and the validity of the logarithmic law is reestablished using both the mean velocity profile and its diagnostic function. The asymptotic behavior of mean velocity and integral parameters in these boundary layers is then examined for Reynolds numbers approaching infinity. Using the classical two-layer approach of Millikan and Clauser with a logarithmic velocity profile in the overlap region between "inner" and ``outer" layers, a fully self-consistent leading-order description of the mean velocity profile and all integral parameters is developed. It is shown that this description fits all the known high Reynolds number data and in particular their Reynolds number dependence exceedingly well, i.e., within experimental errors. The presentation also includes a discussion of the Reynolds number trends of other wall-bounded flows, the challenges in achieving good spatial resolution for the measurements, and the need for a new large well-documented facility for collaborative investigations of wall-bounded flows

at the Center for International Cooperation in Long Pipe Experiments (CICLoPE), at the University of Bologna.

The modification of decaying, homogeneous, isotropic turbulent flows by polymer additives

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The addition of polymers in small concentrations leads to a large amount of drag reduction in wall-bounded flows ([1], [2]). The drag reduction shows up as an increase in the mean velocity of the flow for a fixed applied pressure gradient. Since the size of the polymers, even under maximum extension, is much less than the Kolmogorov dissipation scale therefore, we study the effects of polymer additives on the small-scale properties of turbulent flows. To avoid the complications because of walls we numerically study the effects of polymers in decaying, homogeneous, isotropic turbulence. We model the polymer solution by using the incompressible Navier-Stokes equation coupled to the FENE-P equation. Our study [3] reveals clear manifestations of drag-reduction-type phenomena: On the addition of polymers to the turbulent fluid we obtain a reduction in the energy dissipation rate, a significant modification of the fluid energy spectrum especially in the deep-dissipation range, a suppression of small-scale intermittency, and a decrease in small-scale vorticity filaments.

[1] I. Procaccia, V.S. L'vov, and R. Benzi, arXiv:nlin/0702034. [2] K.R. Sreenivasan and C.M. White, J. Fluid. Mech. 409, 149(2000). [3] P. Perlekar, D. Mitra, and R. Pandit, Phys. Rev. Lett. 97, 264501 (2006).

CICLoPE - a response to the need for high Reynolds number experiments

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The understanding of high Reynolds number turbulence remains a great challenge nowadays. Although recent laboratory experiments, measurements in planetary boundary layer and direct numerical simulations provide a huge amount of information, none of these data sets provide high Reynolds number, high spatial resolution and well converge statistics at the same time. As a response to this problem, an international effort started some years ago to develop a new research facility allowing high spatial resolution even at high Reynolds number. This facility is currently under design and will be built at the Center for International Cooperation in Long Pipe Experiments (CICLoPE), at the University of Bologna. The presentation includes a discussion of the Reynolds number trends of various wall-bounded flows, the challenges in achieving good spatial resolution for the measurements, and the need for a new large well-documented facility for collaborative investigations of wall-bounded flows.

Numerical simulation of turbulent boundary layers affected by localized plasma patches

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The work deals with development of advanced methods of the boundary layer control based on local plasma generation by a system of microwave-initiated discharges. Results are presented on investigations of a turbulent boundary layer structure around an airfoil surface. Turbulence characteristics were studied numerically in a near-wall region affected by localized temperature sources placed on the airfoil surface or at a certain distance from the surface. Fields of temperature, pressure and velocity, shear stresses, lift and drag coefficients were obtained depending on the basic flow parameters, angle of attack, airfoil shape, a number and location of the temperature sources. Structure, intensity and scales of vortices generated in transitional and turbulent boundary layers were analyzed in cases of stationary and nonstationary temperature sources. Efficiency of the boundary layer control was estimated at various modes of operation of the microwave discharges taking into account actual energy consumption. Reynolds and Mach number ranges were evaluated where the developed method could be advantageous; recommendations are given for the method optimization for various control schemes accounting for the number and location of the controlled temperature sources. It was revealed that a properly organized system of localized discharges can influence turbulence structure and behavior due to forming and maintaining regular streamwise vortices of a given scale. In its turn, the modified turbulent structure can favorably affect the airfoil performance. The latter was demonstrated by lift and drag coefficients computed for various combinations of basic flow parameters and control schemes. Obtained numerical results are in a good agreement with experimental data showing the possibility to change turbulence scales in accordance with a specified problem of flow control, for example, one of flow separation aimed at turbulent drag reduction.

Speculation about near-wall turbulence scales

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Intrusion into a turbulent boundary layer results in modification of turbulence scales. In certain cases, it is similar to unsteady situations of transitional boundary layers. Following this analogy, a strategy is offered to impose a regular vortical structure typical for the laminar-turbulent transition over a developed turbulent flow. The basic task is to maintain the modified turbulent structure so that influencing mixing processes near the wall, one would improve flow characteristics. In terms of applications, it can imply better performance of airfoils or turbine blades.

Streamwise vortices were chosen as an imposed structure owing to their inherent presence in various flows. They were generated using resistively heated elements regularly spaced beneath a surface in a spanwise direction. Spanwise temperature gradient over the surface created necessary conditions for the development of streamwise vortices with a given space scale. Combined experimental and numerical investigations showed that persistence or life-time of the generated structure depended on correlation of control parameters (spanwise scale and temperature gradient) with basic flow parameters. The turbulent structure could be modified this way which resulted in an improved aerodynamic quality of an airfoil-type model obtained from measurements of lift, drag and pitch moment coefficients.

There were analyzed regimes of permanent and intermittent heating. The latter was considered as a prototype problem of localized flow heating with microwave-induced plasma patches. Intermittent heating shows a wavy character of aerodynamic coefficients depending on time starting from 5 s periods. That is plasma patches pulsating with a much greater frequency will not cause fluctuations of aerodynamic characteristics and, due to their nature, promise a more flexible and advanced method of flow control.

COMBUSTION

Scaling and renormalization for turbulent flow with reactions

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The problem of determining the upper bounds for the ensemble-averaged reaction front position and speed in a fully developed three-dimensional turbulent flow has been examined. The main area of practical interest concerning this problem is a turbulent combustion in the flamelet regime. It has been assumed that the reaction is of KPP-type and turbulent velocity is a random field exhibiting long-range correlations and infrared divergence in the limit of large Reynolds number. An asymptotic method has been developed that gives the general formalism for determining the upper bounds for reaction front in the long-time, large-distance limit. Two anomalous scaling regimes and corresponding scaling functions have been determined by the use of exact renormalization procedure. A closed equation for the one-point probability density function (PDF) for a scalar field advected by the three-dimensional random velocity field with arbitrary many spatial/ temporal scales has been derived. It has been shown that when the spectral parameters of a random velocity field slightly deviate from their Kolmogorov - Obukhov values, the equation for the PDF in the long-time, large-distance limit can be derived exactly and well described by a conventional diffusion theory, while the Lagrangian scaling function describing the large-scale particle displacements in turbulent flow is essentially superdiffusive. The scaling procedure in the limit of high Reynolds number allows us to completely overcome the well known closure problem associated with diffusion term.

Turbulent mixing and turbulent diffusion

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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. This mixing that must obey certain restrictions is called accurate. This gives an alternative formulation for the stochastic process which is selected to represent the continuous diffusion.

Mixing is used in many practical models which deal with scalar transport and combustion (the brief history of development of these models will be outlined in the presentation). This mixing is, generally, approximate and does not comply with the conditions imposed on accurate mixing. Using approximate mixing, however, has an advantage of significantly reducing computational cost. An approximate mixing scheme can be conventionally called a mixing model. Measures that can improve quality of mixing models without imposing heavy computational burden on simulations are considered.

We establish a fundamental link between Lagrangian pdfs, conditional concentrations and Eulerian pdfs. With the use of this link and Taylor's hypothesis for turbulent dispersion of scalar, the desired conditional properties can be forced upon the conventional mixing models resulting in improved quality of simulations without any significant loss of computational performance. This approach corresponds to generalized understanding of the Multiple Mapping Conditioning concept and it opens countless possibilities for constructing efficient mixing models with desired properties. Examples of this new generation of mixing models are considered.

Turbulent Mixing and Combustion in Explosions

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We consider the energy evolution in Shock-Dispersed-Fuel (SDF) explosions[1]. Energy is released in three phases: (i) detonation of the booster charge; (ii) expansion of the detonation products, leading to turbulent mixing and afterburning; (iii) dispersion of the particulate fuel (flake Aluminum), leading to turbulent mixing and combustion with air. Energy in SDF explosions is dominated by the Heat of Combustion of the fuel—which is 7-10 times larger than TNT explosions[2]. We use a Eulerian two-phase formulation; it is based conservation laws for the gas and particle phases along with inter-phase interaction terms[3]. Combustion is modeled by species conservation laws for the components (fuel, air and products); source/sink terms are treated in the fast-chemistry limit appropriate for such gas-dynamic fields[4]. The model takes into account all three energy release mechanisms (detonation, afterburning and combustion). The governing equations are integrated with high-resolution upwind methods that represent high order generalizations of Godunov's method[5]. The algorithm for the gas phase conservation laws is based on an efficient Riemann solver[6,7], extended to generalized conservation laws[8]. The algorithm for the particle phase conservation laws is based on a Riemann solver for dusty flows[9]. The two phases interact by mass, momentum and energy exchange, which are treated by operator splitting techniques. Adaptive Mesh Refinement (AMR)[10] is used to follow discontinuities, mixing regions and reaction zones. By using AMR, we are able to capture the energy-bearing scales of the turbulence on the grid, without resorting to turbulence modeling (the so called MILES approach[11]). Numerical simulations of 1.5-g SDF explosions in different chamber volumes (7-40 liters) and geometries

(1<L/D<12.5) were performed. Computed pressure waveforms were very similar to measured waveforms[12] in all cases—thereby demonstrating that the Model correctly predicts energy evolution in such explosions.

[1] P. Neuwald et al. "Shock-Dispersed Fuel Charges-Combustion in Chambers and Tunnels", Energetic Materials, 34th ICT Conf, 13.1-13.14, 2003. [2] A. L. Kuhl et al. "Effectiveness of Combustion of Shock-Dispersed Fuels in Calorimeters of Various Volumes" Combustion, Explosion and Shock Waves, Vol. 42, No. 6, pp. 731-734, 2006. [3] R. I. Nigmatulin, 1987, Dynamics of Multi-phase Flows. Vol 1. Moscow, Nauka, 464 pp. [4] A. L. Kuhl et al. "Gasdynamics of Combustion of TNT Products in Air", Archivum Combustionis, 19(1-4), pp. 67-89, 1999. [5] B. van Leer, "Towards the Ultimate Conservative Difference Scheme V: a Second-order Sequel to Godunov's Methods", J Comp. Phys., 32:101-136, 1979. [6] P. Colella and H. Glaz, "Efficient Solution Algorithms for the Riemann Problem for Real Gases", J Comp. Phys., 59, pp. 264-289, 1985. [7] P. Colella and P. R. Woodward, "The Piecewise Parabolic Method (PPM) for Gas-dynamical Simulations", J Comp. Phys., 54:174-201, 1984. [8] J. B. Bell et al. "Higher Order Godunov Methods for General Systems of Hyperbolic Conservation Laws" J Comp. Phys., 92(2):362-397, 1989. [9] P. Collins et al. "Simulation of Shock-Induced Dusty Gas Flows Using Various Models", AIAA 94-2309, AIAA Fluid Dynamics Conference, 1994; [10] J. Bell et al. "A Three-Dimensional Adaptive Mesh Refinement for Hyperbolic Conservation Laws", SIAM J. Sci. Statist. Comput., 15(1):127-138, 1994. [11] J. Boris et al. "New Insights into Large Eddy Simulation". Fluid Dynamics Research, 10, 1992; [12] H. Reichenbach et al. "Waveforms Measured in Confined SDF Explosions" Energetic Materials, 38th ICT Conference, 2007 (in press)

Effect of background turbulence on the propagation of large-scale flames

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On new possible directions of hydrodynamic instabilities and turbulent mixing investigations for the solution some practical problems

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Hydrodynamic instability and turbulent mixing play the important role in a problem of inertial confinement fusion (ICF) and astrophysics; it, first of all, also defines interest to the given problem. In the ICF problem hydrodynamic instability and turbulent mixing are the factors interfering achievement of ignition of thermonuclear fuel. Meanwhile, there are some other practical problems at which hydrodynamic instability and turbulent mixing are the factors promoting the solution of a problem. At the solution of similar problems results lead before researches and the developed methods can be used. And, if till now these developments were conducted from the point of view of the solution of a problem of suppression of instabilities or reduction of their nocuous action now these "harmful" properties can be used address various practical problems. In the report the review of new possible directions of researches hydrodynamic instabilities and turbulent mixing with regard to applied problems is presented. The phenomena of turbulent mixing can be under certain conditions used for creation of atomized liquids [1,2] and others media [3]. Similar aero-suspensions can find of wide application: Suppression of fires [2,4]; Reduction in explosive loadings [5,6]; Localization of harmful (radioactive) aerosols and a dust; Preparation of fuel-air mixtures in engines of internal combustion [2,7]; Hydrodynamic instability and turbulent mixing can play an essential role at explosive suppression of forest fires [8,9]. The powerful explosive short-term light source in which fast cooling of luminous explosive plasma is carried out due to turbulent mixing [10,11] is developed.

