Turbulent Mixing and Beyond

Third International Conference

PROCEEDINGS

ABSTRACTS

21 - 28 August, 2011

The Abdus Salam International Centre for

Theoretical Physics

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Abstracts of the Proceedings of the Third International Conference 'Turbulent Mixing and Beyond,' 21–28 August, 2011, The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

Edited by
Snezhana I. Abarzhi, Malcolm J. Andrews, Serge Gauthier, Christopher J. Keane, Joseph J. Niemela, and Katepalli R. Sreenivasan

ISBN 92-95003-45-4

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Preface

The goals of the program 'Turbulent Mixing and Beyond' (TMB) are to expose the generic problem of Non-equilibrium Turbulent Processes to a wide scientific community, to promote the development of new ideas in tackling the fundamental aspects of the problem, to assist in application of novel approaches in a broad range of phenomena, in which the turbulent processes occur, and to have a potential impact on technology.

'Turbulent Mixing and Beyond' is the program established for scientists, by scientists. It is merit-based, and is shaped by requirements of academic credentials, novelty and information quality.

The program was founded in 2007 with the support of the international scientific community and of the US National Science Foundation, the US Air Force Office of the Scientific Research and its European Office for Research and Development in the UK, the UNESCO-IAEA International Centre for Theoretical Physics in Italy, the Commissariat l'Energie Atomique in France, the US Department of Energy and the Department of Energy National Laboratories, the Institute for Laser Engineering in Japan, and the University of Chicago in USA.

The International Conference 'Turbulent Mixing and Beyond' provides opportunities to bring together researchers from the areas, which include but are not limited to fluid dynamics, plasmas, high energy density physics, astrophysics, material science, combustion, atmospheric and earth sciences, nonlinear and statistical physics, applied mathematics, probability and statistics, data processing and computations, optics and communications, and to have their attention focused on the long-standing formidable task of non-equilibrium turbulent processes.

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

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

The First and Second International Conferences 'Turbulent Mixing and Beyond' found that: (i) TMB-related problems have in common a set of outstanding research issues. (ii) Their solution has a potential to significantly advance a variety of disciplines in science, technology and mathematics. (iii) TMB participants conduct highly innovative research and their interactions strengthen the community's might.

Non-equilibrium turbulent processes is the intellectually rich and highly fascinating problem whose exploration may have a transformative impact on our understanding of a wide variety of physical phenomena, from atomistic to astrophysical scales, on the fundamental principles of mathematical modeling of the dynamics of continuous media and non-equilibrium kinetics, and on the technology development in fusion, nano-electronics, telecommunications, and aeronautics.

Based on the success of the first and second conferences and on the recommendations of the conference Round Table Discussions, and in response to the inquiry of the community, the Third International Conference 'Turbulent Mixing and Beyond' is being organized.

The objectives of the Third International Conference 'Turbulent Mixing and Beyond' are to:

a. Focus the integration of theory, experiments, large-scale numerical simulations and state-of-the-art technologies on exploration of physical mechanisms of non-equilibrium dynamics, from micro to macro-scales, in both high and low energy density regimes.
b. Foster the application of innovative approaches for tackling the fundamental aspects of turbulent mixing problems and for understanding and further extending the range of applicability of canonical considerations.
c. Encourage the development of new approaches and stimulate the application of advanced data analysis techniques for unified characterization of experimental and numerical data sets, for estimation of their quality and information capacity, and for transforming data to knowledge.
d. Further develop the 'Turbulent Mixing and Beyond' community via organizing a positive and constructive collaborative environment, maintaining the quality of information flux in the community, and sharing research methodologies, tools, and data among the community members.

The Organizing Committee hopes that the program 'Turbulent Mixing and Beyond' will serve to advance knowledge of the fundamental aspects of the generic problem of non-equilibrium turbulent processes and will potentially have an impact on predictive modeling capabilities, physical description and, ultimately, control of these complex processes.

The Book of Abstracts includes 207 accepted contributions of 443 authors: lectures, talks, and posters in a broad variety of TMB Themes, sorted alphabetically within each theme. All the accepted contributions have been reviewed by the international team of 27 members of the Scientific Committee, with every abstract considered by 4 to 11 experts. In the majority of cases, the opinions of referees with diverse backgrounds and expertise converged.

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

S. I. Abarzhi, M. J. Andrews, S. Gauthier, C. J. Keane, J. J. Niemela,
K. R. Sreenivasan

CONTENTS

CANONICAL TURBULENCE and TURBULENT MIXING

Compressible turbulence: the cascade and its locality

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We use a coarse-graining approach to prove that inter-scale transfer of kinetic energy in compressible turbulence is dominated by local interactions. Locality here means that interactions between disparate scales decay at least as fast as a power-law function of the scale-disparity ratio. In particular, our results preclude transfer of kinetic energy from large-scales directly to dissipation scales, such as into shocks, in the limit of high Reynolds number turbulence as is commonly believed. The results hold in broad generality, at any Mach number, for any equation of state, and without the requirement of homogeneity or isotropy. The assumptions we make in our proofs on the scaling of velocity, pressure, and density structure functions are weak and enjoy compelling empirical support. Under a stronger assumption on pressure dilatation co-spectrum, we show that mean kinetic and internal energy budgets statistically decouple beyond a transitional conversion range. We propose a physical justification for the latter assumption based on scale-decorrelation effects. We also present supporting evidence from high-resolution numerical simulations. Our analysis demonstrates the existence of an ensuing inertial scale-range over which mean subgrid-scale kinetic energy flux becomes constant, independent of scale. Over this inertial range, mean kinetic energy cascades locally and in a conservative fashion, despite not being an invariant.

Vortex-dipole chaos theory of turbulence

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The talk sketches a new statistical quasi-particle approach to idealized fluid turbulence at asymptotically high Reynolds numbers based on an ensemble of vortex-dipole filaments. These move with classical dipole velocity. The effective, renormalized, vortex radius is related to Prandtl's classical mixing length. A quasi-particle is "dressed", embedded in a cloud of others. Its energy is finite. It performs a locally quasi two-dimensional dipole chaos, reminiscent of real gases. Collisions between stable quasi-particles lead either to scattering: re-connection or re-

combination resembling turbulent diffusion, or to dissipation: particle annihilation through the formation of unstable, likewise rotating couples. The particle annihilation takes the form of quasi-stationary dissipative patches which contain vortex scales down to size zero where the vortex energies are converted to heat. This is the “devil’s gear” of Herrmann 1990. It represents a geometrization of the Kolmogorov-Richardson cascade of turbulence. This geometrization enables the derivation of general equations of turbulent motion and of fundamental constants such as von Kármán’s constant and two Kolmogorov spectral constants. The derived constants are in agreement with observations. For example, in this theory von Kármán’s constant appears as $1/\sqrt{2\pi} = 0.399$. Compared with Reynolds averaging, the vortex dipole approach allows a substantially better understanding of stratified flows. This holds for collapsing turbulence, Monin-Obukhov boundary layers and other flow processes.

This work relates to Department of the Navy Grant N62909-10-1-7050 issued by Office of Naval Research Global. -- Helmut Z. Baumert, IAMARIS Managing Office, Bei den Mühren 69 A, 20457 Hamburg, Germany.

Persistence of incomplete mixing: a key to anomalous transport

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Anomalous dispersion in heterogeneous environments describes the anomalous growth of the macroscopic characteristic sizes of scalar fields. Here, we show that this phenomenon is closely related to the persistence of local scale incomplete mixing. We introduce the mixing scale ε as the length for which the scalar distribution is locally uniform. We quantify its temporal evolution due to the competition of shear action and diffusion and compare it to the evolution of the global dispersion scale σ. In highly heterogeneous flow fields, for which the temporal evolution of σ is superdiffusive, we find that ε evolves subdiffusively. The anomalous evolutions of the dispersion and mixing scales, are complementary, $\varepsilon\sigma \propto t$. This result relates anomalous global dispersion to the dynamics of local mixing.

Laminar bubble chains: a logarithmically exact solution

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The velocity field around a stationary linear laminar bubble chain was recently obtained in the Oseen approximation (A.V. Byalko 2011, Doklady Physics 56, 82).

The liquid velocity at the chain axe is found with logarithmic exactness for an arbitrary velocity of a single bubble. The stability of uniform chains is estimated. The intensity of a bubble chain pump is evaluated. The applicability of the results to a turbulent case is discussed.

Turbulent mixing in isotropic and anisotropic (axisymmetric) flows

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A remarkable property of turbulence is its ability to enhance the mixing of scalar contaminants, either passive or active. Consequently, the accurate prediction and/or control of these phenomena requires a thorough understanding of scalar mixing in turbulent flows. This talk is focused on turbulent, passive and active scalar mixing, characterized by using analytical and experimental tools. Three issues will be addressed: 1) One-point characterisation of gaseous (Schmidt number, Sc=1) mixing, via e.g. the scalar probability density function (pdf). We improve a phenomenological Pdf model based on the self-convolution hypothesis, by taking into account local characteristic times, via strain-rate fluctuations. The model is validated in turbulent mixing in a multiple jets reactor, by using simultaneous measurements of both scalar and velocity fields. 2) Two-point characterisation of gaseous (Sc=1) mixing. The question is: Can we predict mixing from velocity field statistics? A first answer is given in homogeneous isotropic turbulence in which the scalar and the velocity fields are injected in the same way, for which the passive scalar second-order statistics are closer to the asymptotic state than those of the dynamical field which transports it. We explain this peculiar behaviour of the scalar, by considering the role played by the velocity field itself via the characteristic time which takes into account the strain imposed by all scales larger than the one under consideration. The discussion goes beyond, to anisotropic flows. Scalar and dynamic fields are studied by using scale-by-scale energy budget equations developed for axisymmetric turbulence. It is shown that, on the axis of two opposed jets, energy transfer is slower than on the perpendicular directional, thus emphasizing the cascade directionality. 3) One and two-point characterisation of gaseous, variable viscosity mixing. A turbulent propane jet issues in still air (air is 5 times more viscous than propane). In comparison with a constant-viscosity flow, mixing is strongly enhanced, self-similarity and local isotropy are very rapidly achieved, the local Sc progressively increases (from 1 to 7) for increasing downstream positions. The scalar spectra exhibit an increasingly prominent Batchelor regime with a ‘-1’ scaling law.

Asymptotic states in turbulent mixing: the role of Peclet number in scalar fluxes, dissipation, spectra and intermittency

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Some basic properties of turbulence such as the rate of energy dissipation become independent of fluid viscosity when the latter attains small enough values, or the Reynolds number is sufficiently high [1-2]. Similarly, one expects that other basic properties of mixing become independent of the molecular diffusivity when it attains small enough values, though little is known about how small it has to be to realize asymptotic states for different quantities of interest. Using a large database of direct numerical simulations with resolutions up to 4069^3, spanning a Taylor Reynolds number $R_\lambda = u'\lambda / \nu$ (where λ is the Taylor microscale) up to 1000, and Schmidt numbers, $Sc = \nu / \kappa$ (where ν and κ are the viscosity and diffusivity, respectively) between 1/8 and 1024, we examine the parameters governing the approach to the asymptotic behaviors. It is found that asymptotic states for the scalar dissipation rate, intermittency and normalized scalar fluxes (which can be interpreted as a turbulent Schmidt number) scale with $R_\lambda{}^2 Sc$ which is identified with the Peclet number $P = u'L / \kappa$ (where u' is the root-mean-square velocity and L the integral scale). Although different values of P are required for each of these quantities to attain the asymptotic state, the high-P limits typically emerge for P in the range 10^3 to 10^4. It is also found that the widest k^{-1} inertial-convective range is realized at the highest P. Interpretation of the results and further consequences will be offered. The challenges and paths towards simulations at even higher Reynolds and Schmidt numbers at Petascale levels will be briefly discussed.

[1] K.R. Sreenivasan, Phys. Fluids 27, 1048 (1984); Phys. Fluids 10, 528 (1998); [2] D.A. Donzis, K.R. Sreenivasan, P.K. Yeung, J. Fluid Mech. 532, 199 (2005).

Do finite size neutrally buoyant particles dispersed in a turbulent flow clusterize?

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Turbulent flows laden with inertial particles are omnipresent and their study is of great interest for industrial, environmental and fundamental aspects. The trend to concentrate in preferentially sampled regions of the carrier flow has been observed for long (both in experiments and simulations) for small inertial particles with a high density ratio compared to the fluid (see for instance Fessler et al., IJMF 1994 ; Squires et al., PoFA 1991). Because of their high specific density, the dynamics of such small and heavy inertial particles deviates from that of the carrier flow. Clustering phenomenon is one of the many manifestations of this departure from tracer behavior. In the present study we investigate the preferential concentration of particles which are neutrally buoyant but with a diameter significantly larger than the dissipation scale of the carrier flow. Such particles are also known not to behave as flow tracers (Qureshi, PRL 2007) but whether they do cluster or not remains an open question. For this purpose, we take advantage of a new turbulence generating apparatus, the LEM (Lagrangian Exploration Module) which produces homogeneous and isotropic turbulence in a closed water flow (Zimmermann et al., Rev. Sci. Instrum. 2010) driven by 12 propellers evenly distributed in a icosahedral vessel. The flow is seeded with neutrally buoyant particles with diameter 700µm (corresponding to ≈10 times the turbulent dissipation scale). The spatial structuration of these inclusions is then investigated by a Voronoi tesselation analysis from images of particles concentration field taken in a laser sheet at the center of the flow. Such a Voronoi analysis has been recently introduced by Monchaux et al. (PoF 2010) for the investigation of preferential concentration of small water droplets in a turbulent flow of air, and was shown to be particularly efficient and robust to diagnose and quantify clustering phenomenon.

Scale-by-scale energy budget equations for the Mixing of a passive scalar by homogeneous turbulence

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The mixing of a passive scalar with imposed mean gradient by steady homogeneous turbulence is investigated by means of a scale-by-scale scalar energy budget equation in the context of large-eddy simulation (LES). The turbulent energy transport between scales is a crucial quantity which has to be satisfied by sub-grid closures in order to preserve the statistically properties of the flow field. The scalar scale-by-scale energy budget can be expressed by the transport equation of second moment of the scalar increment written in a generalized form accounting for the mean gradient. For comparison with LES a new scale-by-scale scalar energy budget equation for the filtered second order moment of the scalar increment is derived. This equation incorporates the balance between production at large scales due to the mean

gradient, transport at intermediate scales, as well as diffusion at small scales. For LES, diffusion divides into a viscous and a sub-grid part (cf. enclosed document). Based on this equation an a posteriori comparison of LES with filtered direct numerical simulation (DNS) is conducted. An eddy-viscosity sub-grid closure reveals very good agreement for all scales. For reference also the results from DNS are discussed. The effect of the molecular diffusivity is studied by varying the Schmidt number between 0.25 and 6.

Alignment of dissipation elements in a turbulent channel flow

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There have been many attempts to define the structure of geometrical objects in turbulence. For three-dimensional flows geometry can be represented as point, line, surface or volume. Examples of geometrical structures are stagnation points, streamlines, iso-surfaces or vortex tubes. A volumetric object called dissipation element was introduced by Wang and Peters (2006) [1], which is defined by all that points from which gradient trajectories reach the same minimum and maximum point of a scalar field. The statistics of dissipation elements of the kinetic energy field in different turbulent flows have been analyzed extensively lately [2]. In this work the alignment of dissipation elements with respect to local strain rate, the distance to the wall and other geometrical structures was examined. Therefore a code for direct numerical simulations of a turbulent channel flow was developed based on the algorithm of Kim Moin Moser (1987) [3] for highly resolved DNS of $\delta x/\eta = 1.0$ and $Re_\tau = 590$ to run on JUGENE at the Research Center Juelich with up to 16384 cpus.

[1] L.Wang, N.Peters. The length scale distribution function of the distance between extremal points in passive scalar turbulence, J.Fluid Mech., 554:457-475, 2006; [2] M.Gampert, J.H.Goebbert, P.Schaefer, M.Gauding, N.Peters, F.Aldudak, M.Oberlack. Extensive strain along gradient trajectories in the turbulent kinetic energy field. New Journal of Physics, 13, 043012, 2011; [3] J.Kim, P.Moin, R.Moser, Turbulence statistics in fully developed channel flow at low Reynolds numbers. J. Fluid Mech., 177, 133-166, 1987.

Poloidal/toroidal decomposition in Rayleigh-Taylor mixing zones

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The revelance of a poloidal-toroidal decomposition for the velocity field has been largely discussed for stably stratified flows since Riley et al. (1981) (introduced as "vortex-wave" decomposition see [1]). Its major interest lies in the fact that only one component (the poloidal one) is affected by the baroclinic source term. Studying the coupling between poloidal and toroidal (due to non linear terms) may shed light on physical process like the horizontal layering in the low Froude number flows (see [2]). In this work, we consider also a poloidal-toroidal decomposition of the velocity field but for unstably stratified flows. From direct numerical simulations of turbulent Rayleigh-Taylor mixing zones, we observe as expected that the poloidal component is dominant because constantly amplified by the gravitational term ([3]). In the spectral space, the poloidal/toroidal decomposition is directly linked to the Craya-Herring frame. From this formalism, we propose a generalization of the notion of angular spectra to inhomogeneous axisymmetric flows and show the profound differences between poloidal and toroidal spectra.

[1] P. Sagaut and C. Cambon, Homogeneous Turbulence Dynamics, CUP, New York, (2008); [2] F.S. Godeferd C. Cambon, Detailed inverstigation of energy transfers in homogeneous stratified turbulent flows, Phys. Fluids 6, 20842100, (1994); [3] B-J. Grea, J. Griffond and O. Soulard Spectral anisotropy of Rayleigh–Taylor turbulence, ERCOFTAC workshop, Paris, (2011).

Elastic-turbulence-induced melting of a nonequilibrium vortex crystal in a forced thin fluid film

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We perform a direct numerical simulation (DNS) of the forced, incompressible two-dimensional Navier-Stokes equation coupled with the FENE-P equations for the polymer-conformation tensor. We forced it such that, without polymer and at low Reynolds numbers (Re) the steady state of the film is a square lattice of vortices and antivortices. We find that, as we increase the Weisenberg-number (We), this lattice undergoes a series of nonequilibrium phase transitions, first to a distorted steady crystals, then to a sequence of crystals that oscillate in time, periodically at low We and quasiperiodically for slightly larger We. Finally the system becomes disordered and displays spatiotemporal chaos and turbulence. We obtain the nonequilibrium phase diagram for this system in the We-Re plane. We show that the Okubo-Weiss parameter produces a natural mean for the characterizing the phases in this diagram.

Short-range spatial correlations in variable-density turbulence

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It is shown that, in variable-density solenoidal turbulent flows, states without long-range velocity-correlations are allowed. In these states density fluctuations instantaneously scatter pressure waves and “dress” the Green’s function which relates between the velocity field and the pressure. The “dressing” changes the form of the Green’s function from a Coulomb-like function which drops off as the reciprocal distance, to a Yokawa-like Green’s function. i.e. assymtotically, it falls off exponentially with the distance. The emerging physical picture is that the inner structure of variable-density turbulence may be described as a superposition of dressed velocity eddies. Truncated range of correlations also imply that moments of correlation functions (e.g. Loitsianskii and Corssin integrals) are dynamic invariants. All this is in a stark contrast with the canonical constant-density turbulence, which has long range correlations as a major signature. i.e. even if initiated with two-point velocity-correlations which fall off exponentially with the distance between the points, will instantaneously build fluctuations in the pressure which induce long-range correlations which fall off as a power law of the reciprocal distance.

G. K. Batchelor and I Proudman “The Large-scale structure of homogeneous turbulence” Phil. Trans. Roy. Soc. A, 248, 369 (1956).

Anomalous scaling of passive scalars in rotating flows

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We present results of direct numerical simulations of passive scalar advection and diffusion in turbulent rotating flows. Scaling laws and the development of anisotropy is studied in spectral space, and in real space using an axisymmetric decomposition of velocity and passive scalar structure functions. The passive scalar is more anisotropic than the velocity field, and its power spectrum follows a spectral law consistent with $k^{-3/2}$. This scaling is explained with phenomenological arguments that consider the effect of rotation. Intermittency is characterized using scaling exponents and probability density functions of velocity and passive scalar increments. In the presence of rotation, intermittency in the velocity field decreases more noticeably than in the passive scalar. Its scaling exponents show good agreement with Kraichnan's prediction for passive scalar intermittency in two-dimensions, after correcting for the observed scaling of the second order exponent.

Velocity and temperature decay in a near-wake region of a turbulent heated crossbar wake

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The present use a lattice Boltzmann method to investigates the decay of turbulence in the near-wake region of a crossbar with the view to assess the degree of anisotropy of the flow at different stage of the decay. One may argue that the crossbar arrangement can be seen as the "unit element" of a grid made of vertical and horizontal bars. As such it could help shed some light into the generation of the large scale anisotropy and it subsequent degeneresсence towards isotropy. Djenidi (2008) showed that the turbulence along the centerline of the wake decays similarly to that of a grid turbulence, suggesting that the crossbar turbulence can be a surrogate to a grid turbulence . The results show that the flow in the near-wake region, which is dominated by the relatively large scale coherent structures, is not isotropic. It is shown that there is also departure from local (or small scale) isotropy. Indeed, the velocity derivative ratios expressed by the factor K2 and K4 are relatively close but not equal to 2, the isotropic value for these factors. Similar conclusions can be drawn for the temperature field. Interestingly, The gradient ratios for both of velocity and temperature indicate axisymmetry of the turbulence along the centerline.(refer to attachment) Further assessment of the small scale turbulence is currently in progress. Quantities such as the kinetic energy and temperature dissipation rates, the second and third order structure functions will be presented at the conference.

Dynamics of reorientations and reversals of large scale flow in Rayleigh-Benard convection

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Large Scale Circulation (LSC), also known as 'mean wind', appears at large length scales in turbulent Rayleigh-Benard convection (RBC). It is a coherent structure of the flow in which fluid particle ascends from one side of the wall and descends down from the azimuthally opposite side. It has been observed in laboratory experiments that the vertical plane containing LSC undergoes a diffusive motion in the azimuthal direction of the cylindrical container. Sometimes, in the course of its motion, the plane of the LSC changes by a significant angle. This phenomena, called the reorientation of the LSC, leads to flow reversal exhibiting a rich dynamical behaviour. I will present a numerical study of the dynamics of the reorientation of the LSC for air (Prandtl number = 0.7) contained in a cylindrical container of aspect ratio one. We detect the presence of LSC in the turbulent regime of RBC. We propose a conjecture that the dynamics of LSC in the azimuthal direction can be captured quite well by the Fourier mode with the lowest wavenumber. The amplitude and phase of this mode provide a very good estimate of the strength and orientations of LSC. We observe rotation-led and cessation-led partial as well as full azimuthal reorientation of the flow as observed in earlier experiments. We find that the ratio of the amplitude of the second azimuthal Fourier mode and the first azimuthal Fourier mode rises sharply during the cessation-led reorientations which indicates the quadrupolar nature of the flow during the cessation-led reorientations. This behaviour is highlighted first time in our numerical simulation.

Vortex sheet model for a turbulent mixing layer

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The primary aim of this work is to study a temporal mixing layer using the model of instability induced roll up of a slightly perturbed vortex sheet in an Euler fluid. A point vortex model tends to evolve into a chaotic cloud of point vortices instead of smooth double branched spirals. The present model uses linear splines to interpolate the vortex sheet. Computer simulation of this vortex sheet is numerically prohibitive. However, the evolution of the vortex sheet can be performed conveniently using a closed form equation of motion which derived from the basic

equations of vortex dynamics. The vortex sheet rolls up into a smooth double branched spiral. A vortex core is formed by regular windings of the vortex sheet and irrotational fluid in between the layers. Various statistical quantities like the growth rate and mean velocity profiles are computed along with the evolution of the vortex sheet. The problem of spontaneous appearance of singularity in an evolving vortex sheet is treated in detail. The critical time for the present vortex sheet model is calculated analytically and compared to the numerical value. A desingularized vortex sheet model is also in development that will use an infinitesimal amount of viscous diffusion, yet not change the overall dynamics of the system.

The URAPS closure for the normalized Reynolds stress

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The Navier-Stokes (NS) equation and the continuity equation govern the instantaneous velocity and pressure fields of a Newtonian fluid for all Reynolds numbers. For constant density fluids, the divergence of the velocity is zero. If the velocity field is non-Beltrami and if the local inertial forces in the NS-equation are sufficiently large compared with the local viscous forces over some finite spatial domain, then the flow is turbulent throughout the entire flow domain. An instantaneous turbulent velocity field has three non-trivial time and spatially dependent components, satisfies the no-slip boundary condition at a solid/fluid interface, and is highly dependent on initial conditions. Nevertheless, low-order statistical moments (i.e., ensemble averages) provide a practical means to study these complicated flows. An ensemble average of the NS-equation and the continuity equation yields an equation for the mean velocity widely known as the Reynolds average Navier-Stokes (RANS) equation (Monin and Yaglom, 1965; Pope, 2000).

The RANS-equation, albeit exact, is unclosed and requires an additional equation that links the local Reynolds stress to the local mean velocity gradient. This strategy has been employed for more than a century to study the low-order statistical properties of turbulent mixing of momentum (Boussinesq, 1877). A recently developed algebraic model for the normalized Reynolds (NR) stress is used to close the RANS-equation (Koppula et al., 2009, 2011). The new closure is formulated as a non-negative algebraic mapping of the NR-stress into itself and is, thereby, realizable for all rotating and non-rotating turbulent flows. In this presentation, the efficacy of the URAPS (universal, realilizable, anisotropic, prestress) closure is illustrated for a class of rotating and non-rotating simple shear flows. Predictions of the NR-stress based on the URAPS equation are consistent with previously reported direct numerical simulations.

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Rotating turbulence and the return to isotropy

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Using a large-scale numerical simulation of rotating helical turbulence on a grid of 3072^3 points, we show that at scales smaller than the so-called Zeman scale at which the turn-over time and the wave time are equal, isotropy recovers together with a Kolmogorov spectrum whereas at larger sales, a wave-mediated spectrum is found with the dominant influence of helicity (velocity-vorticity correlations). For this flow fored with a fully helical Beltrami vortex at intermediate scale, the Reynolds number is 27,000 and the Rossby number is 0.07. We also show that the helicity spectrum breaks down at the Zeman scale, although the energy and helicity fluxes remain constant throughout the inertial ranges. Angular spectra are computed as well as intermittency exponents, the question being whether the self-similarity observed in the large scales persist at smaller scales.

A small parameter in turbulence: lifting the dynamics to dimensions 4/3 < D < 2

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A method is proposed to simulate the Navier-Stokes equations in fractal dimensions $4/3<D<2$. This provides a 1-parameter family of models which continuously approaches the dynamics at dimension $D=4/3$, while preserving the conservation of energy and enstrophy. We corroborate the theory of [V. L'vov, A.Pomyalov and I. Procaccia, Phys. Rev. Lett, 89, 064501 (2002)], which predicted that at D=4/3 there exists an equilibrium solution with a Gaussian velocity distribution and equi-partition of enstrophy. The energy flux vanishes continuously as D approaches 4/3, providing a small parameter for dimensions D=4/3+ε. Implications for 2-dimensional turbulence are explained and discussed.