[1] E.Meshkov, N.Nevmerzhitskii. Turbulent Mixing Development in a Thin Liquid Layer Acclerated by a Compressed Air in Closed Volume. Technical Physics Letters. Vol.28, N4, 2002, pp.323-324. [2] Yu.Alekhanov, A.Levushov, A.Logvinov, S.Lomtev, E.Meshkov. About possibility receiving of atomized liquid mix with gas by means of a piston machine. Alternative power and ecology. №5, 2002, c.54-57 (in Russian). [3] M.Bliznetsov, I.Zhidov, E.Meshkov, N.Nevmerzhitskii, E.Sen`kovskii, E.Sotskov. Development of the Rayleigh-Taylor Instability at the Boundary of a Friable Medium Layer Acclerated by a Compressed Air Flow. Technical Physics Letters. Vol.28, N1, 2002, pp.80-81. [4] Yu.Alekhanov, M.Bliznetsov, Yu.Vlasov, V.Dudin, A.Levushov, A.Logvinov, S.Lomtev, E.Meshkov. Interaction of Dispersed Water with Flame. Technical Physics Letters. Vol.29, N3, 2003, pp.218-220. [5] V.Gorodnichev, E.Meshkov, N.Nevmerzhitsky, V.Rogachev, Yu.Yanilkin, I.Zhidov. The Effect of Turbulent Mixing on Operation of Liquid Protective Walls. Proc. of the 7th IWPCTM, St.-Petersburg, Russia, 5-9 July 1999, pp.472-477. [6] V.Afanas`ev, L.Belovodsky, I.Zhidov et al. A method of reduction in explosive loading in closed volume, Patent RF #2215983, 2003. [7] E.Meshkov, N.Nevmerzhitsky. A method of receiving of a mix atomized liquids with gas. Patent RF #2220009, 2003. [8] E.E.Meshkov. On Possible Role of Hydrodynamic Instabilities at Explosive Method for Extinguishing Forest Fires. Proc. of the 7th IWPCTM, St.-Petersburg, Russia, 5-9 July 1999, pp.477-478. [9] M.Bliznetsov, V.Dudin, S.Gerasimov, L.Houas, G.Jourdan, A.Logvinov, E.Meshkov, Yu.Vlasov. Development of a Method for Studying the Interaction between Shock Wave and a Flame. Abstracts of 8th IWPCTM, Pasadena, USA, 9-14 December 2001, p.12. [10] S.Gerasimov, E.Meshkov, N.Mischenko, S.Kholin. Mixing Light Source. Proc. of the 7th IWPCTM, St.-Petersburg, Russia, 5-9 July 1999, pp.469-471. [11] Gerasimov S., Meshkov E. Patent RF 215 26 65, 2000.

Multicomponent reactive flows

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Multi-component reactive flows arise in various engineering applications such as combustion, crystal growth or chemical reactors. The aim of this work is to develop a rigorous mathematical theory based on the principles of continuum mechanics. We consider a mixture of viscous, heat conducting compressible reactive fluids, consisting of N distinct components each of which has its own density, pressure, molecular weight but all components having the same velocity and temperature. The balance equations associated with multi-component reactive flows are the Navier-

Stokes equations expressing the conservation of mass, momentum, energy coupled with a system of N species conservation equations. The mathematical model presented here relies on the fundamental principles of continuum mechanics and combustion, where the balance laws, the constitutive relations and other assumptions on the model are based on the following considerations.

(a) The material (gas) is viewed as a viscous, compressible, heat conducting fluid, occupying a bounded domain in the physical 3-dimensional Euclidean space, which is a perfect mixture of N species of real mono-atomic gases.

(b) The motion of the gas is the entropy producing (dissipative) process. The transport fluxes satisfy very general constitutive laws taking into account the multi-component character of the mixture. The reaction rate satisfies a general kinetic relation and the transport coefficients depend on the absolute temperature.

(c) The pressure takes into consideration possible radiation effects.

In most practical applications one has to deal with dozens or rather hundreds of species undergoing many reactions that are, in general, completely reversible. Therefore, there is a fundamental need for developing a relevant mathematical theory. The main objective of the present work is to undertake a first step in this direction.

Numerical study of reactive Rayleigh-Taylor turbulence

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We consider the Rayleigh-Taylor (RT) instability between two miscible fluids in the presence of reaction; the reaction transforms heavier fluid into lighter fluid. The physical model is highly simplified - we use the Boussinesq buoyancy approximation and a one-step reaction mechanism, which allows us to fully resolve all viscous and diffusive effects in three dimensions. The novelty of this work is that the nonreacting RT problem is used as the base case, and the effects of weak/moderate/strong reaction are quantified using traditional turbulence diagnostics. As in the classical RT problem, we follow the evolution of the instability in an "infinite" domain, ensuring that the results are minimally affected by the finite size of the simulation. A number of earlier studies have shown that finite size effect stabilizes the reaction; here we are trying to eliminate the stabilizing effect of the walls. We focus on resolving both the large scale dynamics and the internal structure of the mixing zone/chemical front conglomerate.

MATERIAL SCIENCE

On the Possibility of Cumulative Behavior of Initial Perturbation Evolution on a Surface of Condensed Material Subjected to a Shock Wave

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It is shown numerically, theoretically and experimentally that when a shock wave reaches a curved surface of a condensed material the surface becomes unstable and the topology of this instability can differ from the classical Richtmyer-Meshkov instability. The obtained results prove that cumulative jets can form on a free surface of a condensed material.

Rayleigh-Taylor Instability and mixing in Micro- and Nanohydrodynamics

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Micro- and Nanohydrodynamics (MNHD) is different from meso and microscale hydrodynamics because of non-continuum effects. Surface dominated effects, low Reynolds number effect and multi-scale and multi-physics effects. Some examples of RTI and mixing are considered. The results are applied to some microbubble technology in hydraulic fracturing in oil industry and other problems. The presentation consists of the next parts.

1. Turbulent and Molecular Mixing Induced by Rayleigh-Taylor Instability: The problem of turbulent mixing in MNHD of 2 phase flow at different density contrast is considered on the basis of multiphase hydrodynamics. General problem is similar to “coffee- milk” mixing. At the first stage cascade mixing starts from large vortices and then involve less and less vortices till scales become compared with diffusion molecular mixing. This process is difficult to simulate because of low scale of molecular mixing. Analytical models and numerical simulation are developed and compared with experimental results.

2. Rayleigh-Taylor Instability in Rarefied Gas Dynamics Main difference MNHD RTI instabilities in gas phase from conventional hydrodynamics is in not small Knudsen number (ratio mean free path to the distance between plates). As an example of RTI in rarefied gas dynamics the convective instability of gas mixture placed between parallel plates when upper gas is heavier than lower, supposed to RTI

is considered. The stability problem is solved on the basis of Boltzmann equation and compared with the limits of low and high Knudsen numbers.

3. Rayleigh-Taylor Instability and mixing in microscale Viscous-Plastic Fluids Viscous-Plastic Fluids (VPF) is the fluid with constitutional relations different from Newtonian. In the simple case of elastic Bingham fluid the RTI at linear and nonlinear regime quite different from Newtonian because of effect “dry friction”.

General Theory for RTI in linear and turbulent regime and comparison with experiments is developed. For some widely used VPF there is low limit of mechanical destruction which has influence to developing RTI and material science applications.

INTERFACIAL DYNAMICS

Multi-scale character of the nonlinear dynamics of the Rayleigh-Taylor and Richtmyer-Meshkov unstable fluid interface

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We report nonlinear solutions for a system of conservation laws describing the dynamics of the large-scale coherent structure of bubbles and spikes in the Rayleigh-Taylor (Richtmyer-Meshkov) instability for fluids with finite density contrast. Three-dimensional flows are considered with general type of symmetry in the plane normal to the direction of gravity. The non-local properties of the interface evolution are accounted for on the basis of group theory. It is shown that isotropic coherent structures are stable. For anisotropic structures, secondary instabilities develop with the growth-rate determined by the density ratio. For stable structures, the invariants of the dynamics, independent of the density ratio, are found. Based on the obtained results we argue that the nonlinear large-scale coherent dynamics in the Rayleigh-Taylor (Richtmyer-Meshkov) instability has a multi-scale character and is governed by two length scale: the wavelength and the amplitude of the coherent structure. We discuss the validation of the theoretical approach and outline criteria for estimates of the information capacity of experimental data sets.

Effect of Initial Conditions on Late-Time Development of Rayleigh-Taylor Mixing

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A brief review of Rayleigh-Taylor mixing research will be presented, and previous evidence for initial condition dependence. Then we report recent results from numerical and experimental studies that explore the effect of initial conditions on the development of canonical Rayleigh-Taylor mixing. An extensive set of alternative initial density fluctuation power spectra have been explored on the computer that include: narrow band high wave number, broadband, and discrete banded spectra. A related, but less extensive, experimental study will also be reported. A strong dependence is found on the particular form of the initial power spectrum for density fluctuations, so memory of initial conditions is apparently retained, and the opportunity for “design” of mixing development is discussed.

Molecular dynamics simulation of the Rayleigh-Taylor instability

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There are several phenomena that influence the Rayleigh-Taylor instability (RTI). They include the viscosity, thermal conduction, thermodynamic non-ideality, surface tension, etc. Usual hydrodynamic approach does not take into account all these effects. The molecular dynamics simulation carried out in the present report provides more complete description of the RTI.

Multiphase Flow Model for the Unstable Mixing of Layered Incompressible Materials

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In this work, a model for the unstable mixing of n parallel or concentric incompressible fluid layers is proposed. The approach to constructing this model is pairwise, based on a known two incompressible fluid mixing model. The problem complexity increases significantly in going from two to three fluids, but the increase in complexity is relatively small thereafter. We present a detailed study of the $n = 3$ problem, especially the mixing driven by Rayleigh-Taylor and Richtmyer-Meshkov instabilities, which displays all of the difficult modeling issues applicable to arbitrary $n \geq 3$ while still being reasonably tractable. Its applications to inertial confinement fusion are discussed.

Initial condition vs. mode coupling dominance in the RT, RM and KH hydrodynamic instabilities evolution: theoretical and numerical investigation

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We study analytically and computationally the dependence of Rayleigh-Taylor (RT), Richtmyer-Meshkov (RM) and Kelvin-Helmholtz (KH) instability dynamics on the initial conditions (amplitude and spectrum) using a mode coupling extension to Haan's model. We identify the regimes of initial conditions (i.c.), in which the growth rate of the instabilities are dominated either by the i.c. or by mode coupling, and find the transition region between the two regimes. A comparison between the model and 2D/3D numerical simulation will be given, validating the model in both regimes. Using the model we are able to determine the different power laws and coefficients of the growth rates of the different instabilities as well as the self-similar perturbation spectrum in the mode coupling regime. The model gives a somewhat different picture of instability dynamics than the bubble competition models. Comparison between the new model and the bubble competition model will be given. Also, a possible

application of this model to study the multimode Landau-Darrieus instability in premixed flames will be discussed.

Compressibility effects in Rayleigh-Taylor type instabilities

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We study compressibility effects in Rayleigh-Taylor (RT) type instabilities. For that purpose, we use two examples of such instabilities: the classical RT instability for compressible fluids in a constant acceleration field and the ablation front instability. Ablation fronts appear when a directed high energy density is released in a dense material. As a result, a thermal wave, which may be unstable, propagates. We will first report on the linear stability analysis of the classical RT flow for compressible miscible fluids. Dispersion curves and eigenfunctions have been obtained for various values of the model parameters (stratification, compressibility, aspect ratio of the box and Reynolds, Schmidt and Prandtl numbers). We have shown the opposite effects of stratification and compressibility on the linear growth rate. Some investigations in the nonlinear regime have also been carried out and show that the trend observed in the linear regime usually holds. These results will be detailed in the final paper. On the other hand, a 2D simulation, started from rest and pursued until the return toward mechanical equilibrium of the mixing, has also been carried out. A system of acoustic waves, damped by the physical viscosity, has been identified. Finally the ablation front instability is detailed. The linear stability analysis of exact self-similar solutions of gas dynamics equations with nonlinear heat conduction is performed by solving an initial and boundary value problem. Considering the "laser imprint" problem of direct drive irradiation, we have obtained space-time evolutions of flow perturbations for a wide range of wave-numbers. In particular, maximum amplitudes are achieved for zero wave number and complex wave-like structures of acoustic, vorticity and entropy types are observed between the ablation front and the shock-wave front. All these results have been obtained with a dynamical multi-domain Chebyshev method.

[1] Lafay, M.-A. & Gauthier, S. & Le Creurer, B. 2007 submitted. [2] Abéguilé, F. & Boudesocque-Dubois, C. & Clarisse, J.-M. & Gauthier, S. & Saillard, Y. 2006 Phys. Rev. Lett. 97, 035002. [3] Gauthier, S. & Le Creurer, B. 2006 submitted. [4] Gauthier, S. & Le Creurer, B. & Abéguilé, F. & Boudesocque-Dubois, C. & Clarisse, J.-M. 2005 Int. J. Pure and Applied Math.. [5] Fournier, É. & Gauthier, S. & Renaud, F. 2001 Comput. Fluids. 31, 569-587. [6] Renaud, F. & Gauthier, S. 1997 J. Comput. Phys. 131, 89-108.

Investigation of the Richtmyer-Meshkov instability under re-shock conditions

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The Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities play an important role in astrophysical phenomena such as supernova and in applications such as inertial confinement fusion (ICF). During the past three decades efforts have been made to better understand the RM instability evolution. The single shock situation has been investigated intensively in single and multi-mode cases, and a clear picture of the instability's evolution has been established. However, in many cases the contact surface experiences several acceleration waves. This case is not yet fully understood. In the present study experimental and numerical investigations have been conducted. The experiments utilized a shock tube facility and Schlieren diagnostic technique in which the instability was generated by an incident shock wave that ruptured a thin nitrocellulose membrane separating air from SF6. The reshock from the end wall strikes the turbulent mixing zone (TMZ) evolving on the contact surface between the gases. The passage of the reshock causes a dramatic increase in the instability's growth rate. The numerical tool for the research was the LEEOR numerical code which is an ALE scheme with 2D and 3D capabilities. In the present study, the evolution of the TMZ width was investigated after the passage of the reshock. The dependence of the TMZ growth rate on the reshock strength and on its width prior to the reshock arrival was the focus of the present research. Different reshock strengths were achieved experimentally by controlling the incident shock wave Mach number and by changing the rigidity of the shock tube end wall. By varying the test Theme/Topic: length the TMZ width before the reshock was varied. The experimental results were compared to the numerical simulation and good agreement was found. It was found that there is little dependence of the TMZ growth rate on its width prior to the arrival of the reshock. However, the TMZ growth rate was found to depend strongly on the reshock strength.

The study of turbulent mixing zone development in laser shock tube experiments

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Paper presents the results of experimental and numerical investigations of the development of turbulent mixing zone at laser acceleration of thin films in air. The experiments have been made at KrF laser “GARPUN” (Lebedev Physical Institute, Moscow) (Bakaev, 2005). We have compared the experimental data with the results of 2D numerical simulations. In order to describe the turbulent mixing we have developed the model of turbulent diffusion, based on well-known Belen’ki & Fradkin model (Belen’ki, 1965), and have got good agreement between experimental and numerical results (Krasnyuk, 2006).

[1] Bakaev V.G., Batani D., et al. 2005, Hydrodynamics of high-energy GARPUN KrF laser interaction with solid and thin-film targets in ambient air, J.Phys. D: Appl. Phys., 38, 2031-2044. [2] Belen'ki S.Z. & Fradkin E.S. 1965, Theory of turbulent mixing, Trudy FIAN 29, 207-233. [3] Krasnyuk I.A., Lebo I.G. 2006, Comments on the article "Hydrodynamics of high-energy GARPUN KrF laser interaction with solid and thin-film targets in ambient air." J. Phys. D Appl. Phys., 39, 1462-1464

Shock bubble interaction: Circulation and the multiple bubble array

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Most studies on the shock bubble interaction have focused on either the single bubble interaction or on the transition of a shock wave through an array of bubbles. A basic assumption is that a well based theory on the latter case should make the connection between the two cases. The aim of this work was to investigate the interaction of a single bubble and two bubbles as a corner stone for understanding the more complex case through circulation calculations. Numerical simulations were made for a one, two and an array of bubbles. In the last case the transition from a symmetric to randomly positioned array was examined. The single bubble cases were compared to experiments and theories for circulation deposition and part of the two bubble cases were compared to experiments. The basic characteristics investigated for the two bubble interaction were the type of interactions and the threshold distance of interaction. It was seen that the circulation can be used to identify the transition from interacting to non-interacting flows also in the case of the multiple array. Basic observations were made on the difference in flow between the symmetric and random positioned arrays, mainly showing that the circulation is a measure of the ordered motion of the vortex rings.

Turbulent mixing Development at the Gas-LIQUID Interface under change of the Atwood number from +0.9 to -0.2

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We present the results of experimental and one-dimensional numerical modeling of the turbulent mixing at the gas/liquid interface at the variable Atwood number (A). We have used water as liquid, SF_6 gas (SF_6) or xenon (Xe) as gas. A

water layer is being accelerated in the channel with diameter of Ø50 mm by means of gas compressed by a rigid piston. In the course of gas compression its density increases. This has brought about a change in Atwood number at the contact interface of substances from +0.9 to -0.2: in experiments xenon has been compressed up to density ≈300 g/l, SF_6 gas – up to 1400 g/l. A pressure in compressed gas has accounted for ≈500 atm. The value of layer acceleration has amounted to 1 mln m/s^2. It has been obtained that in the experiments on xenon the constant characterizing a penetration rate of a gas front into liquid accounts for ≈0.03, in the experiments on SF_6 gas the penetration of a gas front into liquid stops at negative Atwood numbers, but the mixing zone formed at A>0 continues to expand slowly to SF_6 gas.

Fluid intermingling and vorticity evolution in two- and three-dimensional simulations for shock-bubble interactions

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Results from a series of simulations for shock-bubble interactions are presented, which contrast the evolution of the flow-field under axisymmetry to the evolution when symmetry is relaxed and a non-axisymmetric perturbation is imposed. The bubble consists of a spherical gas volume suspended in a gaseous medium of contrasting density and sound speed, with a very thin mixed region separating the bubble and ambient fluids. A planar shock wave interacts with the spherical bubble, resulting in the development of vortex rings and a mixing region in the post-shock flow-field. The evolution is simulated using a multifluid, adaptive Eulerian Godunov code called Raptor, at a resolution of 128 grid points per bubble radius. For incident shock wave Mach numbers 1.1<M<5, the solution in two-dimensional axisymmetric (r-z) simulations differs notably from that in three-dimensional Cartesian simulations, for scenarios in which the bubble gas density is greater than the ambient fluid density, with Atwood numbers A>0.2. In these high-A scenarios, diffuse, chaotic vorticity fields arise in the mixing region in three-dimensional simulations, while vortex projectiles and extreme interface deformation dominate in the two-dimensional simulations. In cases with low Atwood number magnitude A<0.2, and in cases with lighter-than-ambient bubble gas (A<0), stable vortices persist without significant development of chaotic effects, in both two-dimensional and three-dimensional simulations for 1.2<M<3.5. Such behavior is characterized here using integral diagnostics on the datasets, such as the circulation, and mechanisms for the observed behavior are proposed on the basis of arguments from gas-dynamics and vorticity dynamics.

Shock tube experiment: half height dense gas region

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This paper reports results from a turbulent mixing shock tube experiment. The experiment consists of a shock interacting with a half height dense gas region. This causes both a Richtmyer-Meshkov instability and a Kelvin-Helmholtz instability. The experiments were conducted on the AWE 200 x 100 mm shock tube with a Mach number of 1.26 (70kPa overpressure). A three zone test cell arrangement of air/air and dense gas/air is used; both the dense gas and air were at atmospheric pressure. The dense gas used was Sulphur Hexafluoride which results in an Atwood number of 0.67 when used with air. The gas regions were separated with fine wire meshes which are used to support microfilm membranes. Flow visualization was achieved by seeding the dense gas with an olive oil aerosol; this was then illuminated with a laser sheet. The Mie scattered laser light is imaged by a camera positioned 90° to the test cell. As the camera is a rotating drum the laser is pulsed so over 50 frames of the mixing process can be obtained. In addition an intensified CCD camera was used to capture one image during the experiment. The half height experiment is configured so the dense gas region is filled halfway (100mm) with seeded dense gas. The front and back surfaces consist of fine wire mesh and microfilm membranes. The top surface is membrane-less so nominally plane. The different shock speeds in the two mediums creates the Kelvin-Helmholtz instability. For a qualitative comparison between experiment and the computational model certain laser sheet images are compared to code images from the AWE TURMOIL 3D LES model. For a semi-quantitative comparison line-outs are taken and substantial agreement demonstrated.

Experimental and numerical investigation of shock-induced distortion of a spherical gas Inhomogeneity

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Results are presented from a series of experiments and simulations, studying the interaction of a planar shock wave with discrete gas inhomogeneities. Experiments are performed in a 9.2-m-long vertical shock tube with a square internal cross-Theme/Topic:, 0.254 m on a side, equipped with a pneumatically-driven retracting bubble injector. This allows for a bubble to be placed in the center of the duct with minimal flow obstruction during shock passage. After a brief period of uniform acceleration under buoyancy, a planar shock wave passes over the bubble, and a number of complex, coupled phenomena are observed, including vortex ring formation, jetting, shock refraction and focusing, intense mixing, and the growth of turbulence-like features. In the present work, experimental flow visualizations are

obtained using planar laser diagnostics rather than integral measures. A numerical study is performed using a multifluid, adaptive Eulerian Godunov code called Raptor, at a resolution of 100 grid points per bubble radius. A series of snapshots from the experiments, characterizing the bubble evolution after shock-wave interaction, are compared with computed flow fields, and a number of features of the shock-bubble interaction for light and heavy bubbles are investigated and parameterized with the incident Mach number and initial density difference, using the experimental and numerical results. These include (1) the variation over time of the axial and lateral extents of the bubble during and after shock passage, (2) the translational velocity defect of the bubble and associated vortex rings relative to the ambient shocked gas, and (3) the intensity with which mixing proceeds. The adequacy of various scaling arguments and analytical models are evaluated on the basis of these results.