The advection regime in turbulent convection across a horizontal permeable membrane

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In convection across a horizontal permeable membrane, created by an arrangement of a layer of brine over a layer of water with the membrane separating them, a regime where transport across the membrane occurs by advection occurs at larger concentration differences. Experiments were conducted with a membrane of open area factor (Γ) = 0.31 and pore size (Ps) = 45 μm to achieve high Rayleigh numbers ($Ra \sim 10^{11}$) and high Schmidt number (Sc ~ 600). The near wall coherent structures were sheet plumes that covered half the area of the membrane; the plume-free area is expected to be due to the impingement of large scale flow (mean wind) on the membrane. The dimensionless flux, Sherwood number (Sh) ~ Ra^2/Sc, this flux scaling is shown to be due to flow that obeys Darcy law driven due to the impingement of the mean wind on the membrane. The boundary layers on the membrane are shown to be natural convection boundary layers with a wall-normal flow at their base, which helps us to approximate the concentration across the species boundary layers to be uniform at high Sc. An integral analysis is performed to calculate the species boundary layer thickness δ d as a function of velocity through the membrane (V_w). Using δ d and gravitational instability condition that the Grashoff number based on δ d~ 1, we obtain that the mean plume spacing $\lambda_b \sim (Z_w Z_{vi})^{1/2}$ where Z_w is a near-wall length scale in convection and Z_{vi} is another viscous length scale due to the wall-normal flow. We obtain an expression for the mean concentration profile by integrating the concentration profile over λ_b. The theoretical mean concentration profile which shows no dependence on V_w matches well with that calculated from laser-induced fluorescence images of the phenomenon in a vertical plane.

Simulation of single-phase mixing in fuel rod bundles using an immersed boundary method

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For the last decades studying the turbulent flow structures and the mixing behavior in fuel rod bundles has been an active research topic. In this paper the (isothermal) turbulent mixing in rod bundles is simulated for two different cases using a finite volume / immersed boundary method with a staggered velocity discretization. Solution procedure is based on an efficient multi-grid algorithm, and simulations are performed on state-of-the-art massively parallel computer architectures. As a first case the cross flow through a staggered tube bundle under fully turbulent conditions is computed using large eddy simulation. The computed velocities were compared with experimental data from the literature and a rather good agreement between experimental and computational results was achieved. As a second case, we considered an experiment performed in the SUBFLOW test facility. The SUBFLOW facility models a 4x4 vertical rod bundle and uses water at atmospheric conditions as the working fluid. Experiments are based on the wire-mesh sensor technique, which measures the conductivity of the working fluid, and report the distribution of the tracer inserted at various heights of the bundle. This case is even more challenging for large eddy simulations, since it does not feature large structures present in the flow crossing the bundles. However, large eddy simulations of the SUBFLOW facility reproduced the concentration of the tracer liquid, and its fluctuations well. The good agreement obtained for two cases of flows in rod bundles serve as an encouragement to focus future research towards modeling of bubbly flows in the same arrangements.

Two-dimensional shearless turbulent mixing: kinetic energy self diffusion, also in the presence of a stable stratification

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Two-dimensional turbulence is important in many natural and engineering contexts. It presents some special and interesting phenomena that does not occur in three dimensional turbulence. Moreover, it also idealizes geophysical phenomena in

the atmosphere, oceans and magnetosphere and provides a starting point for the modeling of these phenomena. In this contest, we would like to present new results concerning the turbulent energy transport in the simplest kind of two dimensional inhomogeneous flow, turbulent shearless mixing process generated by the interaction of two isotropic turbulent fields with different kinetic energy but the same spectrum shape. The self diffusion of kinetic energy is observed in two cases: with and without stable density stratification. In the unstratified case the simulations of mixing with different values of the energy ratio show that, asymptotically in time (in the limit of the observed range), the turbulent diffusion is much larger than the one measured in three dimensions. The analysis of velocity third and fourth moments indicates that the flow is highly intermittent. Moreover, the temporal autocorrelation of the vorticity, at some fixed points, does not depend on the ratio of energy used and on the position. We can interpret this results in term of the existence of a long-range interaction. In the stratified case the evolution of the flow changes significantly. The energy profile in the mixing region is lower than the minimum value imposed by the initial condition, which shows the effect of the buoyancy force work. Finally, the velocity skewness enlightens the generation of an inverse energy flow and intermittent penetration from the low to the high energy field even in the case of mild stratification.

Dimensionality influence on the passive scalar transport observed through numerical experiments on turbulence shearless mixings.

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We present new results concerning the passive scalar turbulent transport in two and three dimensions in a shear-less mixing layer. We consider the system where one energetic turbulent isotropic field is left to convectively diffuse into a low energy one. In this system the region where the two turbulent flows interact is associated to a high intermittent thin layer that propagates into the low energy region. We have seen that the diffusion process in 2D is faster then in 3D. In 2D the time growth of the interaction width is super-diffusive, while in 3D is slightly sub-diffusive, as in the wind tunnel experiments by Veeravalli and Warhaft (JFM 1990). In both cases the passive scalar temporal spreading follows the spreading of corresponding kinetic energy field. The presence of the turbulent energy gradient is felt on the distribution of statistical quantities, as the skewness, kurtosis and spectra, across the layer. In two dimension, the passive scalar spectrum computed inside the mixing region presents an exponent in the inertial range which is half of the usually met exponent of the velocity fluctuation spectrum, typically close to -3. In three dimension, we instead observed a

mild difference between these two spectral exponents. The present results are obtained from direct numerical simulations of the diffusion of the passive scalar across an interface which separates the two isotropic turbulent fields. The size of the computational domain is $4\pi \times 2\pi$ (1200×600^2 grid points, Re_λ=150) in the 3D simulations and $(2\pi)^2$ (1024^2 grid points, Re_λ equivalent of the order of 10^2 in the 2D simulations.

The local dynamics of turbulence along streamlines

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We will extend the idea in [1], where Wang introduced the concept of streamlines and streamline segments in turbulent flows and, based on the projection of the Navier-Stokes equation in the direction locally tangential to streamlines, derived an evolution equation for the absolute value of the velocity u along streamlines. However, in order to interpret the equation in the curvilinear streamline coordinate, a new coordinate system has to be introduced, which, in particular, gives rises to an additional term reflecting the dynamics of streamlines. It is shown that one can associate a field S with this new coordinate, which plays a similar role as the G-field in turbulent premixed combustion. A hyperbolic partial differential equation for S is derived and solved for various turbulent DNS fields. The equation governing u along streamlines is then interpreted as an extended Burgers equation and the new term, being proportional to the temporal derivative of S, plays the role of a non-local convective velocity, cf. [2].

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Anomalous scaling, conformal symmetry and time scales in forced rotating turbulence

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In this short article we present a statistical analysis of the two point velocity structure functions obtained from a large eddy simulation model of rotating turbulence with helical forcing at small scale. It has been known that such turbulent flows are characterized by a reduction in dimension of the flow field. We mainly focus on the inverse cascade regime ($k < k_f$) and comment on the self similar nature of the flow with anomalous scaling exponent. We then provide a stochastic Schramm-Lowner Evolution (SLE) based analysis in an attempt to unify the physics of quasi - two dimensional flow within the framework of conformal symmetry [1]. Finally, we re-present a well known multiple scale based analysis to comment on the different time scales that are involved in the nonlinear exhange of energy between the different Fourier modes that eventually lead to the reduction in flow dimension [2].

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Decay of turbulence in rotating flows

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We present a parametric space study of the decay of turbulence in rotating flows combining direct numerical simulations, large eddy simulations, and phenomenological theory. Several cases are considered: (1) the effect of varying the characteristic scale of the initial conditions when compared with the size of the box, to mimic “bounded” and “unbounded” flows; (2) the effect of helicity (correlation between the velocity and vorticity); (3) the effect of Rossby and Reynolds numbers; and (4) the effect of anisotropy in the initial conditions. Initial conditions include the Taylor-Green vortex, the Arnol’d-Beltrami-Childress flow, and random flows with large-scale energy spectrum proportional to $1/k^4$.The decay laws obtained in the simulations for the energy, helicity, and enstrophy in each case can be explained with phenomenological arguments that consider separate decays for two-dimensional and three-dimensional modes, and that take into account the role of helicity and rotation in slowing down the energy decay. The time evolution of the energy spectrum and development of anisotropies in the simulations are also discussed. Finally, the effect of rotation and helicity in the skewness and kurtosis of the flow is considered.

Turbulent waves: myth or reality?

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Euler hydrodynamic equations for an incompressible fluid when treated for a randomly pulsating flow lead to the 2nd order Reynolds system for the averaged velocity and turbulent stresses. While neglecting the diffusion processes and approximating the pressure strains with the relaxation to the equilibrium one can obtain some 1st order quasi-linear system of partial derivatives. When linearized within a turbulent kernel the system obtained gives rise to a linear one that can be rewrite in the form of Maxwell electromagnetic equations where vectors of stresses flux and vorticity play roles electric and magnetic components and respectively. In the general case one can be obtained a characteristic equation with which one can calculate the slopes of upper and lower characteristics in the initial part of turbulent jet.

Logarithmic law and universal Karman constant in wall-bounded turbulent flows

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The scaling law of the mean velocity profiles (MVPs), as well as of the variation of the friction factors with Reynolds number (Re), has been a central topic in wall-bounded turbulence for a century long. Despite the overwhelming success of the von Karman-Prandtl log-law in engineering applications, there is still some doubt as to the validity of its theoretical arguments. For example, Barenblatt and coworkers have strongly argued for a power-law instead. On the other hand, the universality of the Karman constant κ is also under a vigorous attack, as different κ values were reported for different flows, raising even a new terminology Karman 'coefficient' to replace. Here we present an alternative argument for the existence of log-law in central symmetry flows like channel and pipe. Applying a Lie-group analysis on Prandtl's mixing length function, a (1 - r^n) bulk flow structure is discovered. This yields an explicit log-law when matching to the wall, and redefines the Karman constant as a Lie-group invariant of the bulk layer. An analytical expression of the wake function can also be derived, which, together with a constant κ value (0.45), describes the MVPs and the friction factor curves - in a good agreement with DNS and experimental data at a large range of Re for both channel and pipe flows. In

addition, we offer a possible explanation for the reported κ variations: empirically fitted κ at different sampling regions of MVPs. Thus the long-standing controversy on the scaling of mean-flow properties seems to be laid to rest in favor of the log-law with a universal κ, as enforced by symmetry in the center of the flow. This brings into further corrections for a set of widely-used empirical scaling functions - e.g. the relationship between bulk velocity Reynolds number (Re) and friction velocity Reynolds number (Re_τ) - from power-law into log-law form.

Lagrangian and Eulerian velocity structure functions in hydrodynamic turbulence

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Understanding of statistical properties of fully developed turbulence has been a challenging problem for many years. Even a bridge relation between Lagrangian and Eulerian structure function exponents has been unknown. Also, there has been no theory based on the solution of the Navier-Stokes equation (NSE) up to now. Recent progress in numerical calculations and experiments encourages to develop a statistical theory in terms of both from Lagrangian and Eulerian approaches. On the previous TMB Conference, we presented a statistical theory of turbulence based on the Navier-Stokes equation. We considered the inertial range of scales in incompressible liquid. The idea of the model was that the main role in statistics belonged to the regions where vorticity was very high. We showed that these regions must take the form of vortex filaments, and derived the equation describing the vorticity evolution. It appeared that not decay of eddies but their stretching was the main process responsible for the formation of structure functions. We applied the theory to find the Lagrangian velocity structure functions of different orders. They were shown to obey scaling relations. The scaling exponents were calculated analytically. The results agreed very well with experimental data. Now we develop and generalize the theory, analyzing a boundary of a vortex filament and introducing a notion of a filament's age. This allows to calculate the transverse Eulerian structure functions and to derive a bridge relation between Lagrangian and Eulerian scaling exponents. We also check the stability of the results, in particular we show that they do not depend on the assumed large-scale statistics. We stress that the approach allows to derive both kinds of scaling exponents just from the NSE, using only one fitting parameter. The obtained values practically coincide with experimental and numerical results.

K.P. Zybin, V.A. Sirota, Phys. Rev. Lett., 104, 154501 (2010); K.P. Zybin, V.A. Sirota, A.S. Ilyin, Phys.Rev.E, 82, 056324 (2010)

WALL-BOUNDED FLOWS

On the length of near-wall plumes in turbulent convection

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We present plan forms of line plumes formed on horizontal surfaces in turbulent convection, along with the length of line plumes measured from the plan forms, in a five decade range of Rayleigh numbers (105 < Ra < 1010) and at three Prandtl numbers(Pr =0.7, 6, 602). Using geometric constraints on the relations for the mean plume spacings proposed by Theerthan & Arakeri (1998) and Puthenveettil & Arakeri (2005), we obtain expressions for the total length of near-wall plumes on horizontal surfaces in turbulent convection. The plume length per unit area (Lp/A), made dimensionless by the near-wall length scale in turbulent convection (Zw) remains a constant for a given fluid. Increase in Pr has a weak influence in decreasing Lp/A. The Nusselt number is shown to be directly proportional to LpH/A for a given fluid layer of height H. These expressions match the measurements, thereby showing that the assumption of laminar natural convection boundary layers in turbulent convection is consistent with the observed total length of line plumes. We then show that similar relationships are obtained based on the assumption that the line plumes are the outcome of the instability of laminar natural convection boundary layers on the horizontal surfaces.

Particulate dispersion and reflection layers in a serpentine duct

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Direct numerical simulation of particle transport in curved ducts has been conducted for its relevance to deposition and erosion. In both cases, mean centrifugal acceleration plays a critical role. We have selected an S-shaped duct, as a simple geometry with fully developed flow and no inlet conditions. Fully developed particle concentrations are established only after many through flow times, especially for light particles (low Stokes number). That may limit the direct connection to some practical applications; but a curved channel, centrifugal acceleration and reflection from walls

accelerate the approach to statistical equilibrium of high Stokes number particles and fully developed flow becomes quite relevant to non-equilibrium applications. A planar channel illustrates the intriguing phenomenon of turbophoresis. This is a particle drift, caused by gradients of the mean-square of the fluctuating particle velocity. Turbophoresis plays a very small role in the present, serpentine geometry. Rather, particles are centrifugally accelerated in the bend, causing near-wall concentration layers. A plume of low velocity particles separates from the inner wall of the bend and is dispersed into the flow. For heavier particles, the plume splits in two, or rather into the low speed plume and a ballistic plume of higher speed particles. The higher Stokes number particles reflect from the outer wall of the bend, creating a thick, high concentration layer. This reflection layer thickens with increasing Stokes number. A very simple example of particles in straining flow illustrates the essential elements of the reflection layer.

Merging of sheet plumes in turbulent convection

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We present results on near-wall dynamics in turbulent free convection over a horizontally heated surface for Prandtl numbers (Pr) 0.7 and 6 at moderately high Rayleigh numbers (Ra = 10^5 to 10^9). The predominant dynamics are the merging of sheet plumes mediated by the external shear due to the large scale flow. At lower Ra = 10^5, cell like plume structures are formed which are then transformed to aligned line structures at higher Ra > 10^7 due to the shear of large scale flow. We measure the merging velocities of two nearly parallel sheet plumes at different times of their merging cycle and at different Rayleigh numbers. The merging rates are shown to increase with increase in Ra for both the Pr numbers (0.7 and 6). The plumes merge much faster for Pr = 0.7 (air) compared to the merging rate for Pr = 6 (water). We propose that the plume merging velocity scales as the vertical plume rise velocity (V_c), which is given by the similarity solution of Gebhart (1969). The dimensionless merging velocity $d\lambda / dt \sim Zw / \nu$, a near wall Reynold's number Rew is hence constant for a given Pr number, where Zw is the near wall length scale in turbulent convection. Initial efforts to model the merging of the plumes will also be presented.

Evolution of mean dynamics in transitional boundary layer flow

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Laminar and turbulent wall-flows are characterized by mean force balances whose ordering of terms are clearly defined. The transitional regime is, however, characterized by a non-equilibrium process in which the magnitude ordering of terms evolves. In this talk, the dynamical mechanisms underlying the redistribution of mean momentum and vorticity are explored for transitional two-dimensional boundary layer flow at nominally zero pressure gradient. The transitional regime is taken to include both an instability stage, and a nonlinear development stage, that progresses until the terms in the mean momentum equation attain the magnitude ordering of the four layer structure revealed by Wei et al. (J. Fluid Mech., vol. 522, 2005, p. 303). The four layer structure is estimated to first be realized at a momentum thickness Reynolds number of about 780 or equivalently a Karman number of about 360. The first-principles based theory of Fife et al. (J. Disc. and Cont. Dyn. Sys. A, vol. 24, 2009, p. 781) is used to describe the mean dynamics in the laminar, transitional and four layer regimes. Self-consistently applied criteria reveal that the third layer of this structure forms first, followed by layers IV and then II and I. During the transitional regime, the Reynolds stress gradient (turbulent inertia) rearranges the mean viscous force and the mean advection profiles. This culminates with the segregation of forces characteristic of the four layer regime. Empirical and theoretical evidences suggest that the formation of the four layer structure also underlies the emergence of the mean dynamical properties characteristic of high Reynolds number flow. These pertain to why and where the mean velocity profile increasingly exhibits logarithmic behaviour, and how and why the Reynolds stress distribution develops such that the inner-normalized position of its peak value exhibits its observed Reynolds number dependence.

A theoretical study of the effect of polymer concentration on turbulent drag reduction

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A recent theory has been developed for understanding turbulent drag reduction by polymers in wall-bounded flows. In this theory, which is based on the momentum and energy balance, the effect of the polymers is shown to give rise to a position-dependent effective viscosity. Based on this theory, we have worked out the effect of polymer concentration in the phenomenon. In particular, we have calculated the profiles of the Reynolds stress and their dependence on the concentration of the polymers. We find the interesting result that the value of the maximum Reynolds stress depends linearly on the position of the maximum for a large range of concentration. We have also calculated the friction factor and the percentage of drag reduction and how they vary with concentration. We have further compared our theoretical results with experimental observations and found good qualitative agreement.

The Stokes boundary layer on a cylinder oscillating around its axis in an unbounded fluid

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The flow generated by a cylinder rotating around its axis has attracted the attention of many researchers since the work of Taylor who analyzed the stability of the flow generated between two concentric cylinders rotating at constant velocity. The interest in the case of an oscillating cylinder, arose after the experiments of Donnelly who showed that a modulation of the inner cylinder appeared to stabilize the flow. In the present paper we study, by a numerical spectral method, the flow induced by an isolated cylinder which oscillates harmonically around its axis. Such flow is of interest because it is the prototype of the oscillating flows along a curved wall which arise in both industrial and biological applications. This flow is characterized by two dimensionless parameters, the ratio R between the cylinder radius and the thickness of the Stokes layer and the Taylor number T. First, we analyzed the axisymmetric flow case, where the variables do not depend on the azimuthal coordinate, and determined the values of the dimensionless parameters for which the flow lose stability. The results show that the flow is unstable, in the form of toroidal vortices, for values of T smaller than that predicted by the linear stability theory. Hence the structure of the vorticity was analyzed and the physical mechanism by which the vortices are sustained was described. An increase of the parameter R causes a decrease of the value of T for the onset of instability. For large values of the Taylor number the axisymmetric flow becomes unstable and it is replaced by a flow in which an azimuthal variability is observed. Moreover, when T increases an interaction between the vortices can also be observed which leads to the generation of vortices with a larger wavelength.

In search of the dominant free surface fluctuation frequency downstream of the oscillating hydraulic jump with the Bayesian spectral density approach

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Oscillating hydraulic jump is a particular open-channel flow phenomenon characterized by its abrupt increase in water depth due to the rapid transition from the supercritical to subcritical flow with the inflow Froude number existing between 2.5 and 4.5. The most distinct features of the oscillating jump are its formed turbulent surface roller and the wavy downstream free surface. Previous studies found that this wavy surface should have periodic fluctuation with its signature left in the measured energy spectrum of the surface fluctuation, which has the main trend of an approximately bell-shaped curve but is shadowed with obvious fluctuating spikes (Mok, 2004; Mossa, 1999; Murzyn and Chanson, 2009). Based on the concept proposed by Mok (2004) that the dominant frequency was caused by the periodic generation and advection of the turbulent eddies released from the surface roller and their interactions with the free surface downstream, the present study sets out to model this process with a single-degree-of-freedom (SDOF) system and identify the dominant frequency with the Bayesian spectral density approach (Katafygiotis et al., 2001; Yuen, 2010). This study is the first of its kind since the optimal estimates of the dominant frequencies and their corresponding uncertainties could be estimated without imposing any engineering judgment from the noisy spectra. In this study, a numerical example was employed to demonstrate the proposed methodology. In addition, the validated Bayesian approach was further applied to estimate the dominant frequencies based on the measured energy spectra of the free-surface fluctuation at the jump end for six cases of oscillating jumps with inflow Froude numbers ranging from 2.63 to 3.62. It was found that the main trend of the measured spectrum in each case could be well captured by the modeled one with the identified parameters; hence confirming the validity of the proposed methodology in application.

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Mirror-symmetric travelling-waves in wall-bounded shear flows

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Sliding Couette flow (SCF) is a flow between two infinitely long concentric cylinders subject to an axial sliding motion of the inner cylinder relative to the outer one. In the narrow limit of the gap, SCF becomes identical to plane Couette flow (PCF). Also, the vanishing limit of the inner cylinder corresponds to pipe flow (PF) with an appropriate inclusion of an axial pressure gradient. Therefore, SCF serves as a bridge to connect PCF and PF, which are known as flows without linear criticality and gather much attention recently regarding their instability mechanisms leading to turbulence. In the first half of the current paper we investigate instability of SCF and show that mirror-symmetric property of a travelling-wave plays an important role to trigger finite amplitude disturbances in both PCF and PF. The second half of the paper deals with a new class of travelling-wave solutions found in plane Poiseuille flow, which are obtained by continuing the stationary and travelling hairpin-shaped fluid vortices in plane Couette flow (Deguchi & Nagata, 2010). The solutions arise from a saddle-node bifurcation at a Reynolds number that is smaller than the critical value known to date (Waleffe, 2003). The solutions are characterized by two quasi-stream-wise low-speed streaks in one span-wise period in the vicinity of each boundary, where the low-speed streaks are aligned with the planes of mirror symmetry and a pair of quasi-stream-wise vortices forms a Λ-shaped vortex. This flow structure shows a strong resemblance to the Λ-vortex pattern of Herbert-type (Herbert, 1988) observed in near wall turbulence. Here again, the mirror-symmetric property of travelling-waves is found to play an important role to invoke turbulence. Having these facts described above, we try to establish a universal picture of instability mechanisms due to the mirror-symmetric property of travelling-waves in wall-bounded shear flows.

Effects of wall proximity on vortex shedding from a square cylinder

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This paper presents the numerical simulation of turbulent vortex shedding flow around a square cylinder in various distances of a wall and investigates the effects of wall proximity on the flow. The Reynolds Number of flow based on cylinder diameter and free stream velocity is 22000. The linear and nonlinear k-e models have been used for modeling of turbulence. For modeling of the near wall flows the one equation model has been utilized. The present numerical results have been obtained using a finite-volume code which solves the governing equations in a vertical plane located at the lateral mid-point of the channel. The pressure field is obtained with the SIMPLE algorithm. A bounded version of the third order QUICK scheme is used for the convective terms. First-order accurate fully implicit method is used for time discretization in connection with a relatively small time-step. Results of present numerical simulation including velocity vectors, streamlines, velocity profiles, Strouhal Number, Drag coefficient and turbulent stresses show that the present numerical study is able to predict the vortex shedding behavior for different cylinder to wall distances. Based on the gap distance between cylinder and wall, various vortex shedding behaviors have been observed. When the cylinder is placed in far distances from the wall (G/D=4.0) vortices regularly and symmetrically shed from both upper and lower sides of cylinder. When the cylinder approaches to the wall (G/D=0.75), vortex structure changes Strouhal number generally decreases. The vortices shed from the lower side of cylinder are elongated and weakened while the upper side vortices are formed in higher points relative to the cylinder. Further displacement of the cylinder towards the wall (G/D=0.6, 0.5, 0.4) causes that the unsteadiness of the flow does not be completely observed and regular vortex shedding is not occurred. By approaching the cylinder closer to the wall from a critical distance (like G/D=0.25) the flow is found to be steady and vortex shedding is completely suppressed. Therefore, four different states of vortex flow behavior can be detected based on the various distances of square cylinder to wall. The ranges of distance for these four states of flow are investigated in this study. Comparison of numerical results obtained by two utilized models with experimental data shows that the nonlinear k-e model can reproduce accurate results.

LES of full-depth Langmuir circulation and its impact on bottom boundary layer dynamics and scalar transport

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We report on bottom log-layer dynamics and near-surface scalar transport in large-eddy simulations (LES) of full-depth Langmuir circulation (LC) in a wind-driven shear current in neutrally-stratified shallow water. LC consists of parallel counter rotating vortices that are aligned roughly in the direction of the wind and are generated by the interaction of the wind-driven shear with the Stokes drift velocity induced by surface gravity waves. In neutrally-stratified shallow water, LC engulfs the entire water column (Gargett et al., 2004) and interacts with the bottom boundary layer resulting in a disruption of the log-layer. This disruption is analyzed in terms of mean velocity, budgets of turbulent kinetic energy (TKE) and budgets of TKE components. For example, in terms of mean velocity, the mixing due to LC induces a large wake region extending down to the range $50 < z+ < 200$ and thereby replacing the classical log-law mean velocity profile. The dependence of this disruption on wind and wave forcing conditions is investigated. These results have important implications on turbulence parameterizations for RANS (Reynolds-averaged Navier-Stokes) simulations of turbulent flows on shallow coastal shelves. Approximately 30-40% of anthropogenic CO2 is taken up by the oceans, thus scalar exchange rates between the atmosphere and the oceans have a significant impact on environmental systems. Statistical analysis of the concentration scalar transport equation in the LES will be presented in order to elucidate the impact of turbulent eddies (such as LC) on surface scalar transfer. We will focus on the accuracy of several parameterizations based on surface renewal theory in predicting surface transfer velocity (mass transfer efficiency) and its increase caused by LC.

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A comparative study on drag reduction strategies in pipe flow

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Reduction of drag in turbulent pipe flow is often desirable for practical applications. There are various control strategies for wall bounded flows, which are known to decrease drag, such as spanwise wall oscillations, polymer addition, opposition control, and phase randomization. Except for phase randomization, the mentioned methods had been applied successfully to pipe flow. In this study we employ a solenoidal spectral method to simulate the effects of different approaches to drag reduction at a moderate Reynolds number, including phase randomization. We perform a comparative analysis on the effectiveness of the methods, and on net power savings where applicable. In addition, the similarity between the effects phase randomization and polymer addition is investigated, as a link between these two strategies was suggested earlier.