Mixing in non-homogenous Rayleigh-Taylor driven turbulent flows

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Experimental and numerical results on the advance of a mixing or non-mixing front occurring at a density interface due to gravitational acceleration is analyzed considering the fractal structure of the front. The experimental configuration consists on an unstable two layer system held by a removable plate in a box. The initial density difference is characterized by the Atwood number. As the plate is removed. The gravitational acceleration, generates a combination of spikes and bubbles, which reach a maximum complexity and mixing efficiency before the front reaches the end walls. The instability produced is known as Rayleigh-Taylor (RT) instability, and in its simplest forms occurs when a layer of dense fluid is placed on top of a less dense layer in a gravitational field. The advance of this front is described in Linden & Redondo (1991), and may be shown to follow a quadratic law in time. The width of the growing region of instability is proportional to the Atwood number but the distribution of fractal interfaces between the miscible fluids allow distinguishing the dominant mixing regions located at the sides of the RT blobs, where accelerated shear is greatest. Comparisons between rotating and non rotating environments allow showing the role of interacting body forces.

One of the most important roles of Stratification and Rotation and in general of all body forces, including magnetic fields, is to modify the slope of the spectral energy cascade. While the anisotropy of the Reynolds stresses is obviously linked with the non-homogeneity taking the vertical axis (in stratified flows) and the rotation axis (in rotating flows). Scalar behavior in such flows has non-linear mixing properties Redondo (2002). There are similar effects that depart from Kolmogorov K41 and also for K62 theories, not just in second order structure functions (and related spectra) for spatial non-homogeneity, for anisotropy and for spatial and temporal intermittency. The directions of gravity, rotation axis and magnetic field act as principal axes and play dominant roles in the two dimensionalization due to the body forces this forces a dominance of the enstrophy cascade over the direct energy cascade, but it is important to realize that both direct and inverse cascades may not be in equilibrium at the same time. The intermittency coupled with the non-homogeneity and anisotropy act indistinguishably to modify the dispersion within the flow, here the role of coherent structures is also relevant. Using Kinematic Simulation (KS) for a variety of pseudo-turbulent flows in which the Energy spectra of the turbulence is varied with logarithmic spectral slopes between 1 (white noise) and 6 (flows dominated by a few large vortices) and using also Extended Self Similarity (Mahjoub et al. 1998,2000a,b) to investigate the differences in structure between KS and Direct Numerical Simulations (DNS), the relationship between mixing dispersion and spectral slope is cast as a Generalized Richardson's valid for even strongly non-local flows with steep spectral slopes that may or may not be in local equilibrium. In the context of determining the influence of structure on mixing ability, multifractal analysis is used to determine the regions of the front which contribute most to mixing.

[1] Linden P.F. & Redondo J.M. (1991) "Molecular mixing in Rayleigh-Taylor instability. Part 1. Global mixing". Phys. Fluids. 5 (A), 1267-1274. [2] Linden P.F. Redondo J.M. and Youngs D. (1994) "Molecular mixing in Rayleigh-Taylor Instability" Jour. Fluid Mech. 265, 97-124. [3] Castilla R. (2000) Numerical simulations of particle diffusion in isotropic and homogeneous turbulent flows in Turbulent diffusion in the environment Eds. Redondo J.M. and Babiano A. 69-76. [4] Mahjoub O.B., Redondo J.M. and Babiano A. (1998) Structure functions in Complex flows. Jour. Flow Turbulence and Combustion 59, 299-313. [5] Mahjoub O.B., Redondo J.M. and Babiano A. (2000a) Self similarity and intermittency in a turbulent non-homogeneous wake, Advances in Turbulence VII Eds. Dopazo C. et al. 783-786. [6] Mahjoub O.B., Redondo J.M. and Babiano A. (2000b) Hierarchy flux in nonhomogeneous flows in Turbulent diffusion in the environment Eds. Redondo J.M. and Babiano A. 249-260. [7] Redondo J.M. (2002) Mixing efficiencies of different kinds of turbulent processes and instabilities, Applications to the environment in Turbulent mixing in geophysical flows. Eds. Linden P.F. and Redondo J.M. 131-157.

MATHEMATICAL ASPECTS of MULTI-SCALE DYNAMICS

The Fermi Pasta Ulam (FPU) Problem: Solitons, ILMS, q-breathers and Mixing

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In 1953, Enrico Fermi, John Pasta, and Stan Ulam initiated a series of computer studies aimed at exploring how simple, multi-degree of freedom nonlinear mechanical systems obeying reversible deterministic dynamics evolve in time to an equilibrium state describable by statistical mechanics. Their expectation was that this would occur by mixing behavior among the many linear modes. Their intention was then to study more complex nonlinear systems, with the hope of modeling turbulence computationally.

The results of this first study of the so-called Fermi-Pasta-Ulam (FPU) problem, which were published in 1955 and characterized by Fermi as a "little discovery, " showed instead of the expected mixing of linear modes a striking series of (near) recurrences of the initial state, and no evidence of equipartition. This work heralded the beginning of both computational physics and (modern) nonlinear science. In particular, the work marked the first systematic study of a nonlinear system by digital computers ("experimental mathematics") and led directly to the discovery of "solitons," as well as to deep insights into deterministic chaos and statistical mechanics.

In this talk, I will review the original FPU problem and trace several distinct lines of research that arose from it. Specifically, I will show how a continuum approximation to the original discrete system led to the discovery of "solitons" and how recent treatments of the FPU and related spatially extended discrete systems reveal the presence of "Intrinsic Localized Modes" (ILMs)" and of "q-breathers."

I will then describe briefly the basic mechanism that allows the existence of ILMs, discuss some of their essential features, and illustrate a few of the wide range of physical systems in which they have recently been observed. I will show how "q-breathers" can give a plausible quantitative explanation for the recurrence phenomenon observed by behavior by FPU and how these results can be reconciled with mixing, equipartition, and statistical mechanics.

Linear growth rate for Kelvin-Helmholtz instability appearing in a moving mixing layer

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For the nuclear power plant thermal-hydraulics simulation, Kelvin-Helmholtz instabilities can be encountered locally when a mixing of flows of different velocities, densities and temperatures occur. Extensive efforts have been devoted to understand the physical mechanisms coming with such instabilities. We intend to estimate the linear growth rate in time of the perturbation obtained when we replace the discontinuous velocity profile at the interface by a continuous one varying rapidly inside the moving mixing zone. The theoretical analysis is based on the linearization of the Euler equations around a basic frozen solution. The three-dimensional perturbed equations are then decomposed in Fourier mode. We exhibit a convergence reach of the method applied on mixing layer wide, and recover with classical Kelvin-Helmholtz approach establishes around the discontinuous profiles. The numerical approach is used to prove the existence of the growth rate of the instability in thermal-hydraulics flow, classically simulated by LES computation or averaged Navier-stokes equations solver using $k - \varepsilon$" closure.

Divergent Series, Borel Summation and 3-D Navier-Stokes Equation

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Divergent series occur naturally in asymptotic expansions of solutions to differential systems and can typically be calculated through an algorithmic process to any order desired. Borel summation provides a one-one correspondence between such divergent series expansion and actual functions they represent such that this correspondence is maintained under a whole range of algebraic operations, including addition, multiplication, composition, differentiation, etc. This so-called isomorphism is similar to that between convergent series and analytic functions. Borel summability of a formal asymptotic series therefore provides an actual solution to the differential equations that gave rise to the formal expansion. While the ideas are more generally applicable, we use Borel Transforms and Borel Summability to cast the 3-D Navier-Stokes equation into an integral equation on a half-line for which a unique solution is shown to exist, within a certain class of functions. In this reformulation of Navier-Stokes, the question of global existence can be posed as a question of asymptotic of a known solution. If the solution on the half-line is subexponential at ∞, then global existence of classical solution would follow. The Borel based methods are also constructive and provide precise asymptotic with error-bounds for small time for analytic initial data. Further, there it has consequences in numerical calculations.

Elliptical instability of a vortex tube and drift current induced by it

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We revisit, with some extension to nonlinear regime, the Moore-Saffman-Tsai-Widnall instability, the three-dimensional instability of a straight vortex tube elliptically strained by a pure shear flow. A circular cylindrical vortex tube support neutrally stable three-dimensional waves called the Kelvin waves. A pure shear breaks the circular symmetry, causing a parametric resonance between two Kelvin waves whose azimuthal wavenumbers are separated by two. The eigen-values and functions are written out in full in terms of the Bessel and the modified Bessel functions, and so is the growth rate. A link of this instability is established with the Crow instability in the long-wave limit and with the elliptical instability in the short-wave limit. This result is put on the ground of Krein's theory for Hamiltonian spectra. We rest on a Lagrangian (particle) formulation which facilitates the construction of iso-vortical disturbances preserving energy. The energy of Kelvin waves, thus calculated, reveals that the instability results from a collision of eigen-values of positive and negative-energy waves or of two zero-energy waves. Moreover, the Lagrangian approach supplies us with a bypass to manipulate the wave-induced mean flow, being nonlinear in amplitude. We demonstrate that a Kelvin wave induces a drift current along the vortex tube and thus that the instability enhances the particle transport along it. A discussion is also made of the wave-induced modification of the mean rotation velocity.

Nonlinear behavior of a vortex sheet in incompressible Richtmyer-Meshkov instability with surface tension

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Fully nonlinear motion of a circular interface in incompressible Richtmyer-Meshkov instability is investigated by treating it as a nonuniform vortex sheet between two different fluids. There are many features in cylindrical geometry such as existence of two independent spatial scales, radius and wavelength, and the ingoing and outgoing growth of bubbles and spikes. Geometrical complexities lead to the results that nonlinear dynamics of the vortex sheet is determined from the inward and outward motion rather than bubbles and spikes, and that the nonlinear growth strongly depends on mode number. The temporal evolution of the curvature of a bubble and spike for several mode numbers is investigated and presented that the curvature of spikes is always larger than that of bubbles.

Generation of Non-uniform Vorticity at the Interface and Its Linear and Nonlinear Growth

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Both Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities occur at an interface between two different fluids. In a system with different densities across the interface, vorticity on the interface does not conserve in the nonlinear regime, which determines the nonlinear evolution of the instabilities. For instance RMI essentially grows due to the vorticity left by transmitted and reflected rippled shocks (or reflected rarefaction) at the corrugated interface. We first discuss a wide class of instabilities which, not being caused by the shock-interface refraction, are still driven by exactly the same physical mechanisms as the classical RMI. For instance, in the experiments reported by Jacobs et al, the non-uniform vorticity at interface separating two immiscible fluids contained in a tank grows due to the virtual gravity. Instabilities of shock-piston flows are also RM-like, such as those produced when a shock wave is driven from a rippled surface by a uniform laser beam, or when a nonuniform laser beam irradiating a planar surface imprints mass perturbations into flow.

Nonlinear evolution of the RM-like instabilities has been analytically investigated as a self-interaction of a nonuniform vortex sheet with different densities. We show a nonlinear model, which describes vortex sheet motion in an inviscid and incompressible fluid. The model developed will reveal the importance of the density difference in the nonlinear evolution of the instabilities. The model is also extended for a cylindrical geometry.

We will also discuss nonlinear evolution of RMI and RTI with the use of DNS (Direct Numerical Simulation) and MD (Molecular Dynamic) simulations. In 3d-DNS we discuss the bubble competition for initial multi mode perturbations in RTI. MD simulations are performed for both RTI and RMI, which is free from any numerical difficulties in DNS, although the Reynolds number is still limited. MD simulation reveals many interesting features of the instabilities.

Recent progress in mathematical analysis of vortex sheets

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We consider the motion of the interface separating two domains of the same fluid that moves with different velocities along the tangential direction of the interface. The evolution of the interface (the vortex sheet) is governed by the Birkhoff-Rott equations. We investigate the specific nature of the vortex sheet motion, in particular after the singularity formation; and we consider the question of the weakest possible assumptions such that the Birkhoff-Rott equation makes sense. This leads us to introduce chord-arc curves to this problem. We present three results. The first can be stated as the following: Assume that the Birkhoff-Rott equation has a solution in a weak sense and that the vortex strength is bounded away from 0 and infinity. Moreover, assume that the solution gives rise to a vortex sheet curve that is chord-arc. Then the curve is automatically smooth, in fact analytic, for fixed time. The second and third results demonstrate that the Birkhoff-Rott equation can be solved if and only if ONLY half the initial data is given.

Vortex Processes in Accelerated Inhomogeneous Flows

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We update our review [1] of the role of vortex dynamics [2, 3] in shock-bubble interactions [4, 5, 6] and various Richtmyer –Meshkov [7-10] environments. We emphasize the emergence of complex multiscale vortex structures and their role in evolving morphologies and the growth and scaling of turbulent mixing regions. We compare with other recent experimental and computational results.

[1] Zabusky, N.J., Vortex paradigm for accelerated inhomogeneous flows: Visiometrics for the Rayleigh-Taylor and Richtmyer-Meshkov environments. Ann. Review of Fluid Mechanics, 1999. 31, 495-535. [2] Hawley, J.F. and Zabusky, N.J., Vortex paradigm for shock- accelerated density-stratified interfaces 1989. Phys. Rev Letters 63, 1241-1244. [3] Samtaney R, Zabusky N. 1994. Circulation deposition on shock-accelerated planar and curved density stratified interfaces: models and scaling laws. J. Fluid Mech. 269:45– 78. [4] Zabusky, N.J and S. Zeng, Shock cavity implosion morphologies and vortical projectile generation in axisymmetric shock–spherical fast/slow bubble interactions. J. Fluid Mech. 362, pp. 327–346, 1998. [5] Shuang Zhang, N. J. Zabusky, & K. Nishihara, "Vortex Structures and turbulence Emerging in a Supernova 1987A Configuration: Interactions of "Complex" Blast Waves and Cylindrical/Spherical Bubbles ", Laser and Particle Beams. 21, p.463-470, 2003. [6] Zhang, S., Zabusky, N.J., Peng, G., Gupta, S. Shock Gaseous Cylinder Interactions: Dynamically validated initial conditions provide excellent agreement between experiments and Navier-Stokes simulations to late-intermediate time. Phys. Fluids 16(5), 1203-1216, 2004. [7] Peng, G., Zabusky, N.J. and Zhang, S. Vortex-accelerated secondary baroclinic vorticity deposition and late intermediate time dynamics of a two-dimensional RM interface. Phys. Fluids 15 (12), 3730-3744, 2003. [8] Shuang Zhang and N.J. Zabusky" Shock–planar curtain interactions: Strong secondary baroclinic deposition and emergence of vortex projectiles (VPs) and decaying inhomogeneous turbulence". Laser and Particle Beams. 21, p.471-477, 2003. [9] Zhang, S., Zabusky, N.J. Peng, G. Vortex dynamics and baroclinically forced inhomogeneous turbulence for shock - planar heavy curtain interactions" J. of Turbulence, 6, 1-27, 2005. [10] Lee, D-K., Peng, G. and Zabusky, N. J. Circulation rate of change: A vortex approach for validating and understanding accelerated inhomogeneous flows through intermediate times. Phys Fluids, 18, 097102 (2006).

Wind-driven sea and atmospheric boundary layer

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Three major physical processes in the wind-driven sea are the nonlinear wave interaction, the wave breaking, and the interaction with atmospheric boundary layer. The theory of nonlinear wave interaction is far developed and is describes by the four-wave Hasselmann kinetic equation. This equation has exact power-like Kolmogorov-Zakharov (KZ) solutions, corresponding to a constant flux of energy, momentum, and wave action. It has also a rich family of self-similar solutions depending on a few numbers of free constants. The rear faces of self-similar spectra are described by the

KZ asymptotics. The wave breaking is important because it is the universal sink of wave energy, transported by nonlinear processes to high wave numbers. In the area of spectral peak, this process is essential only for very "young waves." The self-similar solutions of the Hasselmann equation give very good qualitative description of the wind-driven sea spectra. To get quantitative coincidence one has to determine indefinite constants from study of wave excitation due to interaction with atmospheric boundary layer (wind). The waves are excited due to Cherenkov-type instability. Because the wind is turbulent, development of analytical theory, which makes possible to determine the growth-rate of instability (function of wind-input), is not yet resolved problem. The existing heuristic models lead to different forms of interaction term with the scatter exceeding the mean value. We have developed an efficient and fast numerical code for solution of the Hasselmann equation and offer to solve this equation with different models of interaction term and compare the results with the field observations. It will make possible to find the interaction term from experiment and to get an important starting point for development of a reliable analytical model of wind-wave interaction.

ADVANCED NUMERICAL SIMULATIONS

Characterization of implicit LES methods

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The broad range of time and length scales present in high Reynolds number turbulent flows is often prohibitively expensive for direct numerical simulations (DNS) to capture completely. Large eddy simulation (LES) attempts to circumvent this issue by filtering out the small scale motions in the flow, replacing their effects with a subgrid model. High-order finite-volume schemes can accurately capture the inviscid cascade of kinetic energy, and the inherent truncation error acts as an implicit subgrid model, forming a natural form of LES.

However, the absence of a physical viscosity prohibits conventional characterization of these methods, specifically how kinetic energy is dissipated at the grid scale and how to define a relevant Reynolds number.

Kolmogorov's 1941 papers achieve this characterization for real-world viscous fluids in terms of a universal equilibrium range determined uniquely by the rate of energy dissipation and physical viscosity. Analogously, this paper proposes than an implicit LES method results in behavior that can be characterized by a universal equilibrium range determined uniquely by the energy dissipation rate and computational cell width.

Implicit LES simulations of maintained homogeneous isotropic turbulence are presented to support this proposal and highlight similarities and differences with real-world viscous fluids. Direct comparison with data from high resolution DNS calculations provides a basis for deriving an effective viscosity and an effective Kolmogorov length scale.

Constructive modelling of structural turbulence: computational experiment

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A new approach to the analysis of the turbulent structure is suggested when based on the concept of large vortices and mechanical properties of flows: structural instabilities, vortex cascades and principal modes of disturbances. Constructively, the analysis of the structure might be produced with direct numerical simulations. The prime ideology of this many-oriented approach consists in the combination of grid, spectral and statistical methods on the basis of the main laws of the mass, impulse and energy conservation.

Modeling the subgrid-scale flux of a passive scalar: connection to the momentum closure

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In Large Eddy Simulation of flow with a passive scalar one has to close the scalar transport equation. This requires modeling of the subgrid-scale (SGS) scalar flux, which is a vector. Using database of well-resolved DNS of forced isotropic homogeneous turbulence with passive scalar, we a priori evaluate the geometrical statistics of the SGS scalar flux, such as its magnitude and alignment trends in various coordinate systems, alignment trends with resolved and subgrid quantities. Based on our a priori observations we propose a specific model for the SGS scalar flux that does not require test-level filtering and does not contain user-defined constants. A priori and a posteriori analysis of the model will be performed and comparison to other models from the literature will be shown.

Scaling properties of sub-grid-scale energy dissipation and sub-grid-scale scalar dissipation

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In Large Eddy Simulation (LES), the dissipation rates of subgrid- scale (SGS) kinetic energy and SGS scalar variance are arguably the two most elusive quantities to model. In the literature it is customary to model them using assumed power-law correlations between the SGS energy and its dissipation, and between SGS scalar variance and its dissipation. We use DNS of forced homogeneous isotropic turbulence with 512^3 and 1024^3 grid points with Reynolds number based on Taylor microscale up to 400 to examine a priori the scaling properties of the SGS kinetic energy, SGS variance of a passive scalar and their dissipation rates. It is found that the two pairs of quantities are strongly correlated and a power-law scaling assumption holds reasonably well for both pairs. However, the scaling exponent for the power-law approximation of correlation between SGS energy and its dissipation was found to change considerably with the LES filter size, while it was assumed to be varying weakly in previous studies. The scaling between SGS scalar variance and its dissipation, on the other hand, was found to be extremely close to the power-law scaling with an exponent that does not vary with the LES filter size. Based on these findings and our previous studies, we plan to propose new models for SGS energy and scalar dissipation, and evaluate them a priori and a posteriori.

FLASH code tutorial

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We propose a tutorial on the FLASH code, a parallel, adaptive mesh computer program used to simulate astrophysical phenomena and fluid dynamics problems. The code has been developed primarily at the ASC/Alliances Flash Center, funded by the Department of Energy. FLASH has been used to simulate a wide range of astrophysical and fluid dynamics phenomena including X-ray bursts, magnetized galactic bubbles, classical novae, Type Ia supernovae, homogeneous isotropic turbulence, interfacial dynamics including Rayleigh-Taylor and Richtmyer-Meshkov instabilities and mixing. FLASH has over 200 active users, and has become a community code of choice for the astrophysical community. It is available at http://flash.uchicago.edu.

The tutorial will be staggered over two days, with a mix of formal talks on the technical and scientific capabilities of FLASH, demonstrations and hands-on examples. Attendees will learn the capabilities of the current code, how to add a new simulation to the code, customize boundary conditions, and program new algorithms. We will also discuss FLASH’s I/O, visualization using Visit, and Flash-test, an open source code verification tool.

Participant can work hands-on along with our demonstrations by obtaining a copy of the code for their personal use.

Simulation of turbulent flows with strong shocks

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Computation of turbulent flows with strong shocks is a very challenging problem, since the requirements for a method to produce accurate results for turbulence are exactly opposite from those needed to treat shocks properly. In order to prevent an unphysical rate of decay of the turbulent structures, it is necessary to use a method with very low numerical dissipation. Because of this, central difference schemes are widely used. However, computing strong shocks with a central difference scheme can produce unphysical post-shock oscillations that corrupt the entire flow unless additional dissipation is added. This dissipation can be difficult to localize to the area near the shock and can lead to inaccurate treatment of the turbulence. Modern high-resolution shock-capturing methods usually use upwind algorithms to provide the dissipation necessary to stabilize shocks. However, this upwind dissipation can also lead to an unphysical rate of decay of the turbulence. This talk will discuss a hybrid method for simulating turbulent flows with strong shocks that couples a high-order central difference scheme with a high-resolution shock-capturing method. The shock-capturing method is used only in the vicinity of discontinuities in the flow, while the central difference scheme is used in the remainder of the computational domain. Results of this new method will be shown for a variety of test problems, including Richtmyer-Meshkov instabilities and the interaction of a shock with a turbulent flow field.