Four flow regimes for self-similar turbulent boundary layer in pressure gradient

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Self-similar flows in a turbulent boundary layer when the free-stream velocity is specified as a power function of the longitudinal coordinate are investigated. The self-similar formulation not only simplifies solving of the problem by reducing the equations of motion to ordinary differential equations but also provides a mean for formulating closure conditions. It is shown that for the class of flows under consideration that depend on three governing parameters the dimensionless mixing length is a function of the normalized distance from the wall and the exponent in the law specifying the free-stream velocity distribution in the outer region and a universal function of the local Reynolds number in the wall region, the latter corollary being true even when the skin friction vanishes. In calculations this function is set to be independent of pressure gradient, which gives the results very close to experimental data. There exist four different self-similar flow regimes. Each regime is related to its similarity parameter, one of which is the well-known Clauser equilibrium parameter and the other three are established for the first time. In case of adverse pressure gradient when the exponent lies within certain limits, which depend on Reynolds number, the problem has two solutions with different values of the boundary layer thickness and skin friction, which points out the possibility of hysteresis in near-separating flow. Separation occurs not at the minimal value of the exponent that corresponds to the strongest adverse pressure gradient but at a higher one whose dependence on Reynolds number is calculated in the paper. The results of the theory are in good agreement with experimental data.

The interaction of eigen and artificially imposed perturbations in a transitional boundary layer over oscillating surface

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In the present work we consider the laminar-turbulent transition mechanisms in a boundary layer (BL) which type may vary from plane (Tollmien-Schlichting instability waves) to 3D transition (longitudinal vortical structures) depending on a combination of the determining parameters. One of the active methods of transition control is based on a perturbation field generation by specific surface oscillations similar to those naturally developing in BL. The question which remains still unanswered is whether it's possible to change the BL structure in such a way that the resulting interaction of eigen and forced oscillations can lead to drag reduction. We have developed and continue improving the technique of direct numerical solution of the nonstationary Navier-Stokes equations over oscillating surface at high Reynolds numbers that allows observing in space and time the patterns of velocity and pressure perturbation fields as well as their correlation moments in the near-wall region. The main emphasis is placed on the investigation of BL structure depending on amplitude, wave length and phase speed of the imposed wave traveling in the direction of the mean flow. The parameters of oscillating surface are obtained as function of Reynolds number at which the strongest undamped downstream eigen perturbations of the BL are observed. The main conclusion made is that we can control the mechanisms of generation and development of BL eigen perturbations by imposing specific active surface oscillations.

NON-EQUILIBRIUM PROCESSES

Mixing in a nanoscale film driven by convection

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We present results on the dynamics of a thermally driven thin film. The film consists of a very thin aqueous layer confined by sophisticated surfactants and is oriented vertically. We analyse the mixing behaviour of the film while thinning. The mixing changes the thinning behaviour which is typically linear in time to an exponential one. Mixing efficiency is computed from thickness of the film, and pattern analysis to find the folding of thin filaments. We give a description of the experiment, and a phenomenological theory.

Antihydrogen formation by autoresonance-intiated mixing of antimatter plasmas

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In efforts to trap antihydrogen, a key problem is the vast disparity between the neutral trap energy scale $(\sim 50\mu V)$, and the energy scales associated with plasma confinement and space charge $(\sim 1eV)$. In order to initiate mixing between the charged particle species for direct recombination, the larger energy scale must be overcome quickly and accurately to minimize the initial antihydrogen kinetic energy. This issue motivated the development of a novel injection technique utilizing the inherent nonlinear nature of particle oscillations in our traps. We demonstrated controllable excitation of the center-of-mass longitudinal motion of a thermal antiproton plasma using a swept-frequency autoresonant drive [1]. When the plasma is cold, dense, and highly collective in nature, we observe that the entire system behaves as a single-particle nonlinear oscillator, as predicted by a recent theory. In contrast, only a fraction of the antiprotons in a warm or tenuous plasma can be similarly excited. Antihydrogen was produced and trapped by using this technique to drive antiprotons into a positron plasma, thereby initiating atomic recombination [2]. The nature of this injection, in part, overcomes some of the difficulties associated with matching the energies of the charged species used to produce antihydrogen, but we observe that the mixing process heats the plasmas. We present ongoing

characterization and simulation of the process, in our efforts to understand and improve conditions for the production of trapped antihydrogen.

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Kelvin-wave turbulence in superfluids

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We study the statistical and dynamical behavior of turbulent Kelvin waves propagating on quantized vortices in superfluids, and address the controversy concerning the energy spectrum that is associated with these excitations. Finding the correct energy spectrum is important because Kelvin waves play a major role in the dissipation of energy in superfluid turbulence at near-zero temperatures. We show analytically that the energy spectrum enjoys existence, uniqueness and regularity of the pre-factor. Furthermore, we present numerical results of the dynamical equation that describes to leading order the non-local regime of the Kelvin wave dynamics. We compare our findings with the analytical results from the proposed local and non-local theories for Kelvin wave dynamics and show an agreement with the non-local predictions.

Numerical modeling of contaminant transport in integrated two layer hydrological model

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A numerical model, based on the method of moments and Crank Nicholson implicit scheme, is developed for studying the flow and solute transport in open channel and porous streambeds. The transport in each domain is described by a two-dimensional advection-diffusion equation with the exchange between the two domains modelled through boundary conditions that ensure the continuity of concentration and flux at the interface. An exponential decreasing velocity profile of the porous zone links the velocity profile of the open channel at the top. Flow and transport in the two zones are diffusion and advection driven. The expressions for the zeroth, first and second moments of concentration are derived using the Aris method

of moments. The results show that the mean solute velocity decreases with an increase in settling velocity and it is also sensitive towards the ratio of the porous bed depth over the depth of the open channel. It is also found that the effective dispersion coefficient increases with increase in settling velocity. The model is verified using the results for limiting cases whose analytical solutions are known. Since the model parameters can be measured independently, the numerical model developed in this study can be used as a practical tool to model water quality in rivers and sediment beds.

Multiscale modeling of spinodal-decomposition-driven mixing

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Spinodal decomposition of an initially homogeneous (single-phase) mixture of liquids follows a sudden move into the unstable region of the two-phase diagram; the free energy released, which acts as a driving force for the phase separation, leads to the spontaneous formation of single-phase domains which then proceed to grow and coalesce; for low viscosity fluids, this coalescence process is convection-driven and results in vigorous fluid stirring (typically at the micrometer scale, although the exact scale can be tuned by a number of parameters, such as material choice). Recent work has provided evidence that this phenomenon can be exploited for enhancing heat transfer at small scales. In this talk we will review both experimental and modeling investigations of these phenomenon as well as discuss new multiscale approaches that enable simulation of macroscopic devices (e.g. heat exchangers) that utilize spinodal decomposition for improved performance.

Rayleigh-Taylor unstable flames: the development and effect of turbulence

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A Type IA supernova explosion may occur if a subsonic nuclear flame in a white dwarf star is wrinkled by turbulence produced by the Rayleigh-Taylor instability and becomes supersonic. Our research investigates the plausibility of this theory by simulating a very simple case- a model flame in 2D. We performed a

parameter study in which we changed only the non-dimensional gravitational force, G. The overarching goal was to figure out how changing the strength of the Rayleigh-Taylor instability affects the flame surface and therefore the flame speed. At low values of G, this is a transition-to-turbulence type problem and we approached it from the dynamical systems point of view. Specifically, we measured various observables in our simulations and used them to search for simple bifurcation models of the flame behavior. For instance, the initial vortex shedding instability in the wake behind the flame front can be described by a Hopf bifurcation. Overall, simple temporal bifurcations are sufficient to describe the flame for low G. For high values of G, the simple dynamical systems approach breaks down. The area just behind the flame becomes fully turbulent and this turbulence wrinkles the flame front. Because the wrinkling takes place on all scales between integral scale and the viscous scale, the flame assumes a fractal shape. We measured the fractal dimension of the flame front to assess the importance of this effect. For very high G, it turns out that large-scale Rayleigh-Taylor stretching is responsible for creating a larger part of flame surface than the turbulent wrinkling. This suggests that the flame speed is mostly determined by the Rayleigh-Taylor instability, not by the secondary interaction of turbulence with the flame front. The flame speed predicted for this situation is much too small for the flame to become supersonic casting some doubt on the Rayleigh-Taylor mechanism for Type IA explosion.

Turbulent mixing and acoustics in stellar envelopes

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It is well-known that turbulent mixing on the Sun forms multi-scale convective structures: granulation, meso- and supergranulation. By using 3D radiative hydrodynamics simulations we investigate physical properties of mixing and energy transport in the outer layers of more massive main-sequence stars. The results reveal new interesting regimes of the turbulent convection that are qualitatively and quantitatively different from the solar type. In particular, when the stellar mass is about 1.7 times the mass of the Sun, the outer convection zone almost disappears according to the mixing-length theory, but the simulations show that the turbulent convection becomes supersonic and generates strong acoustic emission. The simulation results of the turbulent convection and oscillation spectra for several targets of the Kepler mission will be presented.

Nonperturbative derivation of closed form hydrodynamics from kinetic theory

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We present exact derivation of macroscopic description of arbitrary Knudsen number flow starting from Boltzmann–Bhatnagar–Gross–Krook kinetic theory with constant relaxation time. Without approximation, even in the deep kinetic regime of finite Knudsen number, we obtain closed-form equations for macroscopic flow fields that are differential in space and integral in time. These equations are further simplified for incompressible flow and scalars. Particular cases that can be exactly solved show transition from essentially kinetic to hydrodynamic behavior. Examples of such analytical solutions include Knudsen minimum in channel flow and ballistic-to-diffusive time evolution of no-flow scalar transport.

Numerical investigation of turbulent forced convection of a nanofluid between parallel plates under different thermal conditions

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Turbulent forced convection heat transfer and pressure drop between horizontal parallel plates with a nanofluid consisting of Al2O3 and water was studied numerically. The application of this model is to simulate the heat exchangers, where the enhancement in heating and cooling rate is always in demand and a nanofluid may be used as coolant side. The numerical simulation was performed by solving the conservation equations of two-dimensional, steady incompressible flow between parallel plates in the simultaneously developing hydraulic and thermal boundary layer region. The plates were subjected to a constant temperature/heat transfer at the wall. The set of coupled nonlinear differential governing equations was discretized with the control volume technique. For the convective and diffusive terms the second order upwind method was used while a co-located SIMPLE procedure was introduced for the velocity–pressure coupling. A structured non-uniform grid distribution has been used to discretize the computation domain. A modified k-e model with a two-layer technique for the near-wall region was used to predict turbulent viscosity. In order to verify the results, the method was applied to some cases for base fluid (very low volume fraction) and the computed results were compared with published experimental data and numerical research on the developing length of turbulent flow

and a good agreement between the results was observed. The effects of nanoparticle volume fraction and different thermal boundary conditions have been presented and discussed. The fully developed velocity and temperature profiles at different Reynolds numbers were also reported. The results showed that the nanoparticle volume fraction effect on the thermal parameters and flow turbulent intensity is significant. Also the convective heat transfer coefficient for nanofluid was greater than that of the base liquid. Furthermore, the heat transfer enhancement was increasing with the particle volume concentration and Reynolds number.

INTERFACIAL DYNAMICS

Effect of shear on RT mixing layers at low Atwood numbers

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Growth of interface imperfections between different layers of material that surround the fuel capsule during the implosion process in ICF can cause fuel dilution at the core of the capsule. After the pressure wave passes the material interfaces, the Rayleigh-Taylor instability plays an important role in the growth of these imperfections. Quantizing the R-T instability growth rates becomes important to estimate the growth rates of these interface imperfections and design control methods to retard this growth. To study R-T mixing, a gas channel facility was built at Texas A&M University operating with Air and Helium to create density gradient. The channel consists of two streams separated by a splitter plate. Air flows on top of the plate where as the lower density air Helium mixture flows on bottom and R-T mixing starts right after the splitter plate. Image analysis is used as a tool for measuring the growth rates by analyzing the images of injected fog, scattering light from back-lit test section. Simultaneous 3 wire and coldwire anemometry (S3WCA) is used for measuring velocity spectrum. Experiments are performed upto Atwood numbers ~0.1 with shear to study the effect of shear on turbulent mixing parameters. Simultaneous 3 wire cold wire Anemometry is performed at different vertical locations and four different axial locations. Temperature is used as a marker to measure density. This technique provides all the velocity and density fluctuations. Detailed discussion about image analysis results and other important parameters including θ (molecular mixing parameter), v'_{rms} and vertical turbulent mass flux $\overline{\rho' v'}$ measured from S3WCA technique and their effect on mixing growth is discussed. Shapes of PDF distributions of all the three velocity components, density fluctuations for these cases are also explained.

Instabilities of flat and curved interfaces in the Rayleigh-Taylor and Richtmyer-Meshkov models

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We have studied a non-trivial effect of the interfacial curvature on the stability of uniformly and suddenly accelerated interfaces. The new stability analysis is based on operator and boundary perturbation theories and allows us to treat the Rayleigh–Taylor and Richtmyer–Meshkov instabilities as a single phenomenon and thus to understand the interrelation between these two fundamental instabilities. This leads, in particular, to clarification of the validity of the original Richtmyer growth rate equation and its crucial dependence on the frame of reference. The main finding of this study is the revealed and quantified influence of the interfacial curvature on the growth rates and the wavenumber selection of both types of instabilities. Finally, the systematic approach taken here also provides a generalization of the widely accepted ad hoc idea, due to Layzer, of approximating the potential velocity field near the interface. Also motion of a planar interface in incompressible Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities with surface tension is investigated analytically and numerically. The comparison between the growth rate of an interface with and without surface tension is made, and we show that the growth rate of the interface with surface tension in the RM instability is equal to that without surface tension at the asymptotic stage, however, the growth rate with surface tension in the RT instability differs from that without surface tension for almost all Atwood numbers and surface tension parameters.

Cascade models of a high Weber number liquid jet breakup

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The fragmentation describes the evolution in time of particles system, when particles break up. This review is focused on the fragmentation under scaling symmetry. Along with physical examples, discussion starts with formulation of mathematical background and analysis of statistical universalities of such fragmentation. Our interest is in the question of how, despite many degrees of freedom in dynamic production of new scales, the universal distribution of scale may come about. The resulting statistical universalities arising in the constant frequency fragmentation are used in construction of stochastic process. A high Weber number atomization of a continuous liquid jet, due to interaction with the gas, is considered as application. Emphasis is placed on stochastic simulation of liquid core configuration and droplets production, with control parameters presumed from breakup mechanism. In the case of primary air-blast and of pressure-assisted atomization, the applicability of this approach, along with simulation of turbulent near-to-injector flow, is assessed.

Simulating immiscible interface dynamics in complex turbulent flows

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Flows involving immiscible liquid/gas or liquid/liquid interfaces play a crucial role in many diverse applications ranging from fuel injection systems to underwater petroleum spills. They are typically multi-scale, turbulent, and involve complex geometries. Furthermore, the immiscible interface typically is a discontinuity in material properties exhibiting a singular surface tension force. Numerical methods to solve flows with immiscible interfaces in a stable and accurate manner thus have to be carefully designed to properly account for these special properties. In this presentation, several numerical methods designed for the simulation of immiscible interface dynamics in complex turbulent flows are discussed. These include the RLSG method to describe the motion of immiscible interfaces, the finite volume balanced force method to account for surface tension forces in a stable and accurate manner (Herrmann, 2008), the multi-scale Eulerian interface tracking/Lagrangian point particle coupling procedure to address the range of interfacial length scales present in many flows (Herrmann, 2010), and consistent level set based filter functions to derive novel subgrid models for interface dynamics. To achieve a simulation tool that is predictive, special focus must be placed on both code and solution verification. We will present a novel method of applying the Method of Manufactured Solutions to one-fluid approaches and show that even in the presence of a discontinuous immiscible interface, our finite volume methods are at least first-order accurate. Several examples for application of the presented methods will be discussed, including the dynamics of immiscible interfaces in cylinders driven by rotating endwalls, the dynamics of impulsively accelerated immiscible interfaces, the atomization of drops in turbulent flow fields, and the primary atomization of turbulent liquid jets injected into high-speed gaseous crossflows.

Theory and simulation of moderately and strongly nonlinear dynamics of the Richtmyer-Meshkov instability

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There are many features of early- and late-time nonlinear RM instability growth that are not captured by simplified or ad hoc phenomenological models, such as Layzer's or drag-buoyancy. These include but are not limited to: late-time evolution of the bubble curvature; early-time acceleration of the spike; effect of finite values of ripple amplitude and Atwood number on early-time bubble and spike growth. We compare the results of numerical simulations with the predictions of the nonlinear theory, demonstrating a good agreement. The influences of compressibility, the initial spectra and other effects on the nonlinear dynamics are discussed.

This work is supported by the US National Science Foundation and US Department of Energy

Interaction of planar shock waves with 2D/3D random isotropic flows

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When a planar shock wave travels into a non-uniform medium, its shape gets distorted generating vorticity, entropy and acoustic fluctuations behind it. The intensity of the turbulent flow generated downstream depends on the sort of non uniformities ahead the shock. We show analytical expressions for the vortical structures and entropic spots formed behind the shock ripple that moves into a single-mode non-uniform flow. Besides, we describe the interaction with random isotropic spectra of vorticity, entropy and acoustic perturbations separately [1]. The results are seen to agree very well with numerical simulations and experiments reported in the literature [2-6]. It is also worth to study the interaction of a second shock wave with the already turbulent flow caused by the first one. In fact, the interaction between successive shocks and a non-uniform density fluid is a phenomenon that appears naturally in Inertial Confinement Fusion (ICF) [7]. Reshocking, is also an important phenomenon in Astrophysics, where shock waves driven by supernova remnants propagate through non-uniform interstellar media [8]. We present an analytical model for the re-shock problem of 2D/3D isotropic random density fields. A comparison with numerical codes developed at CEA [9] is shown and it is found a very good agreement.

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Turbulence and mixing characteristics in the variable-density Rayleigh-Taylor mixing layer

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Rayleigh-Taylor instability (RTI), which is generated at the interface between a heavy and light fluid in the presence of a constant gravitational field in an unstable configuration, is of fundamental importance in a multitude of applications ranging from fluidized beds, oceans and atmosphere, to ICF and supernovae. Although this instability has been subjected to intense research over the last 50 years, a large number of open questions remain unanswered and even first order global quantities, such as the layer growth, are not completely understood and still give rise to intense debate. The talk represents an overview of recent results on Rayleigh-Taylor instability including self-similarity, turbulence and mixing asymmetries, and spectral behavior. In particular, results will be shown from a new set of Direct Numerical Simulations on up to 4096^2 x 4032 meshes. The simulations cover the range of Atwood numbers, A=0.04-0.9, to study small departures from the Boussinesq approximation as well as large density ratio effects. The database will be used to address: 1) the long-standing open question regarding the discrepancy between the numerically and experimentally calculated mixing layer growth-rates, 2) the mixing asymmetry influence on the shape of the mixing layer edges, and 3) inertial range dynamics in Rayleigh-Taylor turbulence.

Three-dimensional vortex sheet motion with axial symmetry in incompressible Richtmyer-Meshkov instability

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We consider a three-dimensional vortex sheet motion with axial symmetry in incompressible Richtmyer-Meshkov instability (RMI). When the density of fluid is homogeneous, a vortex sheet with axial symmetry without swirl does not have motion in the azimuthal direction. However, when the density stratification exists in the system, the vortex sheet can develop in the azimuthal direction, even if it does not have swirl. We present the governing equations for the development of the vortex sheet, and investigate this torsional motion in RMI theoretically and numerically.

A computational parametric study of the Richtmyer-Meshkov instability for an inclined interface

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A computational study of the Richtmyer-Meshkov instability will be presented for an inclined interface perturbation in support of experiments to be performed in the Texas A & M shock tube facility. Simulations were performed using a staggered mesh Arbitrary Lagrange Eulerian (ALE) hydrodynamics code developed at Lawrence Livermore National Laboratory. A parametric study was performed for two high Atwood number gas pairs, air-SF6 and helium-SF6, where interface inclination angle and incident shock wave Mach number were varied. Fifteen unique scenarios developed from combinations of these parameters were simulated. The non-linear acoustic effects, associated with the inclined interface will be highlighted, using sequenced visualizations of the density, vorticity and pressure fields. A new scaling method for the interface mixing width, developed specifically for the inclined interface, will also be presented. Select cases from the parametric study will be explored further with higher accuracy simulations. The development of the interface after reshock and the effect of the initial interface development time before reshock will be examined for these cases. The initial circulation deposition on the interface will also be studied for selected cases.

The lives and times of Rayleigh-Taylor bubbles and spikes

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We will describe numerical simulations of the detailed evolution of the single mode Rayleigh Taylor instability to late times and high aspect ratios. In contrast to established potential flow models* that predict a terminal velocity and a constant Froude number, we observe a complex sequence of events that can be summarized in terms of an e-folding time $\tau=\gamma_{RT}$: exponential linear growth $(\tau << 4)$, saturation to terminal velocity $(\tau \sim 8)$, reacceleration to a higher Froude number $(\tau > 8)$, and onset of chaotic mixing (τ>12). The observed reacceleration away from the Froude number predicted by potential flow theory is attributed to the appearance of secondary Kelvin Helmholtz structures, and described with a modified potential flow model. The secondary KH instability is in turn sensitive to several parameters, and can be suppressed by large density contrasts between the fluids, and viscosity, with the bubble/spike velocity in each case reverting to the potential flow value. On the other hand, the KH instability appears immune to surface tension to the point of stabilization of the underlying RT flow. Our simulations delineate the change in dynamics of the primary and secondary instabilities with changes in these flow parameters. When the flow is allowed to evolve to $\tau >> 12$, further instability is observed, resulting in chaotic mixing which is quantified. We expect the results to be relevant to turbulent mix models that are based on bubble growth and interaction.

* Editor's comment: In most likelihood, the authors are referred to so-called Layzer-type potential models. The models describe RT flow by analogy with an incompressible pipe flow, which is distinct from classical RTI. When applied to RT flow, the models disregard to the leading order the conseravation of mass, momentum and energy. Solution for spike, proposed by the models, does not satisfy the model equations.

A nonlinear model for the mixing layer growth of the multimode Rayleigh-Taylor instability

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Rayleigh-Taylor (RT) instability is a fundamental instability that takes place when the pressure gradient opposes the density gradient at a perturbed interface between two media. For fluids, the amplitude of the perturbation initially grows in an exponential fashion. However, the growth soon turns nonlinear because of the increasing intensity of the vorticity field generated by a baroclinic process. Finally, turbulence and turbulent mixing develop between the fronts of heavy and light fluid. The role of RT instability in supernovae explosions, salt dome formation, or during the implosion phase of Inertial Confinement Fusion (ICF) makes this instability a topic of interest for many scientific communities. Recently, research has shown that the latetime RT turbulent mixing is influenced by the initial conditions (ICs) that set off the instability. This finding surely unveils an opportunity for turbulence control, but subsequently implies that it is essential that turbulence models used for predicting turbulent RT mixing must be initialized in accordance with the instability's ICs. Our strategy consists in accurately tracking the RT mixing layer evolution and providing profiles of turbulence model variables whenever appropriate. We present our model for the growth of the RT instability mixing layer. Our model is valid for all stages of the RT instability and for a broad range of density contrasts. Based on our model's prediction, we can compute profiles of turbulence model variables that will be used as initial conditions for a turbulence model. Finally, we present the prediction of our model in the context of the Richtmyer-Meshkov instability which is understood as the impulsive limit of the RT instability.

Numerical simulation of Richtmyer-Meshkov instability with an adaptive central-upwind 6th-order WENO scheme

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Two-dimensional simulations of the single-mode Richtmyer-Meshkov instability using an adaptive central-upwind 6th-order weighted essentially non-oscillatory (WENO) scheme by Hu et al. 2010 are conducted and compared to experimental results of Jacobs and Krivets 2005. The employed adaptive central-upwind 6th-order WENO scheme introduces only very small numerical dissipation while preserving the good shock-capturing properties of other standard WENO schemes. Hence it is well-suited for simulations with both small scale features and strong gradients. The conducted simulations show a significant improvement over other simulations with respect to accuracy of the captured flow structures and numerical dissipation. Sadot et al. 1998 stated that the linear and early non-linear behavior of a harmonically perturbed interface of two fluids with densities ρ_1 and ρ_2

accelerated by a shock are determined by four main parameters, the initial perturbation wavenumber *k*, the post-shock Atwood number A_0, the post-shock amplitude a_0 and the velocity jump ΔU_0 after the incident shock passage. Most simulations of the Richtmyer-Meshkov instability deal with single component flows. They neither match accurately the post-shock Atwood number nor the post-shock amplitude nor the velocity jump, and consequently fail to reproduce accurately the evolution of the instability. By matching the post-shock parameters rather than the initial parameters of Jacobs' and Krivets' experiment we were able to achieve a much better late-time agreement between experiment and simulation. This finding corroborates the experimental finding of Jacobs and Krivets that Mach number (which influences all other post-shock parameters) as well as initial wavenumber significantly effect the Richtmyer-Meshkov instability time development. Furthermore, we investigated the influence due to different diffusion layer thickness of the initial perturbation.

Linear theory analysis of Richtmyer-Meshkov like flows

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The subject of shock interaction with flow inhomogeneities (either at material surfaces separating different fluids or distributed in the bulk of the fluids ahead of the incident shock) is of primary concern in different scenarios. This interaction deforms the shock front surface which then becomes a source for entropy and vorticity fluctuations downstream, thus providing an exciting playground for theoretical analysis [1-4]. These perturbations are deleterious in Inertial Confinement Fusion experiments, where shock waves are necessary to generate the desired high compressions inside the nuclear fuel. Nevertheless, the turbulence created behind the rippled shock fronts is beneficial in Combustion processes because of the enhanced mixing of the fuel. Therefore, underestanding the way in which vorticity and/or entropy disturbances are generated at corrugated shocks is of fundamental importance. We discuss here the linear analysis used to describe the evolution of the hydrodynamic perturbations that grow behind corrugated shock/rarefaction fronts. At first we present the basic building blocks to construct the linear theory taking full account of the fluid compressibility. Different boundary conditions downstream of the shock are considered: isolated shock into homogeneous or inhomogeneous fluids, a shock driven by a rigid piston or by a free surface, and the classical Richtmyer-Meshkov instability at a contact surface (distinguishing between the reflected shock and reflected rarefaction situations). A description of the initial transient phase is presented and the transition towards the asymptotic stage is also described. An estimation of the characteristic time which describes that transition is given. The values of the asymptotic velocities are obtained from first principles and analytical expressions of them are shown.