The further development of LES approach for a high Reynolds number flow, coupling with the subgrid stochastic acceleration model

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In order to take into account the intermittency phenomena in a high Reynolds number turbulent flow, we propose a new approach to the LES of constant-density flows. In this approach, the equation for instantaneous acceleration of a fluid particle is replaced by the model equation, containing resolved (filtered) and non-resolved (unknown) parts. The non-resolved acceleration is modeled stochastically with accounting for its significant dependency on the Reynolds number. The pressure in the model equation is introduced in a way to guarantee the velocity vector to be solenoidal. The stochastic process is based on the well-known from Kolmogorov-Obukhov (1962) estimation of the square of acceleration, conditionally averaged on the viscous dissipation rate. Using the Obukhov's log-normality, the stochastic equation for the norm of acceleration is derived and implemented into computation. The acceleration components are then computed by introducing the unit vector with random direction in time.

This numerical approach was applied in computation of 3D box stationary homogeneous turbulence. The Reynolds number, the kinetic energy, the micro-scales of Kolmogorov and Taylor were close to those mentioned in experiment of Mordant et al ($\mathrm{Re}_{\lambda} = 740$; $\sigma_{v}^{2} = 1 m/s$). The computation reproduced the effects observed in experimental study. While at integral times, the Lagrangian velocity increment was normally distributed, this increment displayed a strong non-Gaussianity at small time lag. The computation showed that the autocorrelation of Lagrangian acceleration decreases very rapidly with progressing of the time lag. However the time scale in decreasing of autocorrelation of the norm of acceleration is of order of integral time. Such effect of the acceleration norm "memory" is in accordance with experimental results.

Vorticity production and mixing in shock bubble interaction

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Shock-bubble interactions, arising from laser induced fusion, supersonic combustion, underwater explosion and supernova astrophysics, are generic configurations for studying shock-accelerated inhomogeneous flows. In this work, the vorticity production and mixing are studied by numerical simulations with no-smearing interface models for a SF6/air cylinder bubble impacted by a 1.095 Mach shock wave. To clarify and separate the effects of different mechanisms, the results obtained with several interface and fluid properties, such as inviscid and viscid interfaces, inviscid and viscid fluids, and perfect gas and barotropic gas, are compared and analyzed. It is found that there are three vorticity production mechanisms: (1) baroclinic vorticity deposited on and detached from the interface, (2) baroclinic vorticity produced far away from the interface due to baroclinic property of air and SF6 and (3) slip-line vorticity originates from the interface by shock diffraction. While the first mechanism contributing the major part of vorticity in the flow field, the third mechanism, which is usually underscored by previous studies, is found playing significantly role for the formation of the main vortex structure, i.e. the counter-rotating vortex pair. However, the analysis suggests that the main vortex structure shows rather minor contribution to material mixing since the corresponding vorticity is far from the interface and only a small part of material line is involved in rolling-up process. The mixing is found mainly contributed by the secondary instability near the interface as the subsequence of initial baroclinic vorticity deposition.

Adapting Moment Closure for Large-Eddy Simulation of Variable Density Turbulence

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Most large-eddy simulation (LES) models rely on primitive algebraic closures and contain minimal physics, simply adding enough dissipation to stabilize the calculation. Such models often provide reasonable results provided that the cutoff length scale is sufficiently deep into the turbulent spectrum. Consequently, these models have very high resolution requirements and the performance gain compared to implicit LES or even under-resolved direct numerical simulation is small. On the other hand, using RANS closures to compute the time evolution of large structures is conceptually unjustified and fails practically for the Rayleigh-Taylor problem. Invoking the averaging invariance of the filtered Navier-Stokes equations, it is possible to construct LES models using moment closure techniques. The simplest closure of this form uses an LES length scale and a single transport equation for the sub-filter turbulent kinetic energy. This model has been proposed in slightly different forms by several authors, and has been demonstrated in a number of simple flows. In the current work this model is extended to variable density flows by the addition of transport equations for the density-velocity correlation and, optionally, the density self-correlation. The model is applied to the Rayleigh-Taylor problem and the results are compared to experiments and direct numerical simulations. In addition to

assessing the fidelity of the model and its predictive capability, the issue of two-dimensional versus three-dimensional solutions will be considered, as well as the self-similar scaling behavior of the model. In particular, for the LES decomposition the correct relative scaling of the resolved and filtered components will be examined in light of the relationship between the layer thickness and the LES length scale.

Retrieval of Collision Kernels from the Change of Droplet Size Distributions with a Simple Inversion Scheme

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We have developed a new simple inversion scheme for retrieving collision kernels from the change of droplet size distributions due to collision growth. Three-dimensional direct numerical simulations (DNS) of colliding droplets in an isotropic steady turbulence are performed in order to investigate the validity of the developed inversion scheme. In the DNS, air turbulence is calculated using a quasi-spectral method, and droplet motions are tracked by a Lagrange method. The initial droplet size distribution is set to be equivalent to that obtained in a wind tunnel experiment. Comparison between collision kernels retrieved by the developed inversion scheme and those obtained by DNS shows that the collision kernel can be retrieved within 15% error. This verifies the feasibility of retrieving collision kernels by using the present inversion scheme.

Study of Instability Driven Mixing Using Improved Tracking and Transport Control

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Experiments of Rayleigh-Taylor and Richtmyer-Meshkov instabilities in the incompressible regime display an apparent consistency of mixing rates. Simulations seeking to duplicate these experiments suffer from (a) numerical artifacts such as numerical mass diffusion, (b) generally idealized modeling of physical phenomena, with omission of transport and other scale breaking physics, and (c) a lack of knowledge of the true experimental initial conditions. We report on a systematic series of simulations using the front tracking code, which has been validated through benchmark problems. A statistical analysis will be presented for the mathematical expectation and variance of the mixing rate. The dependence of the mean and variance of the mixing rate on values of the physical mass diffusion, viscosity and surface tension will be explored, as well as (to a limited extent) the dependence of the

mean and variance on the properties of the ensemble that defines the initial conditions. Other measures of mixing such as the Fourier spectrum of energy and vorticity fluctuations will be presented. Tracked and untracked simulations will be compared.

2D large eddy simulations of turbulent boundary buoyant flow in a cavity

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In this work, numerical investigation by means of Large Eddy Simulation of turbulent natural convection in a square cavity with two differentially heated vertical walls and conductive horizontal walls. Results are confronted to the detailed experimental data of Ampofo & Karayiannis [1] and Tian Y.S.; Karayiannis T.G. (2000) obtained with a Rayleigh number of 1.5x109 which corresponds to a relatively low level of turbulence. Comparisons of results are extended to the hole cavity (nine levels) to capture horizontal walls influence, since in general Author(s) consider only the mid height position as a reference to study all present phenomena. This experimental benchmark case constitutes an excellent tool to indicate the accuracy and limits of LES in 2D Natural convection, since the 3D case was studied by Peng and Davidson (2001). Here we consider three sub grid-scale models such as Smagorinsky-Lilly with and without the dynamic model option and the Wale model. The purpose of this study is to evaluate the capacity of 2D large eddy simulation to reproduce mean and fluctuating quantities first, to compare the different sub grid scale models second and finally to clarify differences with the 3D large eddy simulation especially the tendency laminar behavior of the 2D LES. Thus, and with respect to the available considered experimental data, we first analyze the mean velocities and the mean temperature profiles. Then particular attention is given to turbulent quantities like temperature and velocity fluctuations shear and heat fluxes. Also, we compare the local Nusselt number along the four walls with the corresponding experimental values.

[1] Ampofo F.; Karayiannis T.G. (2003) Experimental benchmark data for turbulent natural convection in an air filled square cavity. Int. J. of Heat and Mass Transfer, v 46, no 19, pp 3551-3572. [2] Germano M., Piomelli U., Moin P. and Cabot W. H. (1996). Dynamic Subgrid-Scale Eddy Viscosity Model. In Summer Workshop, Center for Turbulence Research, Stanford, CA. [3] Nicoud F. and Ducros F. (1999).Subgrid-Scale Stress Modelling Based on the Square of the Velocity Gradient Tensor. Flow, Turbulence, and Combustion, 62(3):183-200. [4] Peng S.-H.; Davidson L. (2001) Large eddy simulation for turbulent buoyant flow in a confined cavity. Int. J. of Heat and Fluid Flow, v 22, no 3, pp 323-331. [5] Smagorinsky (1963).General Circulation Experiments with the Primitive Equations. I. The Basic Experiment. Month. Wea. Rev., 91:99-164. [6] Tian Y.S.; Karayiannis T.G. (2000) Low turbulence natural convection in an air filled square cavity. Int. J. of Heat and Mass Transfer, Parts I & II, v 43, pp 849-884.

On the Spectral Simulation of Periodic Layer in Incompressible Fluid

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The correct formulation of united Couette-Poiseulle-Kolmogorov problem is given. Namely, Navier-Stokes equations are considered in periodic layer of viscous incompressible fluid at admissible uniform shift of bottom and top walls (Couette problem), the no-slip conditions executed on walls, with the fixed constant volume rate of mass (Poiseulle problem), and the given field of external plane-parallel accelerations (Kolmogorov problem). The correctness of statement of a boundary problem is shown. The correctness of a problem is understood as a correctness of statement for corresponding linearized equations. Simple stationary solutions are found. The equations for disturbance are received. The problem for eigen-values and eigen-modes is formulated. Eigen values and eigen-modes are found. Orthogonal decomposition of the disturbed flow on eigen-modes in a periodic layer of a viscous incompressible liquid is received. The new form of system of the equations for an incompressible liquid in terms of the first, repeated curls and for a component of the average speed, essentially considering turbulent pulsations through the equation for average components of velocity is resulted. The new equations appear completely equivalent to the system of Navier-Stokes equations. Results of test calculations for the general three-dimensional case are given.

Large-eddy simulations of shock-generated mixing in Richtmyer-Meshkov Instability

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We will discuss results obtained from large-eddy simulations (LES) of two-fluid mixing produced by three-dimensional Richtmyer-Meshkov (RM) instability in both rectangular and cylindrical geometry. For LES of shock-generated turbulence, a hybrid numerical method is used that is shock capturing but which reverts to a centered scheme with low numerical viscosity in regions of smooth flow. The subgrid-scale (SGS) model is the stretched-vortex (SV) model. LES on both uniform grids and variable grids using the AMROC (adaptive mesh refinement object oriented C++) framework, will be described. For planar geometry, the shock strength, tube geometry, gas composition, initial conditions and initial interface disturbance were tailored to the experimental conditions of Vetter & Sturtevant (1995), while for the convergent, cylindrical geometry, several parameter sets were utilized. Results presented will focus on the evolution of the mixing layer and its internal statistics including various spectra and pdfs of mixed molar and mass fraction. It will be shown that use of the SV, SGS model permits continuation of radial velocity and scalar spectra in the center-plane of the mixing layer, to subgrid scales with self consistent calculation of the viscous and Batchelor cutoff scales. Comparisons will be presented of the signatures of planar RM instability with reshock and cylindrical-convergent RM with shock reflection from the axis.

Numerical Simulation of Turbulent Unsteady Compressible Pipe Flow with Heat Addition

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In this research, a numerical technique was developed to study the boundary layer heating in unsteady compressible pipe flow. The technique was applied on gas flow in a pipeline by heating the developing portion of gas flow at the entrance of a pipe to study the eat transfer effect and pressure drop. The analysis of gas flow in piping system has been studied by many researchers and is usually based upon the consideration of steady state conditions. Also two limiting cases, adiabatic and isothermal, are often considered. Adiabatic flow conditions are usually valid for short pipelines since there is little heat transfer to or from the gas, where isothermal flow conditions assume flow through a pipe held at a uniform temperature and are commonly assumed when studying the flow of a gas in an uninsulated pipeline. On the other hand, the flow is fully turbulent due to high inflow Reynolds number in transport gas pipelines. We investigated the effect of heating numerically for unsteady and various thermal conditions. The coupled conservation equations governing compressible viscous gas flow in the entrance of a pipe are solved numerically using a finite-volume based finite-element method applied on unstructured grids. The convection terms are discretized by well-defined Roe Method while the diffusion terms are discretized by Galerkin formulation. The numerical procedure is based on the explicit multistage Runge-Kutta scheme. A simple turbulent model was used which only consider the turbulent effects on the viscosity and thermal diffusivity. The method of applying the boundary conditions to such a problem is considerable. The boundary conditions were imposed using a new weak formulation based on the characteristic variables. Some interested results were presented on pressure loss and friction, pipe length and other parameters effects. Compared results are in good agreement with some experiments and numerical results in available reports.