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HIGH ENERGY DENSITY PHYSICS

Mix modeling for the NIF ignition capsule design

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The goal of the National Ignition Facility is the demonstration of inertial confinement fusion (ICF) ignition in the laboratory using indirect laser drive. Since ICF implosions are inherently unstable and subject to several mixing instabilities, achieving this goal relies on first understanding and then mitigating the possible sources of mix in NIF implosions. Broadly, ICF capsule mix can be broken down into two categories based on the dominant mixing wavelength: low-mode mix, which predominates at the ablation front as well as around the igniting hot spot, and high-mode mix, which predominates around the interface between the cryogenic fuel layer and the ablator. Additionally, isolated capsule defects or unavoidable capsule asymmetries (such as a fill tube) can seed high-mode ablation front mix in the form of nonlinear jets that perforate the imploding shell. Moreover, none of these sources of mix operates independently, and the ensemble of mixing phenomenon must be assessed in concert to understand the likely performance of an ICF capsule. This talk will review current perspectives on instability and mix in the NIF ignition capsule design. The approach has primarily been simulation-based, using the best available physical data inputs (equations of state, opacities, etc.) coupled with state-of-the-art computer simulation first to predict mix and then modify the design to mitigate its impact. The competing constraints resulting from low-mode and high-mode mix will be emphasized. Finally, the last year has seen a wealth of experimental data on mix generated in the first round of NIF experiments. The evolving perspective on mix in NIF capsules in light of this data will briefly be reviewed.

Progress toward turbulent experiments at high energy density

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Several research teams are focused on fundamental research in hydrodynamics at high energy density that is also relevant to astrophysics. These systems frequently evolve toward turbulent states. This talk will review advances in experimental design,

technique, and results over the past few years. At Michigan we initiate the Rayleigh-Taylor instability by first producing a blast wave within a plastic layer. The blast wave shocks and then decelerates a structured interface between the plastic and a low-density foam. This produces growing structure at the interface. We have explored a many-mode system and the potential that this process produces dynamically significant magnetic fields. We have also observed the Kelvin-Helmholtz instability and are preparing for experiments to study supersonic Kelvin-Helmholtz. Our data show some evidence of the beginnings of a turbulent transition. An international team is studying the interactions of shock waves or jets with clumps or collections of clumps. This system has the potential to develop into a turbulent state. Their focus has been on the early phases of the interaction. Another international team has worked extensively with jets. Experimental design has likewise developed novel experiments that we are likely to see performed in coming years. These include work on diverging, blast-wave unstable system, schemes to produce and observe the longer-term evolution of multimode Rayleigh-Taylor instabilities, and approaches to turbulent systems that might exhibit dynamo effects.

Collaborators: Carolyn Kuranz, Mike Grosskopf, Donna Marion, Forrest Doss, Anthony Visco, Chan Huntington, Christine Krauland, Carlos DiStefano, Eliseo Gamboa, Rachel Young, and members of the Center for Laser Experimental Astrophysics Research and the Center for Radiative Shock Hydrodynamics, University of Michigan. Tomasz Plewa, Florida State University, Hye-Sook Park and Bruce Remington, Lawrence Livermore National Laboratory, and others to be acknowledged during the talk. * The work to be discussed is funded by the Predictive Sciences Academic Alliances Program in NNSA-ASC, the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, and by the National Laser User Facility Program in NNSA-DS. The corresponding grant numbers are DE-FC52-08NA28616, DE-FG52-09NA29548, and DE-FG52-09NA29034.

Radiation hydrodynamics experiments at the National Ignition Facility

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This presentation will describe ongoing laboratory astrophysics experiments at NIF relevant to the complex radiation hydrodynamics that occurs in red supergiant, and corecollapse supernovae. Experiments on NIF can deliver 300 eV radiative heating that can be utilized uniquely access the regime in which radiation affects the development of hydrodynamic instabilities within an evolving object. This is relevant to the dynamics that occur during the core-collapse explosions of red supergiant stars.

These stars have dense circumstellar plasma, producing a strongly radiative shock whose radiation interacts with the hydrodynamic structures produced by instabilities during the explosion. While the current astrophysical models do not include complex, multidimensional radiation hydrodynamics, such effects are very physical and expected to affect the evolution of early stages of astrophysical objects described above. This presentation will include a summary of the two test shots that we have performed on NIF, including a 3.5 mm diameter x 6.4 mm long, gas-filled hohlraum test shot, and a description of the integrated physics shots scheduled at the facility.

Supersonic jets and shocks in laboratory plasma experiments

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In this paper we will present experimental studies of supersonic, radiatively cooled plasma jets, performed at the pulsed power MAGPIE facility (1.5MA, 250ns) at Imperial College. The experiments are scalable to astrophysical flows in that critical dimensionless numbers such as the plasma collisionality, the plasma beta, Reynolds number and the magnetic Reynolds number are all in the astrophysically appropriate ranges. Interaction of the jets with ambient medium leads to formation of bow-shocks, evolution of which can be investigated in detail in the experiment. Quantitative information on the plasma parameters is provided by several spatially and temporally resolved diagnostics, including direct measurements of jet flow velocity using Doppler shift of Thomson scattering spectra. Studies of the properties of radiatively cooled shocks, performed using ablation plasma flow in wire array z-pinches, will be also presented.

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Laser foam targets for production of magnetized thermonuclear plasma

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The parameters of laser compressed plasma are similar of the star plasma one (concentration $n \sim 10^{25}\ 1/cm^3$, temperature~5-10 *keV*, large fluxes of the thermonuclear neutrons). But star matter is magnetized plasma. With help of Atlant-SP code simulations it has been shown that more then 100 MGs fields could be generated in compressed thermonuclear targets. We have proposed the laser target design for the production of high magnetic fields at NIF experiments.

Effect of the driving waveform on the dynamic stabilization of ablative Rayleigh-Taylor instability

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We study the effects of different modulations of the acceleration driving on the dynamic stabilization of Rayleigh-Taylor instability in an ablation front [1-3]. We have already considered a sequence of Dirac deltas [1,4] and here we compare our previous results with the ones resulting from using a more realistic acceleration driving consisting in different kinds of square waves, with symmetric and non-symmetric half-periods. The analysis allows for obtaining explicit analytical solutions for the growth rate and for the boundaries of the stability region in terms of the parameters of the modulation and of the steady ablation front. It is found that the requirements in the modulation amplitude and frequency to stabilize all the wave numbers above a certain value km change significantly not only as a function of the km itself, but it also with the form of the modulation. We find that, in spite of the fact that the simplest modulation based on a Dirac deltas sequence allowed for the front stabilization even in the absence of thermal conduction, it turns out impossible when more realistic driving modulations are considered. Such a result is of great relevance for the case of ablation fronts directly driven by ion beams, as is the case of recently discussed inertial fusion scenarios. [5]

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Rayleigh-Taylor instability in ablation fronts and its dynamic stabilization

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A general physical model for the linear stage of the Rayleigh-Taylor instability is described and then applied to the particular case of the instability in ablation fronts .The model allows for direct physical interpretations and for retrieving well known results for the instability growth in ablation fronts driven by thermal diffusion. In particular, it shows the essential role of thermal conduction in producing a cut-off wave number above which the front is stable. Instead, when the ablation is directly driven by an intense ion beam, it is shown that ablation by itself still provides a mechanism for the growth rate reduction but the cut-off wave number results to be absent. Further reduction of the cut-off wave number and of the maximum instability growth rate is of great interest for inertial confinement fusion as RTI is the main limitation for achieving ignition and high gain. Dynamic stabilization by the vertical vibration of the ablation front has been proposed to this end. Here, it is presented a study by considering a modulation in the front acceleration consisting in a sequence of Dirac deltas and/or square waves. This allows for obtaining explicit analytical expressions for the instability growth rate as well as for the boundaries of the stability region. As a general rule, it is found that it is possible to stabilize all wave numbers above a certain minimum value km, but the requirements in the modulation amplitude and frequency become more exigent with smaller km. The essential role of compressibility is phenomenologically addressed in order to find the constraint it imposes on the stability region.

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

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In inertial confinement fusion (ICF), a spherical shell is irradiated either directly by a large number of overlapping laser beams (direct drive) or by x rays produced in a high-Z hohlraum (indirect drive). During the laser-driven acceleration

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

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. IM release number is LLNL-ABS-481872.

Large- and small-scale structures in Richtmyer-Meshkov flows driven by strong shocks

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Richtmyer-Meshkov (RM) instability plays important role in inertial confinement and magneto-inertial fusion, as RM-driven mixing inherently occurs during the implosion process and significantly influences the formation of ‘hot’ spot. Fusion-relevant conditions are characterized by strong shocks and high Atwood numbers. Accurate numerical modeling of such flows imposes strong requirements on the resolution, accuracy and spatio-temporal dynamic range of the simulations. At the same time it demands shock capturing and interface tracking, and adequate accounting for dissipation processes. We perform a comparative study of the nonlinear evolution of RM instability using the Smooth Particle Hydrodynamics Code

(SPHC) and Center for RAdiative Shock Hydrodynamics (CRASH) code, and compare the numerical simulations with one another and with the analytical theory. Our results indicate that at large scales the nonlinear dynamics of the RM instability is a multi-scale process; at small scales the flow field is heterogeneous and is characterized by appearance of local microscopic structures and cumulative jets. The coupling between the scales has a complicated character. The numerical and theoretical results are in good qualitative and quantitative agreement with one another, identifying new scaling dependencies at the late-time flow evolution.

This work is supported by the US National Science Foundation and the US Department of Energy.

Spike morphology in supernova-relevant hydrodynamics experiments

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This presentation describes experiments performed on the Omega and Omega EP lasers exploring the 3D Rayleigh-Taylor instability at a blast-wave-driven interface. These experiments are well-scaled to the He-H interface during the explosion phase of SN1987A. Laser energy is used to create a planar blast wave in a plastic disk, which then crosses the interface between the disk and a lower-density foam, inducing the RT instability. The plastic disk has an intentional pattern machined at this interface. This seed perturbation is three-dimensional with a basic structure of two orthogonal sine waves with a wavelength of 71 μm and amplitude of 2.5 μm. Interface structure has been detected under these conditions using dual, orthogonal radiography, and some of the resulting data will be shown. Current experiments are further examining the features of the unstable interface using proton radiography.

This work is funded by the NNSA-DS and SC-OFES Joint Program in HEDLP, by the NLUF in NNSA-DS and by the PSAAP in NNSA-ASC. The corresponding grant numbers are DE-FG52-09NA29548, DE-FG52-09NA29034, and DE-FC52-08NA28616.

Intrinsic magnetic stochasticity in fusion plasmas

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Magnetically confined toroidal plasmas for fusion research operate at high central temperatures, kept apart from the surrounding material walls by the magnetic field. One of the most useful shapes has proved to have a D-shaped cross section, with one or two magnetic X-points on the magnetic boundary surface, forming the corners of the D. It has good confinement, connected to the formation of a steep radial gradient of the plasma pressure, in a narrow layer near the plasma edge. The strong gradient, however, can drive large periodic MHD instabilities in the edge. Recent numerical simulations allow the plasma boundary to move freely in a surrounding region with open magnetic field-line that intersect the walls. They show that edge instabilities driven by the pressure gradient self-consistently generate a stochastic magnetic field that has many properties of a near-Hamiltonian homoclinic tangle, where the X-point acts like the homoclinic point. Initially the instability grows slowly, then almost explosively bursts out of the plasma edge, expelling potentially large amounts of plasma and energy. A weaker disturbance also propagates well into the plasma interior. The tangle influences important features of the instability and its evolution that agree with experimental observations. On a longer time scale, the instability saturates and the plasma mostly returns to its initial state, with a low residual level of magnetic and plasma stochasticity. Such stochasticity, also generated by other types of regular edge instabilities, has important consequences for the stability and confinement of the plasma, that up to now have largely been neglected.

Formation mechanisms of jet-like spike in ablative Rayleigh-Taylor instability in the presence of preheating

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There are a large amount of high energy density (HED) jets in astrophysics, HED experiments, and inertial confinement fusion (ICF). The generation of jet-like spike in the ablative Rayleigh–Taylor instability (ARTI) is the greatest threat for the hot spot formation in central ignition ICF. Preheating is an effective way to control the linear growth of ARTI which increases the stabilizations of Atwood number, convection ablation, and density gradient. However, recent results from simulations and experiments indicate that the preheating can yield some disadvantages together, mainly in the nonlinear aspects. Preheating generates jet-like spikes which can lead to large-scale non-uniform mixing reducing symmetry of the target, and hence, undermines the implosion acceleration, ignition and combustion of ICF. Formation mechanisms of jet-like spike in ARTI with preheating are investigated carefully in the past 10 years. It is found that the preheating plays the fundamental role on the formation of jet-like spike. In the early stage, the preheating crucially strengthens the density gradient stabilization, and therefore, the fundamental mode dominates absolutely over other higher harmonics. In the middle stage, the preheating ablation effect effectively stabilizes the nonlinear growths of the ablative Kelvin-Helmholtz instability (AKHI) and ARTI, and meanwhile ARTI dominates overwhelmingly over the AKHI. In the late stage, the bubble acceleration due to the vortex centrifugal force at the bubble tip and the increased acceleration at bubble tip due to the effect of thin shell thickness further increases the spike length, and finally leads to the formation of the jet-like spike in the highly nonlinear ablative RTI. Results presented in this research are important to understand the astrophysical jet formation, HED laboratory jet-like spike phenomena, and hot spot formation in central ignition ICF.

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Review of the Ablative Rayleigh-Taylor Instability

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Spherical shells are accelerated to extreme velocities (up to 400km/s) when irradiated by powerful lasers. Such fast targets are routinely used in inertial confinement fusion (ICF) implosion experiments carried out at major US laser facilities. In ICF implosions, both the outer and inner surface of the shell are hydrodynamically unstable to the Rayleigh-Taylor instability during the shell acceleration and deceleration phase respectively. In both cases, mass ablation off the surfaces modifies the growth of the instability. The so-called ablative Rayleigh-Taylor instability is significantly different from the classical one. The linear growth rates are reduced by mass ablation while the nonlinear growth can be enhanced. In this talk we will review the linear and nonlinear theory of the ablative Rayleigh-Taylor instability in laser accelerated targets.

Editor’s comment: This is a post-deadline submission.

MATERIAL SCIENCE

Turbulent mixing in non-Newtonian fluids

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The turbulence caused by the Rayleigh-Taylor instability represents the complicated phenomena. It usually related with major hydrodynamic activity, tangling of the media contact boundary, merging, separation, intermixing originally smoothed initial structures. The important role in the theory of the Rayleigh-Taylor instability is played by the discontinuity of density on a contact interface between two homogeneous (in terms of density) fluids. Importance of the discontinuity is interpreted by the fact that the turbulence in a wide range of initial conditions is self-similar, and, consequentely, universal and relative simple. In approach of "deep water", neglecting viscous and surface effects, the thickness of the intermixed stratum grows under the law $h = \alpha Agt^2$, where α – the coefficient of turbulent intermixing, g – the gravity acceleration, t – time, A – Atwood number. Numerical modeling of intermixing of two fluids with different rheology which densities differ twice as a result of the Rayleigh-Taylor instability has been carried out. Coefficients of turbulent intermixing in a multimode statement of the problem for Bingham, dilatant and pseudo-plastic fluids have been obtained. In addition, Fourier spectrums of the kinetic energy for fluids with various rheologies have been obtained. Changing of their form on time subject to wave numbers k_x and k_y (along O_x and O_y axis) has been considered.

Estimation of spectral characteristics of particles ejected from free surfaces of metals and liquids under shock wave effect

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One of the mechanisms for shock-wave dispersion of materials is ejecta of particles from free surface after shock wave arrival to it. In many cases, the initial perturbations are roughness obtained by turning processing. Basing on general physical knowledge and the Richtmayer analytical solution, approximated equations were obtained for estimation of quantity of mass ejected from surface versus time for small initial perturbations. Numerical calculations confirmed correctness of the estimations. Authors of the work present approximated equations for estimation of spectral characteristics of particles ejected from substance surface under effect of shock wave in the liquid and solid states. The calculated spectra of particles are compared to results of tests performed in VNIIEF for determination of spectral structure of formed particles. Pressure and surface roughness were varied in these tests. At the qualitative level, the particle spectra calculated by the suggested model are in agreement with the experimental results.

Equations of state and phase transformations of structural materials at high dynamic pressures

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Models of thermodynamic properties of structural materials over a wide range of parameters are necessary for numerical simulations of processes at high energy densities. Accuracy of calculation results is determined mainly by adequacy of equation of state of a medium. In the present work, multiphase equations of state for metals and compounds are considered. A model of thermodynamic potential free energy with taking into account polymorphic phase transformations, melting and evaporation is presented. Thermodynamic calculations are carried out for metals, alkali halides, and polymer materials in a broad region of the phase diagram. Obtained results are compared with available data of experiments at high dynamic pressures in shock and release waves.

Multi-sized nanoparticle effect on convective heat transfer in turbulent flows

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Numerical computation is being carried out for the fluid heat transfer with nanoparticles involves usually single sized particle. However, the present extension involves convective heat transfer enhancement for nanofluids with multi sized nanoparticles. Comparison between the cases when single sized and multi sized nanoparticle dispersion is considered for various volume weighted particle diameter in the turbulent flow conditions. The objective is to investigate the effects of multi sized nanoparticle volume fraction on the flow and heat transfer characteristics in the conditions closer to the experiments. As nanopowder used for experiments contains multi sized particles distribution. The Al2O3 nanoparticles (50-150nm) were used with 0.5% volume concentration. The effect of Brownian force, thermophoresis force and van der Waals force has been taken into account. The results indicate that when multi sized particle dispersion is considered the enhancement in convective heat transfer is relatively suppressed in compare to single sized nanoparticle. A possible explanation for this interesting result is expected as the aggregation of nanoparticles and heat transport between particles and fluid. This finding confirms that effect and behavior of multi sized particle dispersion on heat transfer mechanism of nanofluid in turbulent flow is different from heat transfer in still flow conditions. The results obtained for multi sized heat transfer characteristics reveal interesting behavior of convective heat transfer that warrant further study on the effects of the multi sized nanoparticle, especially in the turbulent flow conditions.

Mixing in thermal convection of very thin freestanding films

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Thin liquid films serve as paradigms of atmospheric convection, thermal convection in the Earth's mantle or turbulence in magnetohydrodynamics. Recent research on colloids, interfaces and nanofluids lead to advances in the development of micro-mixers (lab-on-a-chip devices). In this project the specific experimental results of a setup with focus on the mixing statistics of a thermally driven two-dimensional mixer are reviewed. The developed setup allows to capture thin film interference patterns under controlled surface and atmospheric conditions. The measurement setup serves as a prototype of a mixer on the basis of thermally induced turbulence in freestanding thin liquid films with thicknesses in the nanometer range. The convection is realized by placing a cooled copper rod in the center of the film. The temperature gradient between the rod and the atmosphere results in a density gradient in the liquid film, so that the varying buoyancy initializes turbulent motion. The thermally driven convection is characterized by a newly developed algorithm, named Cluster Imaging Velocimetry (CIV). This routine determines the flow relevant vector fields (velocity and deformation). On the basis of these insights the flow in the experiment was investigated with respect to its mixing properties. The mixing characteristics were compared to theoretical models and the mixing efficiency and entropy of the flow scheme were calculated.

ASTROPHYSICS

Simulations of convective layer of the Sun using the kε-model

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Convective layer in the solar atmosphere was numerically simulated with 1D ERA code [1]. Empirical kε model of turbulence [2] was used. Contrary to widely used in astrophysics the mean length theory (MLT), the kε model in a unified way describes convective processes for different scenarios (gravitational and shear instabilities, convection and semiconvection, overshooting) and conditions (stable evolutionary and unstable explosive) and can be realized in multidimensional codes [3]. We compared numerical results with obtained using the MLT model and experimental helioseismic data on depth of solar convective layer.

The work was performed under ISTC project #3755 "Physical and chemical evolution of nonideal plasma of the Sun inferred from modern helioseismic data". [1] N.A. Barysheva, A.I. Zuev, N.G. Karlykhanov et al., ZhVMMF, 22, 401 (1982); [2] M.I. Avramenko. About kε model of turbulence, Preprint RFNC-VNIITF, 2005; [3] V.A. Simonenko, D.A. Gryaznykh, N.G. Karlykhanov, V.A. Lykov, A.N.Shushlebin. Astronomy Letters, 33, 80–92 (2007).

Dynamos and accretion disks in Astrophysics: Ask not "is Mean Field Theory correct?" but "what is the correct Mean Field Theory

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The questions of how gravitational energy is converted into radiation as magnetized matter accretes onto stars and black holes, and how large-scale magnetic fields are generated in astrophysical rotators have challenged astrophysicists for a half century. Magnetohydrodynamic turbulent transport makes both problems highly nonlinear and so numerical simulations have been important to progress. However, understanding key principles and accommodating the astronomer's need for observational modeling require testable semi-analytic mean field theories that distill the essential physics. Twentieth century versions of mean field accretion theory and mean field dynamo theory remain widely used but also widely criticized. I will discuss twenty-first century progress and directions toward improving and unifying these theories; although accretion and large-scale dynamos are commonly treated separately, they must in fact reflect two faces of a single theory. Observational consequences for accretion disk coronae particular to this unification will be discussed, and connections to laboratory plasmas will be briefly mentioned.

Magnetohydrodynamic shallow-water turbulence on the sphere

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Motivated by astrophysical and geophysical applications, numerical simulations of freely-evolving, magnetohydrodynamic shallow-water turbulence (MHDSWT) on a rotating sphere are performed. MHDSWT is the simplest turbulence model that allows the simultaneous effects of stratification, differential rotation, and magnetic field to be studied over long duration at high resolution. Systematic exploration of the full physical and numerical parameter-space shows novel as well as consistent behavior, compared to those of pure hydrodynamic (HD) and horizontally nondivergent MHD counterparts. For example, when the magnetic field strength in the fluid layer is low (i.e., large plasma beta parameter), the MHDSWT evolution is sensitive to initial conditions, as in traditional HD turbulence, with strong dependence on the peak of the initial energy spectrum. In contrast, as the field strength increases, pronounced anisotropic structures (e.g., zonal jets and vorticity bands) -- typically observed in rapidly rotating HD systems -- do not form. In fact, when the magnetic field strength is sufficiently high (plasma beta parameter smaller than ~0.5), the flow field condenses into robust “magnetic vortices” that compactly fill the domain. In general, with increased magnetic field strength, the flow field is more susceptible to loss of balance and can blow up in finite time for arbitrary initializations. Applications to hot extrasolar planet atmospheres and the solar tachocline are discussed.

Double-Diffusive Mixing-Length Theory, semiconvection, and massive star evolution

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Double-diffusive convection may be defined as the mixing in which the effects of thermal and composition gradients compete to determine the stability of a fluid. In fast convective instability, fluids exhibit the slow, direct salt finger instability

and slow overstable semiconvective instability. We are to examine the nonlinear mixing-length theory (MLT) of double-diffusive convection, in analogy to the more familiar MLT for a homogeneous fluid composition. We present approximate solutions for the mixing rate in the various regimes, and show that the familiar Schwarzschild and Ledoux stability criteria are good approximations to the precise criteria in stellar interiors.We have implemented the self-consistent computation of the temperature gradient and turbulent mixing rate in a stellar evolution code and solved the diffusion equation to mix composition to an appropriate rate. We have evolved stars from the zero-agemain sequence to the end of core He-burning. Semiconvective mixing is fast enough to alter stellar composition profiles on relevant time scales, but not so fast that instantaneous readjustment is appropriate.

Formation and growth of hydrodynamic instabilities during the evolution of Supernova remnants

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The explosion of massive star results in a shock wave that expands out into the surrounding medium, which may have been formed by mass-loss from the progenitor star itself. The expanding shock wave goes through various stages, depending on the mass of material swept-up by the shock wave, and whether the shock is adiabatic or radiative. The evolution of the shock wave, and the transition between various stages, is accompanied by the formation and growth of various instabilities, such as Rayleigh-Taylor, Kelvin-Helmholtz, and a variety of Vishniac-type thin-shell instabilities. In this talk we will describe the evolution of the shock wave, both semi-analytically and numerically, through the various phases. We will study the onset and development of various hydrodynamic instabilities during the shock wave evolution, and the resulting growth of turbulence and small-scale structure within the supernova remnant.

Magnetic field amplification from turbulent flows in core-collapse supernovae

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Core-collapse supernovae (CCSNe) mark the explosive death of massive stars. They are the single most important source of heavy elements in the Universe. In the current paradigm of core-collapse supernova theory, the supernova shock wave is launched when a collapsed iron core forms a proto-neutron star (PNS). Because of energy losses from neutrino emission and iron dissociation, the shock wave turns into an accretion shock when it stalls 100-200 km from the center of the PNS. It is likely reenergized by heating from neutrinos, but no consensus exists on the details, which are currently debated. The region between the PNS and the stalled shock is susceptible to turbulent flows due to neutrino-driven convection, the magneto-rotational instability, and other instabilities. In particular, a powerful instability of the stalled shock, the so-called stationary accretion shock instability (SASI), plays a central role in supernova theory. The SASI may be important to the revival of the stalled shock by the neutrino heating mechanism, and connect birth properties of neutron stars (natal kicks, spins, and magnetic fields) to supernova dynamics. We present results from global three-dimensional MHD simulations of a stalled shock in the supernova environment. We are interested in the evolution and role of magnetic fields in CCSNe and associated observables. In our simulations, magnetic fields are amplified exponentially due to turbulence driven by the SASI. Significant neutron star magnetization may result from SASI-induced magnetic field amplification. The impact of magnetic fields on supernova dynamics is also investigated, but is found difficult to quantify due to numerical resolution requirements in global simulations. Research supported by the Office of Advanced Scientific Computing Research and the Office of Nuclear Physics, US Department of Energy.

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Turbulence and fossil turbulence lead to life in the universe

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The cosmological big bang was the first turbulent combustion, where negative inertial vortex stresses overcame Fortov-Planck gravitational pressures $c^7h^{-1}G^{-2}$ ~ 4.6 10^{113} Pa to extract mass energy of the universe from the vacuum, where c is light speed, *h* is Planck's constant and *G* is Newton's constant. Most of the mass energy of the universe was extracted by negative gluon viscous stresses when the spinning turbulent fireball cooled to quark-plasma temperature, fossilizing the turbulent temperature perturbations by inflation to scales beyond ct, where t is time. Turbulence and gravitational structure formation in the plasma epoch is prevented by photon viscosity values exceeding 4 10^{26} m^2 s^{-1} until t = 10^{12} seconds, when the viscous-gravitational scale of hydrogravitational dynamics HGD matches ct and the expanding universe fragments to form proto-super-cluster-voids with weak turbulence near the expanding boundaries. Further fragmentation occurs in the plasma at cluster and proto-galaxy scales. Cold dark matter condensation is unnecessary and physically impossible for primordial structure formation. Kinematic viscosity decreases to ~ 10^{13} m^2 s^{-1} in the hot hydrogen H-1 helium He-4 primordial gas formed at ~10^{13} seconds (300,000 years), when the proto-galaxies fragment into Jeans mass clumps of hot Earth-mass gas planets. All stars are formed by frictional mergers of these H gas planets within their trillion planet clumps, termed proto-globular-star-clusters PGCs. First stars, first supernovae, first chemicals C, N, O, P, Si, Fe, Ni, first critical temperature 647 K water oceans provide ideal conditions for creation of organic chemistry and the first life, starting at 2 million years and slowing down at 8 million years when the temperature cools to 273 K.