The DNS of thermal convection at moderate Rayleigh numbers under strongly non-Boussinesq conditions

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The Rayleigh-Benard convection has been a topic of intense research recently. One area of main debate is the relation between non-dimensional heat transport, the Nusselt number, and the non-dimensional temperature forcing called Rayleigh number. The results from high-Rayleigh-number experiments differ, and this discrepancy is often directed to the validity of the Boussinesq assumption. The Boussinesq assumption means that any variation in density can be neglected in the governing equation, except in the buoyancy term. In addition, fluid properties like viscosity, thermal expansivity, thermal conductivity and specific heats are considered to be constants. In the present investigation a direct numerical simulation of thermal convection under strongly non-Boussinesq condition is performed. The computational domain is a cylinder with aspect ratio 1/2. The Rayleigh numbers are fixed at 2×108 and 2×109. The governing equations are valid within the "low Mach number approximation" and the properties of working fluid (cryogenic helium in the present study) are temperature dependent. The results show that temperature at the center decreases with increase in the Boussinesq parameter as reported elsewhere. A detailed picture of variation of properties and flow structures will be presented. The heat transport was found to decrease with increase in Boussinesq parameter, which has been noticed in experiments in this range of Rayleigh numbers by other researchers. An explanation for this decrease in Nusselt number will also be presented. Our goal is to extend these simulations to higher Rayleigh numbers. It is entirely possible that the effects and the explanations are different at high Rayleigh numbers.

Direct Numerical Simulation of Turbulent Mixing in Grid-generated Turbulence

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Turbulent mixing of passive scalar (heat) in grid-generated turbulence is simulated by means of the direct numerical simulation (DNS). The computational domain is 800 x 80 x 80mm in the streamwise, vertical and spanwise direction. A square turbulence-generating grid, on which the velocity components are set to zero, is located 20mm downstream from the entrance of the channel and it is numerically constructed on the staggered mesh arrangement. The mesh size of the turbulence-generating grid M is 2cm and the thickness of the square rod d is 3mm. Two fluids with different temperature are provided separately in the upper and lower streams upstream of the turbulence-generating grid, generating the thermal mixing layer with an initial step temperature profile behind the grid. The fractional step method is used to solve the governing equations (i.e., N-S and continuity equations, transport equation for scalar). The governing equations are discretized on the staggered mesh arrangement to construct the finite-difference formation. The spatial derivatives are approximated by the second-order central difference formula. The time integrations are carried out by the fourth-order Runge-Kutta method. The Poisson equation for pressure is solved by the Bi-CGStab method. The result of the turbulent intensities of velocity component show that all the intensities have almost the same values and their decays follow a power law in the developed region after x/M = 5. The correlation coefficients of the Reynolds stress are very small in the whole downstream region. The results for the velocity field show that the typical grid turbulence is generated downstream of the grid. The results of the scalar field show that the typical thermal mixing-layer is generated as well. We will show the higher-order statistics, pressure statistics and energy balance of the grid-generated turbulence, which have not been investigated in the experiments due to the difficulty of the measurements.

On the Theory of Periodic Layer in Incompressible Fluid

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A conceptual error in the formally closed but physically incomplete Kim-Moin-Moser form of equations for viscous incompressible fluid in a horizontal periodic layer is corrected. This form, which has lately become popular, assumes that the vertical projections of the curl and the second curl of the field of accelerations vanish. This assumption considerably simplifies the calculations; however, it is insufficient for the equations of motion. In this report, the fulfillment of these assumptions is ensured by the additional condition that the vector of the horizontal projection averaged over the period of the acceleration vorticity vanishes, which opens new possibilities. The resulting complete form of the equations with the curls of three orders admits a reduction to two scalar equations (of the fourth and the sixth orders), which, however, are not less complicated than the equivalent Navier-Stokes equations.

Dynamics of Large-scale Convective Flow

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We report the new findings on the dynamics of large-scale motion of convective flow in chaotic regime through direct numerical simulation (DNS). We investigated the dynamics of large-scale modes of convective flow in chaotic regime through DNS. We showed that the large-scale modes successfully describe the observations of the recent experiments on mean wind, specially the flip of the mean wind. The evolution of the real and imaginary part of the large-scale modes

w_{101} and θ_{101} show very interesting and novel interplay. The real parts of these modes become very small during the flip, but the imaginary parts of these modes become very large during this period. This corresponds to a horizontal shift of the rolls by one-quarter wavelength. The rolls do not stop during the flip. The dynamics of real and imaginary part of the Fourier mode corresponding to the large-scale flow brings up new directions of investigation. It is an interesting observation that several features of the mean wind is very similar to the Lorenz model. We investigated the energy equations of the large-scale modes using energy transfers, and showed that the time evolution of θ_{101} and w_{101} are captured reasonably well by the generalized Lorenz equation. The energy cascade during the flip may be more complex, and it is being investigated at present. Our simulations are based on pseudo-spectral method on free-slip boundary conditions. We performed simulations in both two and three dimensions. We are in the process of investigating the mechanics of energy transfers in the convective flow.

Numerical Simulation Using High-Resolution Methods

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This paper concerns the validation of a finite volume code (CNS3D [1]) for use in turbulent simulations where the turbulence is driven by some external force (generally gravity). CNS3D can use a range of Riemann solvers along with numerous limiting methods for the inter-cell values. When comparing CNS3D with the Lagrange re-map code Turmoil [2] it is seen CNS3D is significantly more dissipative in the low Mach number regime. This is clearly shown using a Kelvin Helmholz test problem. The results using CNS3D can be significantly improved by using very high order schemes (5th order and greater). Preconditioning techniques have also been used to improve the results [3]. A final comparison of a multi-mode Rayleigh Taylor simulation shows that the large scale features such as mix width and growth rate are very similar for most of the methods. Variations between the methods begin to appear when the smaller scale features such as bubble size are compared.

[1] D. Drikakis, Progress in Aerospace Sciences, 39, 405-424, 2003. [2] D.L. Youngs, Laser and Particle Beams, 12:4 725-750, 1994. [3] B. Thornber et al, submitted, 2007.

EXPERIMENTAL DIAGNOSTICS

Simultaneous PIV-PLIF measurements in a Richtmyer-Meshkov unstable gas curtain

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Simultaneous PIV-PLIF measurements have been performed in a Richtmyer-Meshkov unstable single-mode SF6 gas curtain at Mach numbers ranging from 1.2 to 2.0. Results from measurements before and after reshock will be presented along with error estimates and convergence rates. While canonical turbulence experiments can utilize time averages and ergodicity to compute Reynolds stress tensors, shock-tube experiments operating at small time-scales such as the present facility, require multiple shots to extract true ensemble averages. However, such repetitions require a close control of the initial conditions to calculate sensible late time averages. By monitoring the initial conditions prior to shock-curtain interaction using a separate camera, we provide the scatter in the initial conditions along with velocity-concentration statistics. Indeed, such a complete characterization is absolutely essential for investigating Richtmyer-Meshkov flows that evolve from slightly different starting points during each instance of the ensemble. Such an evolution is, of course, inevitable in experiments that attempt true ensemble calculations. Planar velocity-velocity and concentration-velocity correlations are computed from the simultaneous PIV-PLIF data. These correlations are useful in the development of turbulence models and for the validation of RANS computations in inertial confinement fusion and supernova explosions. The present experiments provide, for the first time, directly measured estimates of the concentration velocity correlations for Richtmyer-Meshkov unstable gas curtains. We then present some results at higher mach numbers and investigate the development of turbulence in the gas curtain while starting from a state with a higher initial energy deposition.

Holographic three-dimensional imaging

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We present a detailed quantitative comparison of two holography-based approaches to 3D imaging: digital holography and volume holography. In digital holography (DH), light scattered from the object interferes coherently with a reference light beam; the interference pattern is captured by a digital camera, and an inverse Fresnel propagator is applied computationally to reconstruct the object. With volume holography (VH), a number of lenses, each focused to a different depth within the object, are multiplexed within the same volume holographic material; in addition, each lens has depth selectivity which means that it can image only a thin region of

space around its corresponding focal plane. In both cases of VH and DH, three-dimensional (3D) image information is captured on a two-dimensional (2D) exit window (camera plane); consequently, the number of resolvable voxels is limited by the number of available pixels (camera space-bandwidth product, or SBP) and the noise affecting the signal. There are also significant differences: DH is lensless and maximizes photon use whereas VH is lossier and requires elaborate design of objective optics to achieve its best resolution in the desired range. On the other hand, DH imposes a requirement of spatially and temporally coherent illumination.

To elucidate the differences between the two approaches, we compare images from several experimental prototypes that we have built at MIT. We discuss how each technique trades off working distance, SBP and dispersion, and related design considerations. We also develop an image quality metric based on information theory, and show how the metric can be used to determine upper bounds on image information acquisition for each method. For example, we relate camera (2D) SBP to voxel (3D) SPB and show how the former limits the latter as function of numerical aperture, hologram thickness in the VH case, and other hardware parameters. Finally, we discuss technology trends that are likely to influence practitioners' choice of holographic imaging instruments in the future.

Three-dimensional imaging using three-dimensional optics

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Traditional optical design is cast as the optimization of a sequence of surfaces to achieve a desired optical response. Raman-Nath holography, though often presented as a "3D imaging" approach, is really limited to imaging 2D manifolds in 3D space; that is, obtaining the brightness $b(x,y)$ as well as elevation map $z(x,y)$ of a surface. By contrast, volume (or Bragg) holography utilizes the interaction of light with an entire volume of modulated index of refraction. The resulting degrees of freedom can be used in designing shift-variant optical transfer functions, which in turn permit combinations of spatial 3D imaging and spectral imaging, i.e. brightness maps of the form $b(x,y,z,\lambda)$. In its most typical form, this form of imaging requires multiplexing several Bragg holograms in the same volume-holographic material. Each hologram is maps a specific 2D manifold of the (x,y,z,λ) space onto a portion of the exit window, where a digital camera is located. By designing the multiplexed holograms to share the exit window, we measure the corresponding manifolds simultaneously; therefore, the entire four-dimensional (x,y,z,λ) space becomes visible in real time on a regular digital camera plane. (The rearrangement of the measured pixel irradiances to 3D space representation and color is done as a simple assignment map.) This technique yields unique solutions for the 4D light distribution with spatially incoherent light, e.g. self-luminous or fluorescent samples. Coherent illumination leads to non-unique solutions, which however can still be resolved using priors or temporally structured illumination (scanning.) We describe the basic physics of 3D optical elements and the resulting performance trade-offs and design approaches, as well as several experimental implementations that we have built in our laboratory. We also report on our recent progress in designing a spatial-spectral microscope for tissue imaging using this technique, and discuss its potential for future application to particle image velocimetry with fluorescent particles under demanding spatially and spectrally variant conditions, e.g. combustion.

New technologies for fluid dynamics experiment and diagnostics

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Modern technologies offer new opportunities for the experimentalists in a broad variety of research areas including hydrodynamics. A significant, several folds, 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 approaches and techniques bringing the quality of experiments to a new level of standards. Application of the new technologies in experimental diagnostics can help to bridge the current quality gap between the observations and the computational fluid dynamics large-scale simulations allowing direct and unambiguous comparison of the data and the modeling results which is detrimental for the code validation.