Turbulent magneto-convection, vortex tubes, and self-organization of solar plasma

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Turbulent behavior of magnetoconvection is a key to the understanding of the phenomena of multiscale convective and magnetic structurization observed on the Sun. Recent radiative 3D MHD LES numerical simulations show that many of these phenomena are related to the formation, dynamics and interaction of turbulent vortex tubes. The vortices are characterized by sharp decreases of density and temperature and high-speed swirling downflows. Their interaction may lead to formation of mesogranular-scale convection. In magnetic regions, the vortex tubes become the centers of magnetic structuring, and spontaneous formation of stable pore-like magnetic structures. In the inclined magnetic field of sunspots the turbulent magnetoconvection leads to formation of filamentary magnetic structures and strong organized shearing outflows giving an explanation to the Evershed effect.

The role of turbulence in the formation of planets

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Turbulence in protoplanetary disks diffuses small solid material, leads to collisions among larger objects, concentrates boulders promoting planetesimal formation via gravity and also has an impact on planet migration. Despite the importance of turbulence, its nature is not completely understood so far. In certain regions of the disk the gas is sufficiently ionized for Magneto-Hydrodynamics to lead to turbulence. Other regions being too cold or dusty could now either be dead zones without turbulence or develop a different kind of instability. Realistic radial entropy gradients and thermal diffusion times in typical accretion disks around young stars can lead to a kind of "baroclinic instability" and the formation of vortices and the generation of turbulent viscosity. I summarize the state of field of entropy gradient driven instability in accretion disks and show latest results from numerical simulations.

Turbulent mixing in the Sun: comparing models with observations

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Traditionally, turbulent mixing in the solar convection zone, which occupies the outer 30% along the solar radius, is described by the mixing-length theory. However, helioseismology observations have revealed significant deviations of the solar structure from the theory predictions, particularly, at the convection boundaries, in the tachocline and in the subsurface turbulent boundary layer. Both these regions are also characterized by strong shearing flows, and probably play a critical role in the generation of solar magnetic fields by turbulent dynamo. I will discuss the current understanding of the solar dynamics and comparison with the recent observations.

Magnetic field amplification associated with the Richtmyer-Meshkov instability

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Recent discovery of the year-scale variability in the syncrtron X-ray emission of supernova remnants (SNRs) suggests that the magnetic field should be amplified in the SNR up to the level of milligauss (Uchiyama et al 2007). Since the typical magnetic field in the interstellar medium (ISM) is on the order of microgauss, amplification beyond the simple shock compression is necessary to achieve a milligauss of a magnetic field. Turbulence and magnetic field amplification has been studied for shock wave propagation through two-phase ISM composed of small-scale cloudlets (Inoue et al 2009). We here present some MHD simulation results of the Magnetic field amplification associated with the Richtmyer-Meshkov instability for a sinusoidal interface corrugation. The field amplification observed is found to be more than a factor of 100, which is consistent with the observation (Uchiyama et al 2007).

Y. Uchiyama et al, Nature, 449, 576 (2007). T. Inoue et al., ApJ, 695, 825 (2009).

The role of the magnetic field in the evolution of the stellar rotation of young low mass stars

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The study of the rotation in young low mass stars ($M \leq 1M_0$) is one of the most active areas in the star formation. Many theoretical efforts have been made during the last years to understand their angular momentum evolution. The current picture reveals the main role of the stellar magnetic field in the rotation during all pre-main sequence. The field is thought to arise from dynamo action, with convection, rotation and shear as players in the processes of field generation. However, stars whose interiors are fully convective have been thought to harbor dynamos that differ from those in stars with radiative cores. In this work, we present preliminary results obtained with a time dependent rotational model for the rotation of young low mass stars accross of a wide mass spectrum and during all pre-main sequence. The model incorporates changes in the moment of inertia of star, magnetic field strength, angular momentum loss by a magnetic wind and an exponential decrease of the accretion rate during the T Tauri stage. We used a simple linear dynamo prescription for the rotational dependence of the stellar field. Even if such as prescription lack of validity for fully convective stars, the bulk of the rotational predictions are in agreement with observational data coming from extensive photometric monitoring as reported in the literature.

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MAGNETO-HYDRODYNAMICS

Basic properties of MHD turbulence

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MHD Turbulence is common in many space physics and astrophysics environments. A well-conductive fluid amplifies initial magnetic fields in a process called small-scale dynamo. Below equipartition scale for kinetic and magnetic energies the spectrum is steep (Kolmogorov's -5/3) and is represented by critically balanced strong MHD turbulence. Near the sources of perturbation, such as the Sun in solar wind or the central engine in jets, MHD turbulence is often imbalanced or cross-helical. The standard Goldreich-Sridhar model does not apply in this case. The keys to understand energy cascades in the imbalanced case are the anisotropies of the Elsasser fields which, as we have found, are notably different. I will outline a predictions of our theoretical model and compare them with our new, state-of-the-art numerical simulations of MHD turbulence.

Turbulent experimental dynamos: from liquid metal to plasmas

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Many astrophysical objects, like the Sun, are composed of highly conducting, turbulent, flowing plasma in which the flow energy is much larger than that of magnetic field energy. Creating such conditions in laboratory plasma experiments is challenging since confinement is required to keep the plasma hot (and conducting), and this requires strong applied magnetic fields. For this reason, laboratory experiments using liquid metals have been addressing fundamental plasma processes in this unique parameter regime. This talk will begin by reviewing self-generation of a magnetic field of energy comparable to the turbulent flow from which it arises--the dynamo process. Then, I'll talk about how experimental studies, using liquid metals, are isolating various processes in the dynamo instability. This includes liquid metal experiments that (1) demonstrated self-excitation of magnetic fields, (3) intermittent self-excitation and a variety of time dynamics including field reversals, and (3) showed the existence of a turbulent electromotive force (mean-field current generation). Liquid metals are, however, not plasmas: dynamos may differ in plasmas

where the relative importance of viscosity and resistivity can be interchanged, and new instability mechanisms, outside the scope of incompressible MHD may be critical in plasmas. This suggests that the next generation of experiments in this important astrophysics regime should be based upon plasmas. The Madison Plasma Dynamo experiment (now under construction) will then be described with an overview of the concept and show how the dynamos might operate in this plasma. Modeling of several experimental scenarios that mimic solar processes will also be described, including experiments on rotating, compressible convection driven by magnetic buoyancy.

Fully three-dimensional magnetic field line reconnection within magnetic flux ropes and current sheets

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Magnetic Field Line reconnection is still considered, by some, to be one of the most important topics in plasma physics. The subject has been static for decades but now with computers powerful enough and experiments capable of acquiring 3D the topic is undergoing a Renaissance. One reason is most of the models for it are still two dimensional. We report on experiments in which fully 3D reconnection plays a role. In the first experiment two and three magnetic flux ropes are generated from initially adjacent, pulsed current channels in a reproducible, repetitively pulsed background magneto-plasma. The currents exert mutual $J \times B$ forces causing them to twist about each other and merge and are also subject to kink instabilities which cause them to crash into each other from time to time. Volumetric space-time data show multiple reconnection sites with time-dependent locations. . The quasi-separatrix layer (QSL) is a narrow region between the flux ropes in which reconnection occurs. Two field lines on either side of the QSL will have closely spaced foot-points at one end of the flux ropes but rapidly diverge from one another as they traverse the reconnection region. In the two current channel experiment a single QSL is measured however two are observed when three flux ropes are present. A second series of experiments involves the interaction of two narrow current sheets separated by several ion gyro-radii. The current sheets filament into flux ropes and twist about one another. The current system is fully three dimensional as well. A single current sheet is also studied and breaks up into flux ropes which interact as well! Quasi-seperatrix layers are calculated and also are fully three dimensional. These measurements will be discussed in the context of solar physics and astrophysical situations. Three dimensional movies and stills using anaglyphs will illustrate the nature of the QSL's. Glasses will be provided.

Simple waves and Riemann problem in magnetohydrodynamic flows in shallow water approximation

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The shallow water magnetohydrodynamic (SMHD) equations are the alternative to solving of full set of magnetohydrodynamic equations for a heavy fluid with a free surface. These equations are derived from the magnetohydrodynamic equations for an incompressible nonviscous fluid layer in the gravity field assuming the pressure is hydrostatic, using the depth averaging and considering that the fluid layer depth is much smaller than the problem character size. The derived system is important in many applications of magnetohydrodynamics to astrophysical and engineering problems. The magnetohydrodynamic shallow water approximation is widely used for the solar tachocline study, for the description of spread of matter over a neutron-star surface during disc accretion, for the study of neutron-star atmosphere dynamics, for the study of extrasolar planets, and for the optimization of aluminum production process. The present work is devoted to the study of nonlinear flows of heavy fluid described by the shallow water magnetohydrodynamic equations over a flat surface. This new set of equations provides general interests in nonlinear physics. These equations serve the basics in developing of multilayer stratified shallow water magnetohydrodynamic models. The hyperbolicity of magnetohydrodynamic shallow water equations leads to the existence of discontinuous solutions as well as the existence of continuous ones. The equations nonlinearity and hyperbolicity can lead to the discontinuous solutions even if the initial conditions are differentiable. In the present paper simple wave solutions for the SMHD equations over a flat plane are studied. Magnetogravity rarefaction wave, magnetogravity shock wave and Alfvenic wave solutions are found. Characteristics of these waves are the straight lines in case of flat plane. The obtained solutions are used to find the exact solution of the initial discontinuity decay problem (Riemann problem) for SMHD equations system. We found the structure of configurations of the solutions over a flat plane. The conditions for realization of each wave configuration are obtained. The initial discontinuity decay solution is represented by one of the following wave configurations: ‘two magnetogravity shock waves, two Alfvenic waves’, ‘magnetogravity shock wave, magnetogravity rarefaction wave turned forward, two Alfveinc waves’, 'magnetogravity rarefaction wave turned back, magnetogravity shock wave, two Alfvenic waves', 'two magnetogravity rarefaction waves, two Alfvenic waves', 'two hydrodynamic rarefaction waves and a vacuum region' between them.

Turbulent generation of large-scale magnetic flux concentrations

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In mean-field hydrodynamics, isotropic turbulence has only a destructive diffusion property. However, anisotropy can introduce competing constructive effects which, for a given parameter range, might dominate the evolution. In this perspective we have studied the influence of magnetic fluctuations on the Maxwell-Reynolds stress tensor. The presence of a background magnetic field is found to lead to a reduction of the effective total turbulent pressure. Here we investigate the possibility of creating magnetic flux concentrations through this feedback of magnetic fluctuations on the pressure. In particular, we study the dependence of this mechanism on various physical parameters including magnetic Prandtl number, magnetic Reynolds number, magnetic field strength, and the degree of stratification.

Investigation of magnetohydrodynamic turbulence described by the space-time functional formalism

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The Lewis-Kraichnan space-time version of the Hopf functional formalism is considered. The Magnetohydrodynamic turbulence equation for an incompressible conducting field are written in terms of the characteristic functional for joint probability distribution of the velocity field and magnetic field .These equations are transformed into the Fourier space and the resulting equations are written in terms of the second characteristic functional .These equations describe the dynamics of various order cumulants which reveal the characteristic difficulty of the turbulence theory (i.e. (n+1)th order cumulant occurs in the equation for the dynamics of nth order cumulant). In order to obtain a closed set of equations for cumulants a method of multiple-scale-cumulant expansion is employed and equations describing the dynamics of kinetic energy spectrum and magnetic energy spectrum are derived.These equations are integrated numerically and the statistical quantities

describing the magnetohydrodynamic turbulence such as kinetic energy, magnetic energy, enstrophies are evaluated. The empirical relation for the ratio of kinetic energy and magnetic energy is derived.

Existence, uniqueness, analyticity and Borel summability of magneto-hydrodynamic and Boussinesq equations

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We give results on existence, uniqueness and Borel summability properties that compliment existing theory for Magneto-hydrodynamic and Boussinesq equations. Results include uniqueness for data for H^2 initial conditions, without assumptions on decay rate. We also prove a right half-plane of analyticity in the 1/t domain for local solutions to these equations and show that for analytic initial data, all solutions are Borel summable. As with Navier-Stokes, global existence problem becomes an issue of the asymptotics of known solutions to integro-differential equation.

CANONICAL PLASMAS

Influence of dust concentration on shock wave splitting in discharge plasma in different gases.

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Experiments were conducted on the exclusive electric discharge installation of Ioffe Institute of Russian Academy of Science. The experimental form of the distribution of pressure after shock wave in the plasma differs significantly from form in the gas without the plasma. “Two-wave” form in the plasma makes it possible to hope for reductions of body drag in the plasma. Experiments are carried out for the careful study of the distribution of pressure behind the shock wave during its propagation across the positive column of the steady-state glowing discharge in the dust-laden air, nitrogen and argon. Dust is nanosize carbon particles. Previous studies have shown that the influence of dust is significant for great concentration of dust in 10 times more than natural concentration. The influence of high concentrations of dust was noticeable only for argon. In nitrogen and in the air, influence in plasma practically is not observed. The influence in all gases without plasma is in limits of experimental accuracy. As to plasma the influence in argon is limited to an increase in the second peak, but does not affect the time characteristic - distance behind the shock wave at which secondary wave occurs. Moreover primary wave also is changed. In contrast to second wave primary shock wave becomes less than the wave without dust in the same conditions. Such behavior of primary shock wave is usual for shocks in dusted gas. Apparently the second wave has the other nature than primary one.

Part of work was made with the support of RFBR, Grant 06-08-00663-a.

Laser fluorescence measurements of a magnetized argon plasma accelerated by momentum transfer from an expanding carbon plasma

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A dense plasma colliding with a background, magnetized plasma is a source of radiation by waves; localized, large fields and currents; and turbulent mixing. For the past ten years, investigations using the Large Plasma Device at UCLA have studied the supersonic expansion of a laser-produced carbon plasma into an ambient argon background plasma $\left(n \sim 2X10^{12} cm^{-3}, v_c \sim 4X10^5 \; cm/s\right)$. Previous experiments detailed the formation of a diamagnetic cavity, ambipolar fields, and current structures radiating Alfven waves into the background plasma. Current experiments aim to characterize the transport properties of the different ion species in the system using laser-induced fluorescence together with magnetic probe diagnostics. In particular, the background Ar-II ions are probed utilizing the standard 611.5 nm excitation transition. Distribution functions from the Doppler broadened transition are collected during the expansion of the diamagnetic cavity using a YAG-pumped tunable dye laser. Spectra along the background field from the target show momentum transfer to the argon ions achieving an acoustic mach number of $v_{par}/v_{\,c} \sim 2-3$ for a significant fraction of the fluorescing ions. Time evolution images at resonance show an expanding population of excited Ar-II ions coinciding with that of the carbon blow off and having a comparable leading edge expansion rate $\left(\sim 1X10^7 \; cm/s >> v_c\right)$. This data in conjunction with fast imaging of the carbon ions is used to explore the interface between the two species.

This experiment is funded by grants from the US Department of Energy and the National Science Foundation and conducted at the Basic Plasma Science Facility.

Electrostatic solitary waves and turbulence in the universe of collisionless plasmas

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Plasma systems without efficient collisions support a special type of non-equilibrium solitary wave whose width, amplitude, and velocity are only loosely constrained by inequalities, in contrast with classical solitons whose constraints are strict one-one mapping relations. Phase-space holes and double layers are among the examples of this special type of wave, and have been observed in a broad spectrum of spatial and time scales in the collisionless space and laboratory plasmas. I will discuss our recent theoretical and experimental studies on phase-space holes and double layers. These include: the inequality constraints for 3D phase-space holes (1) and 1D double layers; the first experimental evidence for loosely constrained electron phase-space holes (2); laboratory measurements of Debye-scale electron solitary waves (3); space observations of electrostatic solitary waves during magnetic reconnection; analysis of solitary waves at shocks and its downstream turbulence (4,5). Our studies indicate ubiquitous presence of electrostatic solitary waves in non-equilibrium collisionless plasma systems, and that these solitary waves are often the main constituents of the observed electrostatic turbulence in these systems.

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Experimental simulation of auroral current systems

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Field aligned plasma potential drops $\left(\Delta\phi/kTe \sim 1\right)$ of a quiescent $\left(\Delta n/n < 5\%\right)$, current-free, magnetized plasma terminating on a neutral gas have been observed, measured, and compared to theory. The experiment was carried out at the ETPD at UCLA, a large toroidal device (major radius = 5 m, 2 m wide, 3 m tall) with a pulsed (1 Hz) DC plasma discharge ($td \sim 20ms$, $Bt \sim 250G$, and $Bv < 6G$, $R_{plasma} = 10cm$, $ne < 10^{13}$, $Te < 10eV$, and Ti ~ Te, $L_{plasma} \sim 30m$ long). Langmuir, emissive, and electrostatic flux probes were used to measure plasma parameters, and electric fields, and transport throughout the axial boundary layer. Far from the boundary, the radial electric field of the plasma edge is inward however, the fields at the boundary are more complicated and will be presented. The end of the plasma is dominated by a field aligned potential structure similar to a double layer but many Debye lengths $\left(\sim 10^4 \lambda_D\right)$ long. The experiment is compared to calculations of the 3-D electric fields and current system in the boundary layers using the local measured plasma conductivities. In the model we consider the axial plasma-neutral boundary as a sink for particles by 3-body recombination, heat loss by thermalization with neutrals, and momentum loss by ion-neutral collisions. A broad spectrum of drift Alfven waves is observed using correlation techniques and turbulent transport studied. The field aligned plasma/neutral gas boundary is important to the understanding of the aurora, gaseous divertors, and plasma thrusters.

Work was funded by the Department of Energy and National Science Foundation.

Stochastic diffusion of ultracold gases and plasmas stimulated by the magnetic field

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The ultracold gases and plasmas, widely studied recently in the magneto-optical traps (MOT), exhibit a number of features very different from the usual high-temperature plasmas [1-3]. The aim of the present report is to discuss one of such phenomena. While a magnetic field in the high-temperature plasmas typically suppresses diffusion and other kinds of transport across the field, just the opposite behavior can arise in the ultracold Rydberg gases and strongly-coupled plasmas. Namely, if the Coulomb force acting on the weakly-bound electron moving around a nearby ion becomes comparable to the Lorentz force produced by the external magnetic field, then the ion after each revolution of the electron will get a kick in a random direction, resulting in the diffusion-like motion of the entire electron-ion pair. The rates of such diffusion, obtained by both analytical and numerical methods, will be presented in our report. This type of diffusion is expected to be measured explicitly in the new generation of MOT experiments (particularly, the one designed now in Moscow), and it also should be of importance in some astrophysical objects (e.g. the cold intergalactic HI clouds).

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Turbulence in photonic plasma

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We treat the nonlinear propagation of partially spatially incoherent light as a photonic plasma. Using wave-kinetic theory, we interpret the speckles of statistical light as quasi-particles which can interact via Langmuir-type modulation waves. We analytically derive a Bohm-Gross dispersion relation and identify an effective plasma frequency, effective Debye length, etc. Experimentally, we confirm the theory by studying the nonlinear propagation of diffused (quasi-thermal) light in a self-focusing photorefractive crystal. Observed phenomena include Landau damping, modulation instability, single and multiple bump-on-tail instabilities, and optical turbulence. By recording a hologram of the internal dynamics, we measure particle-wave and wave-wave interactions that are difficult, if not impossible, to observe in material plasma. In particular, we observe the phase-space transition from weak to strong turbulence, both through intensity (density) modulations in position and through spectral dynamics in momentum. As with any pattern-forming instability, the modulations which emerge are randomly distributed. Nevertheless, since patterns in optics are images, it is tempting to use the wave behavior for dynamical signal processing. We explore this systematically by adding a weak image to the diffused light. For the right range of parameters, we observe nonlinear energy transfer from the noise to the signal. The transfer is well-described by a photonic beam-plasma instability, in which the image seeds the growth of its own, non-random pattern. Remarkably, the plasma formula recovers a formula from information theory describing stochastic resonance, generalized to include the dynamical coupling of transverse modes. The results link the fields of optics, plasma, and information theory in unanticipated ways and suggest new methods and applications of plasma turbulence.

Parallel electric fields producing relativistic electrons at large spatial scales during magnetic reconnection

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An analysis of superthermal electrons from spacecraft observations in the magnetotail provides evidence that direct acceleration by large scale parallel electric fields is a key mechanism for energizing electrons during magnetic reconnection over length scales reaching far beyond the electron diffusion region [1]. Here we present new kinetic simulation results that corroborate this heating mechanism. The parallel electric fields, E||, develop to maintain quasi-neutrality by regulating the electron density, trap a large fraction of thermal electrons, and heat electrons in the parallel direction [2, 3]. With the newly derived equations of state (including the trapped electron dynamics) [4], momentum balance across the electron diffusion region requires that the integrated strength of E|| depends strongly on the upstream β_e (the electron pressure normalized to the magnetic field pressure) and becomes large at low values of β_e [5]. Typically, numerical investigations apply $\beta_e \sim 0.05$. Meanwhile, in our new large scale kinetic simulation, we apply a value of $\beta_e = 0.008$ that is likely more representative for magnetotail reconnection [3]. In accordance with our theoretical scaling [5], the simulation reveals strongly elevated values of E||. Furthermore, the area where E|| is large fills the exhaust region over tens of ion inertial lengths. As additional confirmation of the heating mechanism, the electron distributions in the simulations are in excellent agreement with those observed by spacecraft, reproducing the bi-directional beams in the inflow region, the inward directed beams along the separators and flat-top distributions in the exhaust.

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Nonlocality in turbulent transport of fusion plasmas

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Turbulence in magnetically confined fusion plasmas can spread from the region where instabilities grow to the linearly stable zone [1]. This turbulence spreading can significantly modify the transport scaling which can be obtained from the usual assumption of local diffusive transport process, and affect the performance of future fusion devices. We're currently extending our previous nonlinear fluid theoretical model for turbulence spreading [1,2] and compare to gyrokinetic simulation results from GTS code [3] which exhibit turbulence spreading. Nonlocality in turbulent transport process (beyond local diffusion) is also critically analyzed to understand recent simulation results from GYSELA code [4]. Finally, outstanding issues involving experimental test of turbulence spreading will be discussed utilizing collapse of transport barriers.

Work was supported by WCI Center for Fusion Theory, National Fusion Research Institute, Korea. [1] T.S. Hahm, P.H. Diamond, Z. Lin, et al., Plasma Phys. Control. Fusion, 46, A323 (2004); [2] T.S. Hahm, P.H. Diamond, Z. Lin, et al., et al, Phys. Plasmas 12, 090903 (2005); [3] W.Wang, T.S. Hahm, W.W. Lee, et al., Phys. Plasmas 14, 072306 (2007); [4] G. Dif-Pradalier, P.H. Diamond, V. Grandgirard, et al., Phys. Rev. E 82, 025401 (2010)

Generation and detection of whistler wave-induced space plasma turbulence

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In this lecture we will discuss several methods to launch VLF whistler waves and radar, optical and GPS satellite detection of whistler wave-induced space plasma turbulence in Peru, Puerto Rico, and Alaska. Whistler waves can be launched from a ground-based transmitter (e.g., NAU at Aquada, Puerto Rico), artificial antennae (e.g., HF radio wave-modulated electrojet current over Gakona, Alaska), a space-borne transmitter (e.g., US-USSR Active Space Plasma Program, 1989). Whistler wave-induced space plasma disturbances was detected, for example, by Jicarmarca 50 MHz radarin Peru [Liao et al., 1989] and by Arecibo 430 MHz radar in Puerto Rico [Labno et al., 2007]. Optical detection of whistler wave-triggered particle precipitation from inner and outer radiation belts was investigated by Pradipta et al. [2007, 2011]. Sheet-like artificial waveguides produced in natural spread F process or by HF heater waves can facilitate the coupling of whistler waves propagating from the neutral atmosphere intothe ionosphere [Starks and Lee, 1999; Starks et al., 2001]. Generation of acoustic gravity waves by vertically injected HF waves for controlled study of whistler wave-plasma interactions and whistler wave-particle interactions have been actively conducted at Gakona, Alaska [Pradipta et al., 2011]. Two prominent processes caused by whistler wave interactions with ionospheric plasmas are monitored by radarsin our Puerto Rico and Alaska experiments. They are (1) four wave-interactions leading to generation of Stokes and anti-Stokes lower hybrid waves together with zero-frequency field-aligned modes [Labno et al., 2007], and (2) directed acceleration of electrons by upward propagating whistler waves [Lee et al., 2011]. Radar measurements of plasma lines resulting from electron plasma waves associated with accelerated electrons are distinctly different in these two processes. While whistler wave-excited lower hybrid waves can produce both upshifted and downshifted plasma lines, direct acceleration of electrons by up-going whistler waves can only generate downshifted plasma lines. Verification of these propagation and interaction processes by in-situ/rocket and optical measurements will also be described.

Electrostatic solitary wave experiments in the LArge Plasma Device (LAPD)

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Solitary electrostatic pulses have been frequently observed in space plasmas, particularly in regions supporting large-scale current systems or intensive energy dissipation such as reconnecting current sheets or shocks. These solitary structures are thought to result from kinetic instabilities, and play a role in particle scattering and energy dissipation. We have conducted a series of experiments at the UCLA large plasma device (LAPD) where a suprathermal electron beam was injected into the plasma parallel to a static magnetic field. Solitary structures with dipolar parallel electric fields were detected using micro-probes with tips smaller than a Debye length. The shape, scales and amplitudes of the structures are comparable to those observed in space and consistent with electron holes, spatially localized regions of depleted electron density. The velocities of the solitary structures were found to be incompatible with an instability resonant with the beam electrons, suggesting an

excitation mechanism driven by parallel currents. Wave packets with similar sizes and velocities as the structures were also found, and both might be related in the small-amplitude limit to the electrostatic whistler mode.

B. Lefebvre, L.-J. Chen, W. Gekelman, P. Kintner, J. Pickett, P. Pribyl, S. Vincena, F. Chiang, J. Judy, Laboratory measurements of electrostatic solitary structures generated by beam injection Physical Review Letters 105, 115001, 2010.