One of the new technologies, which will be described in the tutorial is the ultra-high performance digital holographic data storage. The state-of-the-art motion control, electronics, and optical imaging allow for realization of turbulent flows with very high Reynolds number ($>10^7$) in a relatively small laboratory-scale form-factor and quantification of their properties with extremely high spatio-temporal resolutions and bandwidth. Digital holographic technology can provide 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 (~50 cm) with high spatial (1 to 10 microns) and temporal (better than few ns) resolutions and can thus provide extremely accurate quantitative description of the fluid flows, including multiphase and unsteady conditions. These unique experimental and metrological capabilities 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. The technology can be applied for investigations of a large variety of hydrodynamic problems including the fundamental properties of non-Kolmogorov turbulence, flow-particle interactions, accelerating and rotating flows, boundary layer, Rayleigh-Taylor instability and turbulent mixing, magneto-hydrodynamics, and laboratory astrophysics.

On the Possibility of the Hydrodynamic Instabilities growth studies in 2D Flows

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It is shown that it is possible to study the generation and growths of the gravitational and shear instabilities in 2D by use the floating in the water gas bubbles of various volume experiments.

STOCHASTIC PROCESSES and PROBABILISTIC DESCRIPTION

Turbulent mixing viewed from wavelet space

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Fourier space represents information in terms of wavenumber, while wavelet space tracks both scale and location. We have designed a wavelet-based method which decomposes the fluctuations of each flow realization into two orthogonal components. Both are excited at all scales but exhibiting different statistical behaviour, i.e., non Gaussian and long-range correlation for the coherent fluctuations, while the incoherent fluctuations are quasi-Gaussian and decorrelated. We will illustrate this for several 2D and 3D turbulent flows computed by DNS (direct numerical simulation) and study the advection-diffusion of different scalars together with particles. We will show that the coherent fluctuations correspond to transport by coherent vortices while the effect of incoherent fluctuations is turbulent mixing. This decomposition lead us to introduce a new way to compute turbulent flows, called CVS (Coherent Vortex Simulation) where only the coherent fluctuations are integrated in time while the incoherent fluctuations are discarded at each time step.

Related papers can be downloaded from: //wavelets.ens.fr

Nonlinear waves in superdiffusive reaction-diffusion systems

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Chemical oscillations and waves are remarkable manifestations of complex nonlinear dynamics in systems governed by reaction-diffusion equations. In the presence of chaotic or turbulent flows, the normal diffusion of reacting species based on the random walk of molecules can be replaced by a superdiffusive transport characterized by long-tail jump distributions. In the present talk, we consider the appearance and nonlinear development of concentration waves in the framework of a model of the anomalous diffusion which includes a fractional power of the Laplace operator. It is shown that near the threshold of the long-wave oscillatory instability, the nonlinear wave dynamics is governed by a superdiffusive modification of the complex Ginzburg-Landau equation. A superdiffusive Kuramoto-Sivashinsky equation is derived for the description of the propagation of spontaneously modulated waves. The analytical predictions are confirmed and extended by numerical simulations of superdiffusive integro-differential equations.

Covariance modeling and error estimation using an inhomogeneous turbulence closure based statistical dynamical filter.

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We compare the performance of statistical dynamical, square root and ensemble Kalman filters for error covariance modeling with applications to data assimilation. Our studies compare ensemble averaged direct numerical simulations with the statistics of inhomogeneous barotropic flows described by the quasi-diagonal direct interaction approximation closure (QDIA) model [1, 2]. The QDIA is a computationally tractable statistical turbulence closure, derived using renormalization and regularization methods, that has been proven to be very accurate for describing the statistics of highly nonlinear, non-Gaussian and inhomogeneous geo-physical flows. We examine the performance of the stochastic Kalman and deterministic square root filter methodologies to the turbulence closure based filter for covariance modeling during a period in 1979 in which several large-scale atmospheric blocking regime transitions occurred in the Northern Hemisphere. Our results show that for the ensemble Kalman filter sampling error results in a systematic under estimation of the gain; we examine the causes of this underestimation. In contrast, the closure based statistical dynamical filter, and the deterministic ensemble square root filter, which preserves growing error structures through the use of flow dependent perturbations [3], are shown to be in close agreement. In all cases the Kalman gains have bell shaped spectra with peaks at the wavenumbers of the rapidly growing evolved instabilities such as those associated with block development. In 12 hourly data assimilation experiments over a 30 day period the systematic differences from comparison of a square root filter methodology and the truth were found to be very small in relation to the observed error variances. The prior covariances were shown to be small in relation to the mean throughout the entire 30 day period. No localization or inflation factors have been used.

[1] O'Kane, T.J., & Frederiksen, J.S. (2004) The QDIA and regularized QDIA closures for inhomogeneous turbulence over topography. J. Fluid Mech., 504, 133—165. [2] Frederiksen, J.S., & O'Kane, T.J. (2005) Inhomogeneous closure and statistical mechanics for Rossby wave turbulence over topography. J. Fluid Mech., 539, 137—165. [3] O'Kane, T.J., & Frederiksen, J.S. (2007) A comparison of statistical dynamical and ensemble prediction during blocking. J. Atmos. Sci. (In Press)

Statistical closure based subgrid-scale parameterizations of eddy viscosity, stochastic backscatter and the eddy-topographic force for inhomogeneous geophysical wave-turbulence.

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The interaction between retained and subgrid scale transient eddies, topography and the mean flow is a crucial determining factor in the generation of oceanic circulations. Inaccurate parameterizations of those dynamical processes that are not able to be resolved in our numerical ocean and atmospheric climate models, due to the small scales at which they occur, lead to systematic defects in large-scale general circulation models. Traditional approaches to ocean modeling treat fields resolved on the model grid by the classical dynamics of continua. Due to the inherently turbulent nature of oceanic flows any arbitrarily nearby solutions of the fundamental equations of fluid motion (i.e. the Navier-Stokes equation) will become uncorrelated as they evolve over time. Parameterizations of the actions of the many small scale fluctuations are typically treated by replacing the usual horizontal eddy viscosity parameterization (centered at rest) by an ad hoc eddy tendency (centered about a filtered form of the topography) in order to relax toward statistical mechanical equilibrium tuned to observations. New methods, based on non-equilibrium statistical mechanics and statistical dynamics[1,2,3], that allow "exact" statistics to be obtained for highly nonlinear and inhomogeneous barotropic flows are presented. Results for typical global atmospheric flows are presented to demonstrate the methodology.

[1] O'Kane, T.J., & Frederiksen, J.S. (2004) The QDIA and regularized QDIA closures for inhomogeneous turbulence over topography. J. Fluid Mech., 504, 133—165. [2] Frederiksen, J.S., & O'Kane, T.J. (2005) Inhomogeneous closure and statistical mechanics for Rossby wave turbulence over topography. J. Fluid Mech., 539, 137—165. [3] O'Kane, T.J., & Frederiksen, J.S. (2007) A comparison of statistical dynamical and ensemble prediction during blocking. J. Atmos. Sci. (In Press)

1/f noise in a stochastic layer solution in the DNLSE

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We find a robust thin stochastic layer solution in the Discrete Nonlinear Schrodinger Equation. This solution shows 1/f noise over a wide range of parameters. The sticky domains are the neighbourhoods of unstable periodic orbits of period one and two quasinvariant regions in phase space. The robustness of these solutions suggest possible Bose-Einstein Condensate experiments.

C. L. Pando L. and E. J. Doedel, Phys. Rev. E 75, 016213 (2007)

A Conditionally Cubic-Gaussian Stochastic Lagrangian Model for Acceleration in Isotropic Turbulence

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The modeling of fluid-particle acceleration in isotropic turbulence via stochastic models for the Lagrangian velocity, acceleration and a dissipation rate variable is considered. The basis for the Reynolds model (P.R.L. 91, 084503 (2003)) is reviewed and examined by reference to direct numerical simulations (DNS) of isotropic turbulence at Taylor-scale Reynolds numbers up to 650. The DNS data are used to construct a new stochastic model that is exactly consistent with Gaussian velocity and conditionally cubic-Gaussian acceleration statistics. This model captures the effects of small-scale intermittency on acceleration and the conditional dependence of acceleration on pseudo-dissipation (which differs from the Kolmogorov 1962 prediction). Non-Gaussianity of the conditionally standardized acceleration PDF is accounted for in terms of model nonlinearity. The large-time behavior of the new model is that of a velocity-dissipation model that can be matched with DNS data for conditional second-order Lagrangian velocity structure functions. As a result, the diffusion coefficient for the new model incorporates two-time information and their Reynolds-number dependence as observed in DNS. The resulting model predictions for conditional and unconditional velocity autocorrelations and timescales are shown to be in very good agreement with DNS.

Turbulent Transport: A Wiener Chaos Approach

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The standard formula for a solution of transport (passive scalar) equation does not hold if the driving velocity field is not Lipschitz continuous. Therefore, it is not applicable to important statistical models of turbulence such as Kolmogorov's and Kraichnan's models were the velocity field is only Holder continuous. In this talk we will concentrate on Kraichnan's turbulent velocity. A stochastic flow corresponding to this velocity will be constructed and a Lagrangian representation of the solution of the transport equation extending the standard formula to Kraichnan velocity field will be presented. It will be shown that the flow corresponding to Kraichnan velocity is super-unstable which leads to the dissipation of energy of the passive scalar. Moreover, it will be shown that the dissipation of energy takes place if and only if the flow is super unstable. Using the Wiener chaos expansions we will be show that in contrast to the non-unique Lagrangian representation the solution of the transport

equation driven by the Kraichnan velocity field is pathwise unique and square integrable as in the classical setting. It will be shown that the solution of this equations remains to be well defined and unique even for the velocity fields much less regular then the Kraichnan velocity.

Stochastic analysis of the turbulent cascade process

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We present an analysis for measurement data of turbulence by means of the estimation of Kramers-Moyal coefficients, which provide access to the joint probability density function of velocity increments [1]. In this contribution we report on new findings based on this technique and based on the investigation of different flow data over a large range of Re numbers. In particular, our contribution includes the following aspects:

1. A method to reconstruct from given data the underlying stochastic process in form of a Fokker-Planck equation, which includes intermittency effects, will be presented.

2. It is shown that a new length scale, the Markov length, for turbulence can be defined, which corresponds to a memory effect in the cascade dynamics, and which is closely related to the Taylor micro-scale. For length scales larger than the Markov length, the complexity of turbulence can be treated as a Markov process [2].

3. For longitudinal and transversal velocity increments we present the reconstruction of the stochastic process equations, which show that the cascade evolves differently for the longitudinal and transversal increments. A different 'speed' of the cascade can explain the reported difference for these two components. The rescaling symmetry is compatible with the Kolmogorov constants and the von Karman equation and gives new insight into the use of extended self similarity (ESS) for transverse increments [3].

4. We present first results from the analysis of Lagrangian turbulence, using data provided by J.F. Pinton [4], and examine the Markov properties and the underlying stochastic process in comparison to the Eulerian framework.

[1] Ch. Renner, J. Peinke, and R. Friedrich: Markov properties of small scale turbulence, J. Fluid Mech. 433, 383 (2001). [2] St. Luck, Ch. Renner, J. Peinke, and R. Friedrich: the Markov coherence length - a new meaning for the Taylor length in turbulence, Phys. Lett., in press. [3] M. Siefert and J. Peinke: On a multi-scale approach to analyze the joint statistics of longitudinal and transversal increments experimentally in small scale turbulence, J. of Turbulence 7, (No. 50) 1-35 (2006). [4] N. Mordant, E Leveque, and J.F. Pinton: Experimental and numerical study of the Lagrangian dynamics of high Reynolds turbulence, New Journal of Physics 6 (2004) 116

INDEX of PRESENTATIONS