Exponential frequency spectra and Lorentzian pulses in magnetized plasmas

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Two completely different experiments involving pressure gradients across the confining magnetic field in a large plasma column are found to exhibit broadband turbulence with an exponential frequency spectrum for frequencies below the ion-cyclotron frequency. The origin of the exponential feature has been traced to the generation of solitary pulses having a Lorentzian temporal signature. These pulses arise from the nonlinear interaction of drift-Alfven waves driven by the pressure gradients. The temporal width of the pulses is measured to be a fraction of a period of the initially coherent drift-Alfven waves. This time width sets the scaling frequency for the observed exponential spectrum. The experiments are performed in the Large Plasma Device (LAPD-U) operated by the Basic Plasma Science Facility at the University of California, Los Angeles. One experiment involves a controlled, pure electron temperature gradient associated with a microscopic (3 mm gradient length) hot-electron temperature filament created by the injection of a small electron beam embedded in the center of a large, cold magnetized plasma. The other experiment is a macroscopic (2 cm gradient length) limiter-edge experiment in which a density gradient is established by inserting a metallic plate at the edge of the nominal plasma column of the LAPD-U. The temperature filament experiment permits a detailed study of the transition from coherent to turbulent behavior and the concomitant change from classical to anomalous transport. In the limiter experiment the turbulence has been associated with blob phenomena. The similarity of the results suggest a universal feature of pressure gradient-driven turbulence in magnetized plasmas that results in non-diffusive cross- field transport. The findings may explain previous observations in helical confinement devices, research tokamaks and arc-plasmas.

Investigation of acoustic gravity waves created by anomalous heat sources: experiments and theoretical analysis

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We have been investigating high power radio wave-induced acoustic gravity waves (AGWs) at Gakona, Alaska, using High-frequency Active Aurora Research Program (HAARP) heating facility (i.e., HF heater) and extensive diagnostic instruments. This work is aimed at controlled study of space plasma turbulence, triggered by acoustic gravity waves originating from anomalous heat sources, as observed in our earlier experiments at Arecibo, Puerto Rico [R. Pradipta et al., 2007]. HF heater operated in CW O-mode can heat ionospheric plasmas effectively to yield depleted magnetic flux tube as rising plasma bubbles [Lee et al., 1998]. Two processes responsible for the depletion of magnetic flux tube are (1) thermal expansion and (2) chemical reactions caused by heated ions. The depleted plasmas create large density gradients that can augment spread F processes via generalized Rayleigh-Taylor instabilities [Lee et al., 1999]. It is thus expected that the temperature of neutral particles in the heated ionospheric region can be increased. Such heat source in the neutral atmosphere may potentially generate acoustic gravity waves (AGWs) in the form of traveling ionospheric plasma disturbances (TIPDs). We should point out that these TIPDs have features distinctively different from ExB drifts of HF wave-induced large-scale non-propagating plasma structures. Moreover, it is noted in our recent study of naturally-occurring AGW-induced TIDs that only large-scale AGWs can propagate upward to reach higher altitudes. Thus, in our Gakona experiments we select optimum heating schemes for HF wave-induced AGWs that can be distinguished from the naturally occurring ones. The generation and propagation of AGWs are monitored by Modular UHF Ionospheric Radar (MUIR), digisonde, and GPS/LEO satellites. Our theoretical and experimental study have shown that anomalous heat sources produced by, for example, global warming can become potential causes to induce extensive large-scale turbulence in the neutral atmosphere and space plasmas.

Multi-diagnosis of large plasma sheets and geomagnetic field fluctuations excited concomitantly by injected radio waves

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We report on further investigation of large plasma sheets and micropulsations/geomagnetic field fluctuations simultaneously excited by injected high power radio waves via thermal filamentation instabilities [Cohen et al., Phys. Scrip., 2010]. These large plasma sheets generated by HF heater have different configurations, depending upon the polarizations (i.e., O- or X-mode) of the heater waves. It is expected that O-mode heater wave-created parallel-plate waveguides within the meridional plane, and those generated by the X-mode heater waves are orthogonal to the meridional plane [Lee et al., Geophys. Res Lett., 1998]. One striking feature of thermal filamentation instabilities is the simultaneous excitation of sheet-like plasma density fluctuations (δn) and geomagnetic field fluctuations (δB). The physics can be simply understood as follows. The differential joule heating, resulting from the interactions of HF heater waves and excited high frequency sidebands, yields a thermal pressure force on electrons. Thermal pressure force (denoted by f_T) leads to a $f_T X B_0$ drift motion of electrons and, consequently, induces a net current perpendicular to both the background magnetic field B_0 and the wave vector k of the excited plasma density irregularities. Therefore, magnetic field fluctuations (δB) associated with micropulsations are excited along the background magnetic field (B_0 designated as the z-axis) simultaneously with the density irregularities in both O- and X-mode heating processes. The excited magnetic field fluctuations (δB) have three components designated as δB_D, δB_H, and δB_Z. Based on above explanation of the simultaneous excitations of δn and δB, we can expect that δB_D and δB_Z (or δB_H and δB_Z) will be highly correlated in O-mode (or X-mode) heating experiments. Our theoretical predictions are confirmed by GPS satellite measurements, range–time–intensity (RTI) plots of UHF and HF backscatter radars, ionosonde data, as well as magnetometer data analyses. As these plasma sheets experienced E×B drifts, they were intercepted by the HAARP UHF radar and seen as slanted stripes in the RTI plots, as also seen in our earlier Arecibo experiments. Furthermore, based on the GPS satellite measurements, we infer that kilometer-scale plasma sheets can be generated by vertically injected O-mode heater waves.

Fast-framing camera and probe measurements of intermittent turbulence and nonlinear structures in a linear, magnetized plasma

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In magnetized plasmas, cross-field transport behind obstacles is often dominated not by diffusive, but by turbulent or intermittent transport. We present measurements of the linear growth of drift waves, and the development of cross-field transport via the production of nonlinear structures. Two-dimensional intensity maps from a fast-framing camera (max $5x10^5$ frames per second [1]) are correlated, pixel-by-pixel, with in situ triple Langmuir probes. Linear drift waves are observed to grow spontaneously along the pressure gradient. Later, nonlinear structures detach from the linear waves and penetrate behind the limiter, perpendicular to the background magnetic field. A pair of fast-framing cameras is also employed in an attempt to reveal the three-dimensional morphology of the structures. Dramatic movies of the dynamics of these intermittent structures will be presented. The axial magnetic field is varied from 500 G to 2000 G to investigate the scaling of the size and velocity of the turbulent structures with the ion gyro-radius. These experiments are perform in the Large Plasma Device at UCLA, USA. The cylindrical plasma has dimensions: L=18 m, d= 60 cm. Plasmas are created via cathode-anode discharge for 15 ms; the discharge is reproduced at a rate of 1 Hz. Here, a rectangular, conducting limiter plate is introduced at a distance 10 m from the cathode, with the plate normal parallel to B0. This produces a 'D'-shaped plasma profile in half of the device with a sharp boundary between the 10^{12} cm^{-3} 6eV plasma and region of neutral gas. Such a configuration has been studied previously by Carter [1] using probes, who showed the ejection of blob-like structures into the low-density region and corresponding density holes entering the high-density region. One a semi-log plot, the summed frequency spectra of the camera pixel time series show the presence of both a coherent mode and a region of broadband turbulence which exhibits an exponential amplitude decay as a function of frequency, shown by Pace et al. [2] to be evidence for solitary pulses with Lorentzian temporal signatures.

This work is supported by the U.S. DoE and NSF, which also fund the operation of the host facility: the Basic Plasma Science Facility. http://plasma.physics.ucla.edu/bapsf. [1] Carter, T.A., Phys. Plasmas, v13, 010701 (2006); [2] Pace, D.C., M. Shi, J.E. Maggs, G.J. Morales, and T.A. Carter, Phys Plasmas, v15, 122304 (2008).

PHYSICS of ATMOSPHERE

Underwater Tornado

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A criterion for the stability of atmospheric vortices follows from a recent theory by E.A. Pashitsky: the vertical velocity in central region should have some acceleration. This condition can be easily satisfied in a bubble jet in a liquid with a sufficient vertical pressure gradient. In a cylindrical vessel filled with water to the height of approximately H = 1 m, the pressure in its upper part was fixed at 20 KPa while air entered through a tube connected to the atmosphere. A general stationary bubble jet formed in initially stationary liquid. When the liquid in the upper part was initially rotated, a tornado formation developed upward from the air source. The air flux through the tornado increases compared with the bubble jet in stationary liquid; the air velocity reaches values $U \sim c(a/H)^{1/2} \sim 10$ *m/s* depending on the air flux. Here c is the sound velocity and a is tornado radius. This experiment presents a new hydrodynamic phenomenon. Its theoretical study will be reported.

Cascade of axisymmetric turbulence in a stably-stratified fluid

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Shearless buoyant turbulence is analysed in a stably stratified fluid, where a mean density gradient yields a space-uniform Brunt-Vaisala frequency for internal waves. Using a toroidal / poloidal (velocity) / potential (buoyancy) decomposition, both linear and nonlinear mechanisms are revisited. It is shown that the toroidal cascade explains the main anisotropistructure, i.e. the horizontal layering, starting from unstructured isotropic initial data. This nonlinear process is shown to be very different from the `dual' cascade, direct for the enstrophy, inverse for the energy, in quasi-geostrophic turbulence, in spite of formal analogies. Some of our conclusions are similar to the one of Lindborg, Chomaz and coworkers, but are independent of preexisting 2D structures, as for the zig-zag instability, and less dependent of a priori semi-empirical scalings in term of the Froude number(s). Typical axisymmetric multi-modal spectral theory is used in addition to DNS.

Turbulent entrainment and mixing in steady cloud-like jet and plume flows

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The present work is a part of our current effort in understanding the dynamics of turbulent entrainment in cumulus-cloud flows. Experiments are being conducted in a laboratory apparatus on jets and plumes with off-source heat generation to simulate the release of latent heat of condensation in natural clouds (Narasimha et al. 2011, EMU/JNCASR preprint). Here we present some results on the entrainment and mixing in steady-state flows. A careful reanalysis of the previous experimental data on heated jets and plumes has been carried out, which shows that the entrainment coefficient first increases above the base of the heating zone (from the classical value), reaches a maximum and decreases to very low values further above. Different physical models have been proposed in the literature to explain the effect of heating on entrainment. Here we revisit these models in light of the new picture emerging as a result of the above analysis. In recent work, Kaminski et al. (2006, JFM) have proposed an integral formulation to parameterize entrainment coefficient. Motivated by this work we come up with a formulation better suited for the present problem which, under certain reasonable assumptions, predicts quite well the qualitative variation of the entrainment coefficient in the vertical. The formulation allows us to identify different physical mechanisms responsible for entrainment and how they are affected by heating. The process of entrainment is known to comprise of three stages- engulfment, mingling and mixing. Previous studies have shown that the off-source heating disrupts large-scale coherent structures (resulting in fluid-dynamical 'non-equilibrium') and enhances small-scale vorticity. This results in a reduced rate of engulfment and dilution, and consequently in a state of higher 'mixedness'. This feature has direct consequences towards the issue of 'homogeneous' vs. 'inhomogeneous' mixing in cumulus clouds (Lehmann et al. 2009, JAS) which is of great importance to cloud microphysics.

Inhomogeneous closure theory and applications

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The theory and application of non-Markovian inhomogeneous closures to problems of atmospheric and oceanic dynamics, predictability, data assimilation, subgrid modelling and inverse modelling is reviewed. It is shown that the quasi-diagonal direct interaction closure (QDIA; Frederiksen 1999) is a numerically tractable statistical closure that is only a few times more computationally intensive than the homogeneous direct interaction closure (DIA). This is in contrast to Kraichnan's (1972) inhomogeneous direct interaction approximation which is computationally intractable at any reasonable resolution. In simulations of Rossby wave dispersion on a beta-plane, where eastward flows impinge on topography, in the presence of weak or strong turbulence, pattern correlations between the 10 day evolved mean fields in the QDIA and from the statistics of 1800 direct numerical simulations (DNS) are 0.9999. The statistics of the fluctuations are also in excellent agreement. A regularized version of the QDIA, with, essentially universal, empirical vertex renormalization, is also described. It is shown that the regularized QDIA is in excellent agreement with the statistics of DNS in all cases considered and for problems of atmospheric predictability, data assimilation and subgrid modelling. The QDIA framework has also been successfully applied to the inverse problem of determining the forcing functions responsible for a given mean field climate anomaly. The QDIA closure and methodology is applied to data assimilation and atmospheric prediction of regime transitions in situations where coherent structures, like large-scale blocks, form during 10 day forecasts. It is applied to the subgrid modelling problem for flow over topography and the implications for atmospheric and oceanic flows are discussed. It is applied to the inverse problem of attributing the causes of climate change.

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Diffusion in strongly stratified fluids

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We review recent results from the study of homogeneous stably stratified turbulence, with special emphasis on the role of the horizontal layering that results from strong stratification. We shall discuss the several theories that have been proposed to describe such flows; their spectra and structures. We compare direct numerical simulation (DNS), to elements of the statistical theory of turbulence. Finally, we discuss the possible use of non-dissipative turbulence on a finite wavenumber band in determining the inertial power range for the spectra. Much of the results reported here are in collaboration with Yoshi Kimura.

Mixing efficiency in natural flows

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In evaluating vertical eddy diffusivities within stably stratified layers of oceans and lakes, a commonly used assumption is that the mixing efficiency G is approximately constant. This is because of the difficulties associated with direct measurements of heat, mass, and momentum fluxes in natural waters. Nevertheless, a majority of recent work suggests otherwise. In this talk, it is argued that for stratified shear flows G is dependent on at least two parameters, the gradient Richardson number Ri and the buoyancy Reynolds number Rb. Based on direct flux and gradient measurements in a stable atmospheric boundary layer and using homogeneous/stationary TKE balance equations, it was shown that in a limited range of the Richardson number, $\sim 0.03 < Ri <\sim 0.4$, which in this case span $10^4 < Rb < 10^6$, the mixing efficiency is nominally similar to that evaluated based on scalar balance equations. Outside this parameter range, one or more assumptions used in developing the methodology of flux estimation break down. This is consistent with shear-induced (internal) mixing, where TKE production balances the local buoyancy flux and dissipation. In a wide range, $0.002 < Ri < 1$, the mixing efficiency is a growing function on *Ri*, while decreasing with Reb . When the Richardson number is in the proximity of a critical value $Ri_{cr} \sim 0.1 - 0.25$, G can be treated approximately as a constant with a typical value of $0.16 - 0.2$. The results shed light on the wide variability of G noted in previous studies.

Nonequilibrium turbulence and inhomogeneous wave dynamics in the upper Troposphere and lower Stratosphere

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The generation mechanisms and physical characteristics (mixing, transport) of inertia-gravity waves radiated from an unstable forced jet at the tropopause are investigated through high-resolution numerical simulations of the three-dimensional Navier-Stokes anelastic equations. Such waves are induced by Kelvin-Helmholtz instabilities on the flanks of the inhomogeneously stratified jet. From the evolution of the averaged momentum flux above the jet, it is found that gravity waves are continuously radiated after the shear-stratified flow reaches a quasi-equilibrium state. The time-vertical coordinate cross-sections of potential temperature show phase patterns indicating upward energy propagation. The sign of the momentum flux above and below the jet further confirms this, indicating that the group velocity of the generated waves is pointing away from the jet core region. Space-time spectral analysis at the upper flank level of the jet shows a broad spectral band, with different phase speeds. The spectra obtained in the stratosphere above the jet show a shift toward lower frequencies and larger spatial scales compared to the spectra found in the jet region. The three-dimensional character of the generated waves is confirmed by analysis of the co-spectra of the spanwise and vertical velocities. Imposing the background rotation modifies the polarization relation between the horizontal wind components. This out-of-phase relation is evidenced by the hodograph of the horizontal wind vector, further confirming the upward energy propagation. The background rotation also causes the co-spectra of the waves high above the jet core to be asymmetric in the spanwise modes, with contributions from modes with negative wavenumbers dominating the co-spectra. In the second part of the talk, we present high resolution simulations in real atmospheric conditions of mountain waves in the upper troposphere and lower stratosphere (UTLS) during the Terrain-induced Rotor Experiment (T-REX).In these simulations, the finest nest of WRF is coupled with microscale nests, within which the three-dimensional fully nonhydrostatic compressible moist atmospheric equations are solved with refined grid in the vertical and improved resolution in the UTLS region. Comparison of simulations with in situ balloon and aircraft measurements obtained during T-REX show favorable agreement.

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Stochastic modeling of turbulent condensation

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Turbulence affects the condensational growth of cloud droplets by creating fluctuations in the temperature and humidity fields in the vicinity of the droplet surface that leads to a broadening of droplet size distribution (as often observed in field experiments). This is relevant to a number of important processes such as the enhancement of particles collision rate that lead to rain formation or the turbulent dispersion and heterogeneous chemical reactions of pollutants in the atmosphere. We have recently developed a model for turbulent condensation based on the solution of Langevin (stochastic) differential equations for supersaturation fluctuations and droplet size, which explicitly takes into account the feedback of droplets on the flow through the condensation of water vapor onto droplets surface [1]. The model was shown to reproduce the second order turbulence statistics, including the droplet size/supersaturation correlation, obtained from direct numerical simulation of forced isotropic and homogeneous turbulence. We propose to further develop the model for cloud condensation nuclei (CCN), which represent an important ingredient in the formation of droplets in natural clouds and exhaust plumes but also in the formation of ice crystals from aircraft exhaust jets as in the case of condensation trails (contrails) [2]. The model has been reformulated to treat the additional terms arising in the stochastic condensational growth of droplets, namely the Kelvin effect (that scales as 1/r2) and solute effect (that scales as $1/r^4$). This was accomplished by expansion up to third order in the droplet size, so that corresponding evolution equations for the first three moments of the distribution (mean radius, area and volume) can be derived and integrated to mean transport equations. Comparison with recent DNS of turbulent condensation of CCN [3] as well as additional DNS are also planned. A generalization of the model to non-homogeneous cases such as jet turbulence (relevant to contrail formation) will be finally addressed.

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Modeling probability distributions of density in stratified turbulence, comparisons with grid turbulence experiment

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A phenomenological model for turbulent mixing in a stratified fluid is presented. While usual approaches deal with the mean and variance of fluctuating quantities, this model predicts (within the Boussinesq approximation) the whole probability distribution of density fluctuations. First the limiting case of a passive scalar is treated as a self-convolution process, following Venaille and Sommeria (Phys. Rev. Lett. 2008). This describes a cascade toward small scales by the effect of the local strain. The effect of stratification is then introduced by arguments of maximum entropy production, leading to a competition between eddy diffusivity and sedimentation by gravity (or buoyancy). In the absence of cascade and molecular diffusion, the system ends up in the state for which the fluid particles are sorted by density (state of minimal energy). Finally a term of kinetic energy is introduced, with dissipation and diffusion treated like in the k-epsilon model. The kinetic energy interacts with the fluctuating potential energy by the buoyancy flux. The behaviour of the resulting model will be discussed for different cases of vertical mixing in a stratified fluid, in particular a laboratory experiment producing mixing in a stratified fluid by a vertically oscillating grid. The statistics of density fluctuations is measured by Laser Induced Fluorescence. Refraction is suppressed by producing density stratification with a mixture of alcool and salt with constant refraction index. Density fluctuations at a given point are due to a mixture of wave oscillations and turbulence, while the proposed theory applies only to the turbulent component. The wave component is obtained by sorting the fluid particles along vertical lines. The fluctuations around this sorted state are considered as turbulent. Using this procedure a good agreement is finally obtained between the model and the experiments. This yields to promising perspectives for the modelling of tratified turbulence.

Atmospheric turbulence forecasting: a new approach based on Bayesian hierarchical modeling and the high-resolution simulations

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Meaningful atmospheric turbulence forecasts would be useful for many applications, ranging from aviation safety to free-space optical communication.

Nevertheless, numerical weather prediction models 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 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 specific dynamical 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 simulations. 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.

Generation of vortical structures and internal waves an impermeable solid in a continuously stratified fluid

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Nonuniform distribution of dissolved substances in the natural systems causes formation of a variety of fluid motions which are absent in homogeneous fluid. Among them there are so-called diffusion-induced flows on topography which lead to formation of intensive valley and mountain winds in a stably-stratified atmosphere and density flows in ocean. Diffusion-induced flows may cause a propulsion mechanism leading to self-movement of neutral buoyancy solids with special shape and influence essentially on a variety of physical processes, including the melting of icebergs, the migration of tectonic plates, mineral and plankton transport, as well. A moving object in a continuously stratified fluid causes formation of internal waves which are an important element in ocean and atmosphere dynamics. They form medium fine structure, transport energy and impulse to a great distance and intensify heat-mass transfer, as well. Breaking of internal waves leads to formation of turbulent spots which intensify mixing processes and substance transport in ocean and influence upon flight safety in atmosphere. As a basis of the investigation the set of fundamental equations is analyzed including the Navier-Stokes accounting for the gravity in the Boussinesq approximation, the continuity and diffusion equations and the closing linearized state equation. The boundary conditions are no-slip for velocity components and no-flux for substance on the plate surface and attenuation of all perturbations at infinity. The flow around a sloping plate in a quiescent, stably-stratified fluid has a complicated structure including thin main jet flows along the both plate surfaces with adjacent backflows and a number of compensatory circulation cells. The plate edges serve as sources of dissipative-gravity waves or so-called horizontal streaky structures. Uniform movement of a plate along a sloping trajectory leads to generation of attached internal waves around the moving object and a complex system of vortex structures within its wake. The total values of drag and lift forces and moments depend essentially on trajectory slope angle and buoyancy frequency. The calculated flow patterns are compared with the results of exact solution of the analogous linearized problem and the schlieren images of stratified flows around both motionless and moving plates.

GEOPHYSICS and EARTH SCIENCE

Flow rate in tornado and tornado –'ghost'

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Usually tornado appears with "proboscis" formation. A "proboscis" is a cone-shaped formation, which comes down from a mother thunder cell and reaches the earth ground. This formation represents condensed water vapor. Vapor is condensed as a result of air cooling in the flow due to adiabatic expansion. If we neglect mixing and heat conductivity, then air flows in tornado can be considered adiabatic. For adiabatic stationary flows in the atmosphere one can write the Bernoulli equation analogue as

$$v^2 / 2 + P_0^{(1/\gamma)} \gamma P^{(\gamma-1)/\gamma} / (\rho_0 * \gamma - 1) = const \,.$$

This relationship allows one to introduce the concept of critical flow rate, with which water vapors begin to condensate and tornado "proboscis" is formed. It should be noted that tornado is formed at the latest stages of tornado formation when it has gain its destructive force but has not reached is critical velocity. Before it tornado remains invisible. Rooted out trees are consequences of such tornado "ghost", which has not reached its critical velocity and its "proboscis" is invisible. If to use experimental data on water vapors condensation from Ref. [1], then flow rates in the "proboscis" have a scale of 250 m/s, which is two times higher than the maximum level on the Fujita scale F6. Consequently, for adequate evaluation of flow rate in the "proboscis" it is necessary to perform experiments on investigation of kinetics of water vapor condensation. A facility represented the closed channel having the form of a parallelepiped with a working volume of 3000 cm^3 was filled with compressed air up to pressures of 2-1.3 bar. The presence of water in the working volume helped to reach water vapor saturation. After a membrane was broken pressure in the volume has fallen to the level of atmospheric. The initial temperature of the working gas was 24 °C. A rarefaction wave going through the working volume adiabatically expanded the working gas, thus providing conditions for condensation. The condensation process was recorded using a LED laser and a photoresistor. As more water drops appear in the working volume the rate of flow against the photoresistor decreases. We recorded a condensation delay and a front width. The data allow us to construct an experimental model of condensation kinetics, which is necessary for mathematical simulation of fast atmospheric processes including tornado.

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There is no responsibility of Coriolis force

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In 1962 there appeared the publication by the two classics of hydrodynamics, Batchelor and Gill [1] “Instability of axially-symmetrical flows”. The authors discovered instability of helical perturbations in axially-symmetrical flows. It was shown that cylindrical tangential rupture is unstable relatively small perturbations same as plane tangential rupture is. Waves winding along the surface of the cylindrical rupture have the largest increment. For a long time it has been considered that these perturbations have zero angular momentum. In this work it is shown that helical perturbations spin up the flow and retain total zero angular momentum, but they violate the Thomson circulation theorem. Specific flows related to instability result in formation of two contours with non-zero circulation from one contour with zero circulation. Consequently the reason for formation of a whirlpool in a bath and tornados is helical perturbations rather than Coriolis force, which normally has been considered to be responsible for it. Helical perturbations at water outflow from a bath [3]. The brightest example of the role of helical perturbations is illustrated in [2], which refers to simulation of screech-tone mechanism generation. A screech-tone is a basic tone appearing with the operation of a jet engine. Its intensity is by 40% higher than the rest of a background. The 3-D calculation provides the pressure distribution in a supersonic flow.

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Lithospheric-Plume interaction beneath Mt. Cameroon volcano, West Africa

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Precise measurements of 238U-230Th-226Ra disequilibria in lavas erupted within the last 100 yr on Mt. Cameroon are presented, together with major and trace elements, and Sr-Nd-Pb isotope ratios, to unravel the source and processes of basaltic magmatism at intraplate tectonic settings. All samples possess 238U-230Th-226Ra disequilibria with 230Th (18-24%) and 226Ra (9-21%) excesses, and there exists a positive correlation in a (226Ra/230Th)-(230Th/238U) diagram. The extent of 238 U-230Th-226Ra disequilibria is markedly different in lavas of individual eruption ages, although the (230Th/232Th) ratio is constant irrespective of eruption age. When U-series results are combined with Pb isotope ratios, negative correlations are observed in the (230Th/238U)-(206Pb/204Pb) and (226Ra/230Th)-(206Pb/204Pb) diagrams. Shallow magma chamber processes like magma mixing, fractional crystallization and wall rock assimilation do not account for the correlations. Crustal contamination is not the cause of the observed isotopic variations because continental crust is considered to have extremely different Pb isotope compositions and U/Th ratios. Melting of a chemically heterogeneous mantle might explain the Mt. Cameroon data, but dynamic melting under conditions of high DU and DU/DTh, long magma ascent time, or disequilibrium mineral/melt partitioning, is required. The most plausible scenario to produce the geochemical characteristics of Mt. Cameroon samples is the interaction of melt derived from the asthenospheric mantle with overlying sub-continental lithospheric mantle which has elevated U/Pb (>0.75) and Pb isotope ratios (206Pb/204Pb > 20.47) due to late Mesozoic metasomatism.

Parameterization of eddies in a simple model of the extratropical tropospheric circulation

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How does the statistically steady state, or `climate', of a simple model of an extratropical tropospheric circulation depend on its controlling parameters, such as the degree of instability of the radiative equilibrium jet, the width of the unstable baroclinic zone, the rate of radiative relaxation and the strength of surface friction? The answer to these questions requires a `turbulent closure' or parameterization that

relates eddy fluxes to the mean climate. A long-standing suggestion for such a closure is to represent eddy fluxes by a downgradient diffusivity acting on the potential vorticity field. Analysis of the momentum and energy budgets for such a closure, however, reveals that care must be taken with this approach. A spatially homogeneous diffusivity, for example, is highly unlikely to conserve total zonal momentum - a global invariant for the system. A new variational principle to parameterize the eddy fluxes is suggested. It based on the downgradient diffusion of potential vorticity but leads naturally to a spatially inhomogeneous diffusivity profile. Momentum conservation and a physically realizable energy budget are enforced using Lagrange multipliers. The new parameterization is used to predict the `climate' of a simple model across a range of parameter settings. The results are compared with numerical simulations and a detailed assessment of the parameterization is given.

An analytical theory of the buoyancy - Kolmogorov subrange transition in turbulent flows with stable stratification

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The buoyancy subrange of stably stratified turbulence is defined as an intermediate range of scales larger than those in the Kolmogorov inertial subrange. This subrange encompasses the crossover from internal gravity waves to small-scale turbulence. The energy exchange between the waves and turbulence is communicated across this subrange. At the same time, it features progressive anisotropisation of flow characteristics on increasing spatial scales. Despite many observational and computational studies of the buoyancy subrange, its theoretical understanding has been lagging. We present an investigation of the buoyancy subrange using the quasi-normal scale elimination (QNSE) theory of turbulence. This spectral theory employs a recursive procedure of small-scale modes elimination based upon a quasi-normal mapping of the velocity and temperature fields using the Langevin equations. In the limit of weak stable stratification, the theory becomes completely analytical and yields simple expressions for horizontal and vertical eddy viscosities and eddy diffusivities. In addition, the theory provides expressions for various one-dimensional spectra that quantify turbulence anisotropization. The theory reveals how the dispersion relation for internal gravity waves is modified by turbulence thus illuminating some unique features of the waves. Predictions of the QNSE theory for the buoyancy subrange are shown to agree well with various data.

Generation of internal solitary waves in an oceanic pycnocline

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Internal gravity waves are due to the restoring force of buoyancy and, since gravity has a fixed direction, are anisotropic waves. Internal gravity waves transport the momentum of their source over long distance and may lead to significant wind acceleration or to long-range mass transport through momentum deposition when they break. In the ocean, the main sources of internal gravity waves are the wind and the tide, the waves being referred to as the internal tide in the latter case. In this talk, we focus on a mechanism through which the internal tide transfers energy to internal solitary waves, which are smaller scale waves. Oceanic observations have indeed provided evidence of the generation of internal solitary waves due to an internal tidal beam impinging from below on a seasonal pycnocline (i.e. a sharp density interface). Here we present the first direct numerical simulations of such a generation process with a fully nonlinear non-hydrostatic model (the MITgcm) for an idealised two-dimensional configuration.

For this purpose, an internal tide beam is forced at a lateral boundary of the domain in a constantly stratified fluid and propagates upwards toward the pycnocline surmounted by a thin layer of homogeneous fluid. We shall show that the impinging of the wave beam on the pycnocline generates a quasi-linear internal wave, which becomes trapped in the pycnocline close to the beam impact. For a mode-n wave to be generated in the pycnocline, the horizontal phase speed of the beam has to match the phase velocity of that mode, implying that the forcing mechanism is resonance. This mode next evolves into an internal solitary wave. We shall provide examples of internal solitary waves trapped in the pycnocline as first, second and third modes by using this phase speed matching condition. Energy transfer from the wave beam to an excited mode will be quantified to estimate the importance of this process in internal tide dissipation in the ocean.

A diagnostic for evaluating the representation of turbulence in atmospheric models at the kilometric scale

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Turbulence is well represented at meshes coarser than 2 km by meso-scale models for which the turbulence is entirely subgrid and at very high resolutions (10 to 100 m) by LES models for which turbulence is mainly resolved. However we do not know which part of the turbulence should be resolved and which part of it should be parameterized when a model runs at kilometric scales, the so-called 'Terra Incognita' from Wyngaard (2004). Thanks to increasing computational resources, in a near future, limited area NWP models will reach grid sizes on the order on 1 km or even 500 m. The aim of this research work is to develop a parameterization which provides adequate turbulence to these new-generation, high-resolution models. At first, this study describes a new diagnostic based on LES, which clarifies which part of turbulence should be parameterized at kilometric scales. The LES reference is a precious tool for quantifying the errors made by atmospheric models when running at kilometric scales. These errors are quantified for a state-of-the-art meso-scale model with several turbulence mixing options: a K-gradient scheme or an EDMF approach (K-gradient with a mass-flux scheme). K-gradient turbulence schemes are unable to reproduce the counter-gradient zone. In the gray-zone, this characteristic has a disastrous effect. As the instability is too large, the boundary layer is mixed by the dynamic of the model and the resolved mixing is too strong. The counter-gradient zone can be reproduced by adding a mass-flux scheme to the K-gradient turbulence scheme (Pergault et al. (2009)). However the mass-flux scheme in its original form only produced wholly subgrid thermals at a grid size for which boundary-layer thermals should be partly resolved. In this case, the subgrid mixing is too strong. The mass-flux scheme is adapted to produce a new parameterization which depends on the grid-size and is valid in the gray zone of turbulence.

The influence of turbulence on the equilibrium floc size and settling velocity of estuarine macroflocs

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Cohesive sediment occurs naturally in estuaries as suspensions of aggregates. The formation of aggregates is a result of the process of flocculation. Flocculation is a

dynamic process characterized by the antagonistic processes of aggregation and disaggregation. The process is driven by turbulent mixing where the turbulence characteristics and suspended sediment concentration influence the frequency and intensity of collisions between suspended particles and the breakup of aggregates. The potential for aggregating collisions is determined by the cohesive nature of the sediment and the ionic strength of the ambient fluid. This study investigates the response of the floc size distribution and settling velocity at quasi-steady equilibrium to changes in the shear rate, concentration and salinity. The drivers are varied in a controlled laboratory test where floc size distributions and settling velocities are determined using digital imaging techniques. The study also tests the hypothesis that maximum floc size is limited by the Kolmogorov microscale. Results of the investigation are validated in a nearby estuary where the natural turbulent spectrum and characteristic settling velocity are quantified by acoustic Doppler velocimetry. The results of the study have applications to the modelling of transport and deposition of fine suspended sediments where the drivers of flocculation constantly vary.

Bath-tube vortex attenuation at water level increase in the vessel

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Since 2008, the hydrodynamic laboratory of SarPhTI NRNU «MEPhI» has been conducting experimental research of the mechanisms of the bath-tube vortex formation and development as the water leaks out through the hole in the experimental vessel's bottom [1]. In the course of the researches it was found out that, as the level of water in the vessel is increasing due to the addition thereof from outside, the attenuation, up to the total disappearance, of the bath-tube vortex is observed [2]. The report set outs the results of the experimental research of the observable phenomenon. It is supposed that the observed bath-tube vortex' attenuating with the addition of water in the vessel is related to the break of balance of two counteracting forces: the pressure of the water column forcing to close the vortex and the centrifugal force of the water mass rotating around the bath-tube vortex.

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Wind-driven turbulence and sediment re-suspension in shallow lakes

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Wind induced turbidity within shallow lakes can greatly affect the biological functioning of a system in either a positive or negative manner. This research aims to understand and model the physical processes that cause sediment re-suspension. Lake St Lucia on the east coast of South Africa, an UNESCO World heritage site was used as a case study. A simple model has been developed which accounts for sediment re-suspension due to wind-driven waves and their associated bed shear stresses. The wave heights within a shallow lake such as St Lucia is controlled either by the fetch (for a large water depth), or the water depth (for a large fetch). When the wind is strong enough, the wind-driven turbulent mixing cause the water column to become fully mixed. When the wave-driven boundary layer becomes turbulent, sediment being entrained within the water column increases significantly. The model also accounts for the effects of temporal consolidation on the re-suspension of sediments by setting a time scale for the erosion processes. Further developments of the model will also consider the effect of turbulence on the flocculation and hence deposition of the sediment.

Anisotropic geostrophic turbulence and convection in the laboratory, and in planetary atmospheres and oceans

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Geostrophic turbulence may occur on a rapidly rotating sphere or (local tangent) beta plane and is well known as a context in which wave propagation effects lead to highly anisotropic nonlinear exchanges of energy and the spontaneous formation of zonal jets. This paradigm underlies current interpretations of the large-scale organization of the atmospheric circulations of the giant planets (Jupiter, Saturn, Uranus and Neptune) and (more controversially) in the world oceans. In this presentation, we discuss investigations of the behaviour of geostrophic turbulence on a topographic beta-plane (using a conically sloping bottom) in the laboratory over a wide range of conditions, using the 13 m diameter Coriolis platform in Grenoble,

France. Small-scale motions were driven via unstably stratified convection by heating from below, and led to the production of weak but persistent zonal jets through nonlinear eddy-zonal flow interactions. Results will be presented that explore the energetics and vorticity dynamics of the flows produced and their dependence on external parameters. We then place these results into a geophysical and astrophysical context with a discussion of their possible implications for our understanding of the zonally banded features on the gas giant planets and 'striations' observed in the oceans. Recent analyses of winds and currents in the atmospheres of Jupiter and Saturn are placing new constraints on how the observed jets are produced and maintained. But our evolving understanding of anisotropic geostrophic turbulence raises some new and important issues that will require further observations of these complex natural systems to resolve.

Large-eddy simulations of a turbulent Stokes-Ekman boundary layer

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Unsteady rotating turbulent boundary layers can be considered as prototypes of the tidal bottom boundary layer in the open ocean ([1], [2], [3]). Basically, these are oscillatory boundary layers subjected to rotation of the frame of reference. Considering an eastward-westward tidal driving flow in the streamwise direction, the Earth background rotation vector has two components: one is parallel to the wall-normal direction (WN), and the other is parallel to the spanwise direction (SP). In the present contribute, we discuss the main results of a series of resolved large-eddy simulations (i.e. the near-wall layer is directly resolved without the use of wall functions) of three different latitude cases: a fully WN-rotation polar case (PL), a mid-latitude case (ML) characterized by an equal contribute of WN and SP components, and a quasi-equatorial case (QE) where the SP component dominates over the WN one. First- and second-order statistics are also compared to the purely oscillating flow case without rotation (OF), that was widely studied in [4]. The PL case significantly differs from the other two: the WN rotation component develops a mean spanwise velocity and tends to suppress vertical fluctuations of velocity and to redistribute energy from the streamwise direction to the spanwise one. Such WN-related effects become weaker moving towards the Equator. On the other side, the SP rotation component, increasing with decreasing latitude, originates an asymmetry between the two semi-cycles of oscillation, particularly in the QE case. The analysis of the transport equations of the Reynolds stresses reveal the critical role played by the WN and SP rotation components on the turbulent field, with production and destruction terms not present in the OF case that interact each other and redistribute the turbulent energy in the three directions. These results are in agreement with previous literature (e.g. [5], [6]).

The nature of zonal jets in geostrophic turbulence

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We examine different regimes obtained in forced-dissipative geostrophic turbulence on a midlatitude beta-plane. The regimes are obtained under different values of two length scales, (i) the usual Rhines scale associated with the total energy, and (ii) a length scale derived from the energy input rate and the background gradient of potential vorticity. The number of jets obtained at equilibrium is broadly consistent with the Rhines scaling, whereas the sharpness of jets (suitably defined) depends on the second length scale. With strong forcing, regimes are characterized by zonal jets that remain indistinct, being continually disrupted by the energetic background turbulent flow, which contains strong eddy motions and coherent vortices. With small forcing, in contrast, zonal jets emerge with a clear potential vorticity staircase structure comprising near discontinuities in the zonal mean potential vorticity in the jet cores with perfectly mixed zones in between. The uniformity of the jet structure is found to depend on the mechanism for energy input, whether traditional narrow-band, random-phase spectral forcing or broad-band coherent physical space forcing, although the dependence of jet coherence on forcing strength is obtained in all cases. Further, with small forcing, measured energy input rates are in general found to be larger than would be predicted on the basis of isotropic arguments, indicating strong eddy-jet correlations at the scales of the forcing. Finally, extensions of the analysis to the case of finite Rossby deformation length and thermal-like energy dissipation, which is more effective at larger scales, will be discussed briefly. The introduction of an extra length scale greatly enhances the variety of flow regimes obtained, with jets typically becoming increasingly undular at small deformation length.

Inertia-gravity waves and deep-ocean mixing

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For the existing pattern of global oceanic circulation to exist there should be sufficiently strong turbulent mixing in the abyssal ocean. It is commonly believed that it is breaking of inertia-gravity internal waves which provides the required mixing. However this belief is not supported by understanding of why internal waves should break so intensely in the abyssal ocean. The specific physical mechanisms causing the breaking have not been identified and investigated. The lecture discusses the a very plausible mechanism leading to intense breaking of near inertial waves near the bottom of the ocean. The simultaneous account of both the horizontal component of the Earth rotation and its latitude dependence (the beta-effect) reveals the existence for near inertial waves of wide waveguides attached to the bottom. These waveguides are narrowing in the poleward direction. Near inertial waves propagating poleward get trapped in waveguides; in the process the waves are focussing more and more in the vertical direction, while simultaneously their group velocity tends to zero and wave induced vertical shear significantly increases. This results in developing of shear instability, and, hence, to wave breaking and local intensification of turbulent mixing in the abyssal ocean. It is showed that similarly to wind wave breaking on a beach the abyssal ocean always represents a surf zone for near inertial waves.

Turbulent models for stratified flows

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Turbulent flows in stratified flows are investigated from theoretical, experimental and numerical point of views. Experiments are developed at two setups - strtified chamber 7 m diameter and 5 m height filled by heavy Freon and air mixtures based gas of stable strratification and rotating tube where rotational flows simulate gravity stratification. Measuring diffrent order moments up to 6th have been developed and presented in different correlation function drawings. Numerical simulation of the lab experiments are provided by different methods. New turbulent models are proposed and used for comparison experiments and modelling.

A.T. Onufriev, R.A. Safarov, K.E. Son, E.E. Son, Semi-empirical models of turbulence. Theory and Experiment, Begell House, 2011, 358 pages.

Quasi-normal scale elimination theory of turbulence anizotropization by Coriolis force

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The understanding of the physics and transport properties of turbulent flows in systems with solid body rotation is hampered by interaction of anisotropic turbulence and inertial waves. We present theoretical results that advance our understanding of rotating turbulence and passive scalar diffusion in it by treating these phenomena within the quasi-normal scale elimination (QNSE) theory. Previous application of the theory to turbulent flows with stable stratification has demonstrated that QNSE is a powerful tool for studies of anisotropic flows with dispersive waves. The theory is capable of explicit accounting for the effects of anisotropy and waves yet its analytical derivations can be carried out to the final results. For flows affected by Coriolis force we derive expressions for the eddy viscosities and eddy diffusivities in the directions parallel and normal to the axis of rotation. The theory sheds light on anisotropization of homogeneous turbulence by solid body rotation, clarifies various aspects of the interaction between turbulence and inertial waves, and yields analytical expressions for anisotropic one-dimensional spectra of kinetic energy and temperature variance. In particular, the theory predicts a modification of the Kolmogorov k-5/3 spectrum by rotation. The results can be used to derive subgrid-scale parameterizations for large eddy simulations and Reynolds stress models.

Energetics, mixing efficiency, and non-viscous dissipation in turbulent stratified fluids

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Turbulent mixing in stratified fluids is a key process that is central to the understanding of the atmospheric and oceanic circulations. Yet, even some of its most basic physical features, such as its energetics, remain poorly understood and much debated. For instance, it has generally been assumed until recently that the conversion of internal energy into geopotential energy, which is known to occur in a laminar fluid, is irrelevant to understanding the rapid rate of change of geopotential energy that occur in turbulent fluids. In that case, it is usually thought that such rapid changes occur at the expenses of turbulent kinetic energy (as in the case of an unstable parallel shear flow) or available potential energy (as in the case of Rayeigh-Taylor instability).

The concept of mixing efficiency thus measures the relative fraction of kinetic energy or available potential energy that contributes to the mixing versus that being irreversibly dissipated by viscous processes. The purpose of this talk will be to show that such a view is inconsistent with the energetics of the fully compressible Navier-Stokes equations, and that in fact, the irreversible changes of geopotential energy can only be explained physically as due to an enhanced conversion of internal energy into geopotential energy. This result has many important consequences. For instance, it implies that molecular diffusion may significantly contribute to the non-viscous dissipation of kinetic energy into heat, which in turn requires adopting a completely different perspective on the concept of mixing efficiency, for which a new definition will be proposed. It also implies that compressible effects are also significantly more important than previously thought, requiring a re-examination of how such effects are represented in the compressible Boussinesq approximation, which has served as the main framework to study turbulent stratified fluids so far.

COMBUSTION

Large eddy simulations for turbulent mixing and combustion

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Mixing zone boundaries have been successfully modeled for classical hydro instabilities such as the Rayleigh-Taylor Instability, at the level of comparison to experimental data. Progress with validation and verification (V&V) and uncertainty quantification (UQ) issues will be presented. Turning to microscopic measures of mixing and combustion, we start with a reformulation of the notion of large eddy simulations (LES) convergence, in terms of limits of probability density functions and Young measures. Mathematical theory and assumptions regarding K41 Komogorov turbulence provide guidance. The same goals of V&V/UQ apply. Standard function space norms can be applied to the distribution function (indefinite integral) of the probability density functions; convergence results will be presented. A more classical notion of convergence, to a weak solution, would represent the mean of the Young's measure; in contrast, the Young's measure contains important fluctuation information. As a result, nonlinear functions of the solution, such as chemical reaction terms, can be evaluated without use of subgrid models. In this manner, we propose large eddy simulations with finite rate chemistry, in a flow regime for which the Kolmogorov scale is much finer than the steepest gradient in the internal structure of the flame. In this framework, the heat release is also a Young measure. The needed ensembles to realize the Young measure numerically are generated by sampling from a space time region about the x, y, z, t point of convergence. This coursening of the mesh resolution to obtain a Young measure can be compared to the conventional coarsening of resolution to define a filter and the filtered equations. Recent results of the author and colleagues will be presented.

Flame acceleration and onset of detonation in channels

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The flame acceleration in channels of different widths and lengths and onset of detonation in hydrogen/oxygen mixture are studied using two-dimensional high resolution simulations with a detailed chemical kinetic model. For "long" channels it is shown that the compression waves produced by the accelerating flame form the shock close to the flame, the unreacted mixture of increased density enters the flame producing a high pressure pulse, which enhances reaction rate and the heat release in the reaction zone with a positive feedback coupling between the pressure pulse and the reaction rate. As a result the peak of the pressure pulse grows exponentially, and after the flame front achieves locally supersonic speed the pressure pulse occurs to be localized within the reaction zone. Later issue causes super-high rate of the flame acceleration and pressure pulse increase directly in the reaction zone. Such a coupling of the supersonic flame and the pressure pulse transforms the obtained complex (flame front – pressure pulse at the flame front – shock ahead the flame front) into detonation wave. The proposed new mechanism of transition to detonation conditioned only by intrinsic features of flame evolution in channel and does not connected with the emerging of external sources of detonation like “hot spots” or like. For shorter channels the flame propagates in conditions of upwind flows generated behind compression waves and weak shocks generated by the flame and then reflected from the end-wall. Depending on “short” channel’ length such an impact on the flame dynamics can cause even prevention of the detonation formation. However further interaction with the reflected shocks can trigger a new regime of flame acceleration and transition to detonation. Results of the high resolution simulations are fully consistent with experimental studies of deflagration-to-detonation transtion (DDT) in hydrogen/oxygen gaseous mixtures.

Vortex dynamics in two-dimensional variable-density turbulent mixing

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The instability of a density front perpendicular to gravity or to a shock-induced acceleration triggers the growth of a mixing layer with implications for geophysical and astrophysical flows, or applications in inertial confinement fusion. Premixed combustion may also involve fuel-oxidizer gaseous pairs that may exhibit a large density contrast, such as the hydrogen-air pair. The mixing progress between the two species determines the features of the flow and sometimes sets the efficiency of the associated system. In such flows, the misalignment between the acceleration and the density gradient yields a baroclinic vorticity source associated with any loss or initial offset from barotropy. At large Atwood numbers, the baroclinic torque not only results from buoyancy or initial shock-induced acceleration but also from the flow acceleration itself, the Boussinesq approximation does not hold and the flow is termed a variable-density flow. We address the specific features of turbulent mixing beyond the Boussinesq approximation in the inertial regime, i.e. with no buoyancy effects. This is first illustrated from the instability of an isolated vortex with a heavy core and from the merger of a corotating vortex pair. Then, we turn towards a more complex situation of a two-dimensional decaying turbulence initially offset from barotropy. The baroclinic sources and sinks of vorticity, located on density fronts, bias the evolution of the vortex population and of the mixing progress compared to a passive scalar reference case. The scenario is twofold with a primary increase in vortex number and decrease in vortex radius, followed by opposite standard trends. Vortices carrying high-density fluid break-up into filamentary debris subjected to rapid mass-diffusion. Meanwhile, robust vortices merge and trap almost unmixed low-density fluid. Both effects yield a large negative skewness of the density PDF, meaning uneven mixing and mass segregation by vorticity.

Numerical simulation of the hot spot growth in detonation with regard to the turbulent mechanism of energy transfer

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The concept of hot spots (HS) and the hot spot mechanism of detonation initiation are the fundamental concepts in the modern physics of detonation. The initiation of heterogeneous explosives can be conventionally divided into the following stages: 1) Generation of hot spots. 2) Growth of hot spots. 3) Interaction of hot spots and rapid merging. The hot spot growth rate should be not less than 50¸100 m/s. The ordinary laminar burning velocity is below 1 m/s, but it is not enough for detonation. Thus, there is an issue concerning the mechanism of hot spot growth in heterogeneous explosives. According to the hypothesis of the paper, turbulence governs the energy transfer process. Because of a high rate of turbulent mixing, turbulent flows have an excessive heat transfer capability and accelerate the spread of chemical reactions. To give a description of the physical process, 2D and 3D computations of burning and hot spot growth with regard to heat transfer and turbulence were carried out. 2D computations were carried out using κ-e model. 3D computations were carried out using the direct numerical simulation. The numerical simulation allowed calculating the hot spot growth rate (it is about 100-200 m/s) and proving the hypothesis that turbulence in the zone of chemical reaction is a governing factor under the material transport conditions, which should be necessarily taken into consideration.

Mechanisms of detonation formation

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There are numerous variants of detonation initiation in gaseous combustible mixtures. The most interesting mechanisms of detonation initiation are deflagration-to-detonation transition (DDT) and detonation ignition by the temperature or concentration non-uniformities presenting in the volume filled with combustible mixture. There were a lot of attempts to connect the phenomena of DDT with the Zeldovich's gradient mechanism however there were no clear understanding of the problem. This work represents results of the series of numerical simulations of both problems in different setups. To achieve comprehensive examination of such complex processes we used full gasdynamic model of viscous heat-conductive compressible multicomponent mixture of hydrogen with oxygen. The equations of state for real multicomponent mixture and detailed chemical kinetics scheme of nine equations were used. Such approach allows us to investigate the qualitative and quantitative differences in the detonation ignition process between detailed chemical kinetics and the predictions from one-step models. The obtained results showed that in case of detailed chemical kinetics model the steepest gradient sufficient for detonation initiation is at least one order of magnitude shallower compared to that predicted from a one-step Arrhenius model for a highly reactive mixture (H2/O2). The obtained result makes questionable applicability of the gradient mechanism as a mechanism of the DDT in channels. On the other hand detailed computational approach allows us to describe DDT phenomena in channels filled with highly reactive H2/O2 mixture. We proposed model of detonation formation out from the accelerated flame coupled with the pressure pulse arisen on the flame surface only due to the features of flame acceleration in channel.

Transformation of flying cylindrical water shell model

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The hydrodynamic laboratory of SarPhTI NRNU "MEPhI develops the technology of suppression of large-scale (wood-riding) fires by water shells accelerated by the pressure of the products of burning or/and the detonation of the combustible gas mix. The report presents the results of the first stage of work -- the experimental research of the process of deformation (under the influence of

aerodynamic forces) and disintegration (owing to the development of hydrodynamic instabilities) of a model of a cylindrical water shell flying in the air. The flight of the shell's model was its free falling from the height of up to 10 meters. The flow was recorded by photocamera Casio Exilim EX-F1 in the mode of video shooting with a speed up to 1,200 shots per second. In the experiments, the diameter and length of the shell's model were varied.

Factorized cumulant expansion approximation method for turbulence with reacting and mixing chemical elements of type A+B->Product

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The Lewis-Kraichnan space-time version of Hopf functional formalism is considered for the investigation of turbulence with reacting and mixing chemical elements of type A + B -> Product. The equations of motion are written in Fourier space. We first define the characteristic functional (or the moments generating functional) for the joint probability distribution of the velocity vector of the flow field and the reactants' concentration scalar fields and translate the equations of motion in terms of the differential equations for the characteristic functional. These differential equations for the characteristic functional are further written in terms of the second characteristic functional (or the cumulant generating functional).This helps us in obtaining the equations for various order cumulants. We notice from these equations for cumulants the characteristic difficulty of the theory of turbulence that the (n+1)th order cumulant C(n+1) occurs in the equation for the dynamics of nth order cumulant Cn. We use the Factorized Cumulant Expansion Approximation Method to obtain a closed set of equations for cumulants. Under this approximation an arbitrary nth order cumulant Cn is expressed in terms the lower order cumulants C(2) , C(3) and C(n-1) and thus we obtain a closed but untruncated system of equations for the cumulants. On using the factorised fourth-cumulant approximation a closed set of equations for the reactants' energy spectrum functions and the reactants' energy transfer functions are derived. These equations are solved numerically and the similarity laws of the solutions are derived analytically. The statistical quantities such as the reactants' energy, reactants' enstrophy, reactants' scale of segregations etc. are calculated numerically and the statistical laws of these quantities are discussed.

Properties of micromixing model on an averaged chemical reaction in a turbulent flow

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The problem on mixing with chemical reacting in the homogeneous turbulent flow was studied. A mixing model was formulated by the method of statistical moments. An unknown averaged chemical reaction rate was determined using both the concepts of mixture fraction f and progress variable Z and the PDF method, and was expressed through the conditional statistical moment of Z and the mixture fraction PDF. The analyzed models for mixing time scale identically describe the segregation intensity for the initial time. At the intermediate and final mixing stages, a difference lies in the results by the model with a constant time scale ratio R, by the algebraic model considering the R time variation with decreasing Ret, and by the transfer equation for mixing time scale. Based on the numerical results obtained the multi-zone mixture fraction PDF model, the IEM/LSME, and Langevin micromixing models adopted in the equation for such a PDF are compared. For the IEM/LSME model, the time PDF variation remains invariable. This fact is untrue proceeding from the physical behavior of mixing. For the Langevin model, the PDF describes mixing from a segregated to a sufficiently mixed state of mixture. At the same time, its behavior is two-mode at the intermediate mixing stages and points to the presence of different-concentration flow regions. The same results are obtained by the multi-zone PDF. For all PDF models, the averaged progress variable is an increasing time function. As compared to the multi-zone PDF results, others show higher values of Z over the entire time range and at all Damköhler numbers. Such a difference is made by the approximations adopted for the averaged chemical reaction rate, which should be further taken into account at the adequate modeling of mixing with chemical reacting in inhomogeneous turbulent flows.

Turbulent mixing in the plane liquid jet with the second-order chemical reaction

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The turbulent plane liquid jet with the second-order chemical reaction (A+B→R) is investigated experimentally. The reactants are 1-naphthol (A) and

diazotized sulfanilic acid (B), and the product is 4-(4'sulphophenylazo)-1-naphthol (R). In the experiment, the main stream contains the species B and the water solution of species A is issued into the main stream by the plane jet. Other non-reactive blue dyestuff (C: Acid Blue 9) is also added into the jet flow, and the concentration of species C can be considered to be the conserved scalar. The streamwise velocity and the concentrations of all species are measured simultaneously. The concentrations of species C and the product species R are directly measured by the optical fiber probe based on the light absorption spectrometric method, and the concentrations of species A and B are obtained from the conserved scalar theory. The streamwise velocity is measured by the I-type hot-film anemometer. In this study, the new combined probe which consists of the I-type hot-film probe and the optical fiber probe is developed. The experimental results show that near the jet exit the turbulent mass flux of species A becomes large and the one of species B becomes small by the chemical reaction. On the other hand, in other region of the jet, the effect of chemical reaction works in the opposite direction. Those effects can be explained on the basis of the mass conservation law and the nonlinear property of chemical reaction rate. It is also shown that the turbulent mass flux of the product species R has the negative value near the jet exit and the positive value in the other region. These results seem to be very useful for the modeling of reactive turbulent mass flux.

MATHEMATICAL ASPECTS of NON-EQUILIBRIUM DYNAMICS

Nonlinear evolution of Rayleigh-Taylor instability in a finite domain

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For the first time the theoretical analysis was developed to systematically study the late-time evolution of Rayleigh-Taylor instability in a domain of a finite size. Fluids may have similar or contrasting densities, acceleration can be sustained or time-dependent, and the flow is periodic in the plane normal to direction of acceleration. The concepts of theory of discrete groups are applied to capture properties of the interfacial dynamics. Asymptotic nonlinear solutions are found, and their structure and stability are investigated. Flow evolution is described far from and near the outside boundaries, and the influence of the height of the domain on diagnostic parameters of the flow is identified. In particular, it is shown that in a large domain of a finite size, the flow is slower when compared to spatially extended cases. Our theoretical results resolve the long-standing discrepancy between the approaches of Garabedian 1957 and Birkhoff 1957 and forgo common beliefs on applicability of ad-hoc approaches for problem solution, including Layzer-type or drag model. The outcomes of the theoretical analysis for numerical modeling of Rayleigh-Taylor instability and for design of experiments are discussed.

The work is supported by the US National Science Foundation and by the US Department of Energy.

3D Euler equations and ideal MHD mapped to regular systems: probing the finite-time blowup hypothesis

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We prove by an explicit construction that solutions to incompressible 3D Euler equations defined in the periodic cube can be mapped bijectively to a new system of equations whose solutions are globally regular. We establish that the usual Beale-Kato-Majda criterion for finite-time singularity (or blowup) of a solution to the 3D Euler system is equivalent to a condition on the corresponding regular solution of the new system. In the hypothetical case of Euler finite-time singularity, we provide an explicit formula for the blowup time in terms of the regular solution of the new system. The new system is amenable to being integrated numerically using similar methods as in Euler equations. We propose a method to simulate numerically the new regular system and describe how to use this to draw robust and reliable conclusions on the finite-time singularity problem of Euler equations, based on the conservation of quantities directly related to energy and circulation. The method of mapping to a regular system can be extended to any fluid equation that admits a Beale-Kato-Majda type of theorem, e.g. 3D Navier-Stokes, 2D and 3D magnetohydrodynamics, and 1D inviscid Burgers. We discuss briefly the case of 2D ideal magnetohydrodynamics. In order to illustrate the usefulness of the mapping, we provide a thorough comparison of the analytical solution versus the numerical solution in the case of 1D inviscid Burgers equation.

Hamiltonian bifurcation theory for a rotating flow subject to elliptic straining field

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A weakly nonlinear stability theory is developed for a rotating flow confined in a cylinder of elliptic cross-section. An axisymmetric rotating flow supports a family of three-dimensional neutrally stable oscillations called the Kelvin waves. The straining field associated with elliptic deformation of the cross-section breaks the O(2)-symmetry of the basic flow and amplifies a pair of Kelvin waves whose azimuthal wavenumbers are separated by 2, being referred to as the Moore-Saffman-Tsai-Widnall (MSTW) instability. When proceeding to nonlinear stage, a difficulty lies in deriving the mean flow induced by nonlinear interaction of the Kelvin waves, which is unattainable within the traditional Eulerian framework. A steady Euler flow of an inviscid incompressible fluid is characterized as an extremum of the total kinetic energy (the Hamiltonian) with respect to disturbances constrained to an isovortical sheet (the coadjoint orbits). An isovortical perturbation preserves vortex-line topology and is expressible only by the Lagrangian variables. The criticality in the Hamiltonian facilitates the calculation of the wave-induced mean flow, of second order in amplitude. With the mean flow at hand, we can build the weakly nonlinear amplitude equations to third order not only for the Hamiltonian pitchfork bifurcation caused by a resonance between the stationary left- and right-handed helical waves but for the Hamiltonian Hopf bifurcation caused by nonstationary resonances. The integrals of the amplitude equations are identified with the wave energy and the wave-induced mean flow, which has a link with the Noether currents associated the steadiness and

the translation symmetry of the basic flow. The amplitude equations tell that MSTW modes ultimately saturate. A discussion is made of the three-wave resonance that brings in the secondary instability of a MSTW mode.

Stretching and folding in stratified Euler/Navier-Stokes equations

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Stretching and folding (SF) are major features of mixing problems. Diagnostics of SF in fluid flows are discussed theoretically, based on the dynamics of the gradient of potential vorticity q=$\nabla\theta$ associated with solutions of the 3D Euler and Navier-Stokes equations. The vector $\nabla q\times\nabla\theta$ satisfies the same type of SF equation as that for the vorticity field in the incompressible Euler equations , Gibbon & Holm, J. Phys A, **43**, (2010) 17200. The quantity θ may be chosen, for instance, as the potential temperature for the stratified, rotating Euler & Navier-Stokes equations. Another example of a SF flow-diagnostic concerns the evolution of the Lamb vector, which is the nonlinearity for the Euler equations excluding the pressure. It turns out to possess similar SF properties to that of the $\nabla q\times\nabla\theta$ vector.

The lack of gas dynamic analogue for shallow water flows

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The well-known classical shallow water equations describing an incompressible heavy fluid flow with a free surface on flat plate coincide with those of a polytrophic gas with the specific heat ratio equals to two. This analogy is widely used in studies of basic problem of shallow flows on step by assuming stationary flow zone in step vicinity. Indeed, the shallow-water equations are an approximation of the Euler equations for invicsid fluid with a free surface in the gravity field and hence, inherit all restrictions adopted in deriving these initial equations, in particular the condition of simple connectedness of the region occupied by the fluid in the neighborhood of the step. The problem of a steady-state fluid flow over a step in the shallow-water approximation is considered. Taking into account this condition made it possible to find the new steady-state flow regimes. The limitations on the possible flows depending on the flow direction are considered. All flow regimes characterized by the ratio of the fluid depth to the step height and the flow direction is found. Analytical expressions for the limitations imposed on the hydrodynamic flow parameters are obtained for each flow regime. It is shown non-uniqueness of solutions to stationary shallow water equations on step. Mathematical and physical natures of non-uniqueness are discussed. Initial discontinuity decay problem (Riemann Problem) for nonstationary shallow water equations on step is considered. We sagest novel quasi-two-layer model for shallow flows in the step vicinity, namely, by effective subdividing shallow flows in sub layers and subsequent consideration of classical equations on flat plate. The suggested model reproduces clearly the diversity of flow patterns around the step. Results obtained confirmed selfsimilar properties of solutions. It is shown the stationary property of flows bellow step boundary. Computations based on our model proved all possible analytical patterns of the Riemann Problem solutions. The numerical method for study of hydrodynamic flows over an arbitrary bed profile in the presence of external forces is proposed. This method takes into account the external force effect. It uses the quasi-two-layer model of hydrodynamic flows over a stepwise boundary with consideration of features of the flow near the step. A distinctive feature of the proposed method is the consideration of the properties of the process of the waterfall, namely the fluid flow on the step in which the fluid does not wet part of the vertical wall of the step. The presence of dry zones in the vertical part of the step indicates violation of the conditions of hydrostatic flow. The quasi-two-layer approach allows to determine the size of the dry zone of the vertical component of the step. Consequently it gives an opportunity to figure out the amount of kinetic energy dissipation. There are performed the numerical simulations based on the proposed algorithm of various physical phenomena, such as a breakdown of the rectangular fluid column over an inclined plane, the large-scale motion of fluid in the gravitational field in the presence of Coriolis force over an underlying mountain-like surface. Computations have been made for two dimensional dam-break problem on slope precisely conform to laboratory experiments. Interaction of the Tsunami wave with the shore line including an obstacle has been simulated to demonstrate the effectiveness of the developed algorithm in domains including partly flooded and dry regions.

Statistics of multiple filamentation of strong optical turbulence

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We consider the statistics of light amplitude fluctuations for the propagation of a laser beam subjected to multiple filamentation in Kerr media with both linear and

nonlinear dissipation. Dissipation arrests the catastrophic collapse of filaments, causing their disintegration into almost linear waves. These waves form a nearly-Gaussian random field which seeds new filaments. The correlation length of that field is determined by the scale of the modulational instability. The rare optimal fluctuations on that scale seed new collapsing filaments. For small amplitudes the probability density function (PDF) of light amplitude is close to Gaussian, while for large amplitudes the PDF has a long power-like tail which corresponds to strong non-Gaussian fluctuations, i.e. intermittency of strong optical turbulence. This tail is determined by the universal form of near singular filaments and the PDF for the maximum amplitudes of the filaments.

Investigation of magnetohydrodynamic turbulence described by the space-time functional formalism

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The Lewis-Kraichnan space-time version of the Hopf functional formalism is considered. The Magnetohydrodynamic turbulence equation for an incompressible conducting field are written in terms of the characteristic functional for joint probability distribution of the velocity field and magnetic field .These equations are transformed into the Fourier space and the resulting equations are written in terms of the second characteristic functional .These equations describe the dynamics of various order cumulants which reveal the characteristic difficulty of the turbulence theory (i.e. (n+1)th order cumulant occurs in the equation for the dynamics of nth order cumulant). In order to obtain a closed set of equations for cumulants a method of multiple-scale-cumulant expansion is employed and equations describing the dynamics of kinetic energy spectrum and magnetic energy spectrum are derived.These equations are integrated numerically and the statistical quantities describing the magnetohydrodynamic turbulence such as kinetic energy, magnetic energy, enstrophies are evaluated. The empirical relation for the ratio of kinetic energy and magnetic energy is derived.

Transport statistics in stirred point-vortex flows

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A simple randomly stirred two-dimensional point vortex flow shows Lagrangian statistical properties remarkably similar to those observed in homogeneous three-dimensional turbulence. This results because the stirring provides a vortex stretching mechanism, and although the orientations of the vortex filaments are artificially confined to be perpendicular to the plane the restriction is only significant to the degree that non-nearest vortex-neighbor interactions are important to the flow statistics. We describe the flow setup, the unusual kinetic energy spectrum that results, and the one and two point Lagrangian statistics observed. We examine the origin of these statistics using both the results of the n-body point-vortex simulations and analytic statistical analysis of randomly distributed vortices. We conclude that the single point Lagrangian velocity distribution is be best understood in terms of a series of vortex trapping events which are statistically equivalent to a random walk in velocity and that at smallest temporal increment Lagrangian accelerations are dominated, not by the motion of the Lagrangian tracers, but by vorticity reconfiguration within the domain. The two-pont statistics also clearly indicate the importance of structures within the flow. Pure scaling laws are only subdominant. The average rate or separation is dominated by a wide distribution of "delay times," the duration for which particle pairs remain together before their separation increases significantly. The observed pair dispersion behavior is best modeled as an average over separations that individually follow the Richardson-Obukhov scaling, but each only after a fluctuating time delay, where that time is distributed uniformly.

Mathematical analysis of Floquet problem as they arise in pipe/channel flows

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Stability analysis of oscillatory or periodic states involve Floquet analysis. Almost all analytic work thus far for nontrivial problems involve small amplitude oscillations; we compliment the set of existing methods by new techniques involving functional analysis and rigorous asymptotics that address what happens for arbitrary amplitude oscillation. While this was originally developed in 3-D schroedinger equation in the context of ionization of hydrogen atom, similar theory is relevant to

study of hydrodynamic stability of channel and pipe flows; and for large Reynolds number, this is relevant to transition to turbulence.

Theory of wind-driven sea

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Huge amount of experimental data on wind-driven sea, accumulated during decades of observations and measurements by physical oceanographers, can be satisfactory explained in frame of relatively simple theory. Spectra of gravity waves composing the wind-driven sea and their temporal and spatial evolution are determined by competition of three major effects: the four-wave resonant interaction that provides energy exchange between modes of different scales, the input of energy and momentum from wind, and the dissipation of energy and momentum due to wave breaking. For relatively long waves in the spectral range between the frequency of the spectral peak ω_p and some critical frequency $\omega_c > 3\ \omega_p$ (this is the energy-containing range, accumulating 90% of wave energy) the weakly nonlinear resonant interactions are dominating. In this range, the shape of spectra together with evolution of the spectral peak obeys to almost conservative Hasselmann equation and demonstrates tendency to formation of its self-similar solutions. The weak-turbulent theory breaks at $\omega \sim \omega_*$ where the local steepness reaches its critical value $\mu^2 = 0.01$. In the 'Phillips range' $\omega > \omega_*$ the spectrum is defined by competition of all three major effects; the result of this competition is the formation of universal Phillips spectrum $I_{\omega*} \sim \omega^{-5}$. In this range, statistical properties of wind-driven sea remain a subject for further investigation.

STOCHASTIC PROCESSES and PROBABILISTIC DESCRIPTION

Intermittency-like transport in porous media

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We present a numerical study of the Lagrangian acceleration statistics in porous media. Our high resolution pore scale simulations show that the velocity fluctuations follow a non-Gaussian distribution. Very low velocities are associated with recirculation zones and no-slip conditions close to grain walls. The Lagrangian accelerations display an intermittent-like behavior, with power law correlated amplitudes. The probability density functions of the velocity time increments are characterized by exponential tails that evolve slowly towards Gaussian for larger lag times. Although of very different nature, transport in porous media is found to share several characteristics of intermitency with transport in turbulent flows. Analyzing the pore scale statistical properties of the flow, we show the spatial Markovian, and temporal non Markovian, nature of the Lagrangian velocity field. Therefore, an upscaled model can be defined as a correlated Continuous Time Random Walk (Le Borgne et al. PRL 2008). This accounts for both non Gaussian velocity distribution and long range temporal correlation property. We investigate the ability of this effective model to represent correctly these intermittency properties and their consequences on mixing and reaction kinetics.

Direct numerical simulations of a spatially developing turbulent mixing layer

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A direct numerical simulation (DNS) of a spatially developing turbulent mixing layer has been performed in a computational domain discretized with 3072 × 940 × 1024 = 3 Billion grid points. A Kelvin-Helmholtz instability develops starting

from a laminar hyperbolic tangent profile perturbed with low amplitude white noise. In the fully developed region, the flow achieves a turbulent Reynolds number $Re\lambda$ = 250; the Reynolds number is high enough to study small scale flow features and compare the DNS statistics to other flow configurations, such as homogeneous isotropic turbulence, homogeneous shear and wall turbulence. The shear layer starts from a perturbed laminar profile and, after a region characterized by strong vortex pairings, achieves a self-similar behavior. The characteristics of the self-similar state support the conclusion that the asymptotic behavior of the mixing layer is very similar to other simulations [1] and experiments [2] where the flow begins from turbulent conditions and vortex pairing phenomena are weak. These observations indicate the universality of the self-similar state of the turbulent mixing layer. In addition, we have analyzed the scaling of longitudinal velocity structure functions in the developed turbulence region; the extended self similarity (ESS) approach has been applied to identify a wide range of scales with the same exponents and intermittency levels of homogeneous isotropic turbulence [3]. Moreover, for larger scales, we observed an additional scaling range with smaller exponents, with values which are very similar to those reported in the literature for strong shear flows.

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Entrainment of stable zones and turbulence spreading in magnetized plasmas

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Turbulence in magnetized plasmas, especially tokamaks, is composed of flux driven convection cells a few gyro-radii ρ_i in width, and mesoscale structures which can approach the device size a (n. b. In tokamaks, $\rho_* = \rho_i / a << 1$). Of particular note, tokamak turbulence exhibits the tendency to entrain regions of local stability or, more simply put, to spread in space from unstable to stable domains. In a related vein, interaction of neighboring cells tends to form intermittent, spatially extended transport events which resemble avalanches. Not surprisingly, turbulence spreading and avalanche formation are intimately related and together constitute a fascinating class of emergent mesoscale turbulent mixing phenomena which also are central to tokamak confinement physics. In this lecture, I will discuss progress on the dynamics of mesoscale turbulent mixing and entrainment. Special focus will be given to:

a) dynamics of avalanches and their implication for secondary flow structures. E × B shear flow staircase formation is a prime example.

b) modeling of entrainment and spreading by nonlinear mean field reaction-diffusion equations and the front propagation phenomena which these models exhibit. Predictions from spreading front propagation models have been critically tested against the results of perturbative transport experiments.

c) the interaction of spreading and entrainment in drift-Rossby wav turbulence with secondary zonal shear flows. In particular, I will address the impact of this self-generated shearing on entrainment dynamics.

Nonlinear reaction-transport systems with memory effects: anomalous diffusion and fractional derivatives

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The main goal of the lecture is to discuss how to incorporate the nonlinear kinetic term into non-Markovian transport equations describing long-memory effects and anomalous diffusion. The emphasis is on the reaction-transport systems that are non-standard in the sense that the transport processes are described by fractional derivatives in space and time. We address the problem of the derivation of the basic fractional reaction-transport equations for the number density from the nonlinear mesoscopic random walk models. We focus on the nonlinear master equations for the density of reacting particles corresponding to the continuous time random walks with arbitrary jump and waiting time distributions. We employ these equations to the problem of front propagation in the reaction-transport systems with anomalous subdiffusion. The applications of new fractional equations span a vast range of interdisciplinary fields including turbulence, complex chemical reactions and population theory.

Statistical dynamical and stochastic subgrid modeling for geophysical flows

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Statistical dynamical closure based and stochastic model approaches to subgrid-scale modelling of eddy interactions are reviewed. It is shown how statistical

dynamical closure models can be used to calculate eddy damping and stochastic backscatter parameters required in large eddy simulations (LES) self-consistently from higher resolution simulations. A direct stochastic modelling scheme that is more generally applicable to complex models is then described and applied to large eddy simulations of quasigeostrophic turbulence of the atmosphere and oceans. We discuss the fundamental difference between atmosphere and ocean large eddy simulations which is related to the difference in the deformation scales in the two classes of flows and point out why the stochastic approach is crucial in the latter. A universal scaling law, which represents how the eddy viscosity and stochastic backscatter change with resolution, is developed for atmospheric flows. Finally, we discuss the application of inhomogeneous closure theory to the complex problem of general flow over topography. In all cases considered large eddy simulations incorporating the subgrid scale parameterizations are in excellent agreement with the statistics from higher resolution direct numerical simulations at the scales of the LES.

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Strain along gradient trajectories in passive scalar fields

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Based on direct numerical simulations of homogenous isotropic forced turbulence, homogenous shear turbulence, isotropic decaying turbulence, a turbulent channel flow as well as a Kolmogorov flow with Taylor based Reynolds numbers Re_λ between 69 and 295, the normalized probability density function of the length distribution $P(l)$ of dissipation elements, the conditional mean scalar difference $\langle \Delta k / l \rangle$ at the extreme points as well as the scaling of the two-point velocity difference along gradient trajectories $\langle \Delta u_n \rangle$ are studied. Based on the field of the instantaneous turbulent kinetic energy k, a good agreement between the model equation for $P(l)$ as proposed by Wang and Peters (JFM, 2008) and the results obtained in the different DNS cases is found. This confirms the theoretically predicted independence of the model solution from both, the Reynolds number and the type of turbulent flow, so that it can be considered universally valid. In addition, a 2/3-scaling for the conditional mean scalar difference following K41 is found.

In the second part of the contribution, the scaling of the conditional two-point velocity difference along gradient trajectories is examined. In particular, the linear s/τ scaling, where τ denotes an integral time scale and s the separation arclength along a gradient trajectory in the inertial range as derived by Wang (PRE, 2009) is compared with an $s.a_\infty$ scaling, where a_∞ denotes the asymptotic value of the conditional mean strain rate of large dissipation elements. The latter normalization not only provides a linear increase but also a unique slope for all DNS cases, thereby illustrating the physically meaningful generalization used in dissipation element analysis.

Competitive mixing and competitive thermodynamics

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Turbulence and other nonlinear stochastic processes of high complexity are characterized by a significant degree of regularity in their behavior, which restricts randomness and introduces a sophisticated order into the system. Although these processes are, of course, constrained by the laws of thermodynamics (as any other physical phenomena), explaining the complex behavior observed in these processes from the first principles of thermodynamics proved to be rather difficult. From the thermodynamic point of view these processes are non-equilibrium and dissipative. In the present work we investigate the possibility of introducing alternative or apparent thermodynamics that can be used to characterize this thermodynamically non-equilibrium behavior. Lagrangian methods of modeling turbulent reacting flows that have been developed during last decades own much of their efficiency to using notional particles with properties and mixing (Pope particles). The approach presented here views these particles not only as tools of modeling turbulent reacting flows but also as universal elements for constructing stochastic models capable of simulating a wide range of non-equilibrium phenomena, although this may require generalization of the concept of mixing. The conventional conservative mixing can be replaced by competitive mixing to simulate combustion and invasion waves and, more generally, properties of complex competing systems.

A novel model of spin-down of solar type stars

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Modeling the rotation history of solar-type stars is one of the outstanding problems in modern astrophysics. One of the main challenges is to explain the dispersion in the distribution of stellar rotation rate for young stars. Previous works have advocated diverse mechanisms to explain the presence of fast rotators and also of slow rotators. Here, we present a new model that can account for the presence of both types of rotators by, for the first time, incorporating fluctuations in the solar wind. This renders the spin-down problem probabilistic in nature, some stars experiencing more braking on average than others. We show that random fluctuations in the loss of angular momentum enhance the population of both fast and slow rotators compared to the deterministic case. Furthermore, the distribution of rotational speed is severely skewed towards large values in better agreement with observations than conventional models.

Nonlocal transport

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Transport studies are usually based on diffusion models. A key assumption of these models is the Fourier-Fick prescription that relates the fluxes to the local gradients of the transported field. From the statistical mechanics perspective, diffusive models assume an underlying Gaussian, Markovian, uncorrelated stochastic process. Although these models have been successfully applied to many problems, they fail to apply to systems exhibiting anomalous diffusion. From the Lagrangian perspective, anomalous diffusion is characterized by the anomalous scaling of the rate of change of the moments of the single particle displacements and by the slow decay of the Lagrangian velocity autocorrelation function. In the continuum, anomalous diffusion is characterized by non-local, in space and time, flux-gradient relations. Following a general overview of anomalous diffusion we discuss a class of non-local transport models of anomalous diffusion. In these models, the non-locality is incorporated using fractional derivatives that are integro-differential operators with self-similar, algebraic decaying kernels. We discuss the statistical foundations of these models in the context of continuous time random walk models with algebraic waiting times (modeling non-locality in time) and jump statistics corresponding to general Levy processes (modeling non-locality in space). We present applications of these models to non-diffusive test particle transport in three-dimensional plasma turbulence, non-diffusive chaotic transport in vortices in shear flows, and fast heat pulse propagation in high temperature plasmas. We also discuss comparison of the models with experiments in rapidly rotating fluids and magnetically confined fusion plasmas.

Statistical analysis of global wind dynamics in vigorous Rayleigh-Benard convection

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Experimental and numerical studies of thermal convection have shown that sufficiently vigorous convective flows exhibit a large-scale thermal wind component sweeping along small-scale thermal boundary layer instabilities. A characteristic feature of these flows is an intermittent behavior in form of irregular reversals in the orientation of the large-scale circulation. There have been several attempts towards a better understanding and description of the phenomenon of flow reversals, but so far most of these models are based on statistical analysis of few point measurements or on simplified theoretical assumptions. The analysis of long term data sets (greater than 5 10^5 turn-over times) obtained by numerical simulations of turbulent 2D Rayleigh-Benard convection allows us to get a more comprehensive view on the spatio-temporal flow behavior. By means of a global statistical analysis of the characteristic spatial modes of the flow we extract information about the stability of dominant large-scale modes as well as the reversal paths in phase space. We examine PDF's and drift vector fields of two-dimensional phase spaces spanned by different large-scale spatial modes. This also provides information about the coexistence of dominant modes.

Stochastic modeling of statistically unsteady turbulent mixing

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Rayleigh-Taylor and Richtmyer-Meshkov turbulent mixing are statistically unsteady processes. For their quantities, the mean value and the fluctuations are both

time-dependent. These turbulent processes have, however, a number of symmetries and are characterized by a set of invariant measures [EPL 91, 12867]. Employing these invariant measures, and further developing stochastic model in [Physics Letters A 371, 457] we analyze statistical properties of Rayleigh-Taylor and Richtmyer-Meshkov turbulent mixing in the case of sustained, time-dependent and impulsive acceleration. The effect of fluctuations on the flow quantities is studied. Requirements for statistical quality of experimental and numerical data are outlined. Mechanisms of mitigation and control of turbulent mixing processes are proposed. Their implementation in high energy density plasmas experiments is discussed.

Front propagation in anomalous diffusion-reaction systems.

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Reaction-diffusion systems describe numerous phenomena in nature. It has been recently understood that many diffusion processes are described by models of anomalous diffusion, which explain the observation of anomalously fast (superdiffusion) or slow (subdiffusion) growth of displacement moments of corresponding random walks. These models include spatial non-locality or/and temporal memory and involve integral operators (e.g., fractional derivatives) in addition to differential operators. The interplay between the anomalous diffusion and the reactions is not yet well understood. In the present talk, we analyze the propagation of reaction fronts in systems with anomalous diffusion. In the case of reaction-superdiffusion equations (spatially non-local equations), we start with the exactly solvable case where the reaction term is a discontinuous piecewise linear function. Applying the Fourier transform, we find traveling fronts and pulses, and discuss the effect of superdiffusion on the solutions. Specific problems that we consider include FitzHugh-Nagumo equations, domain wall pinning, and systems of waves. Also, we investigate the dynamics of fronts governed by a superdiffusive Allen-Cahn equation in one and two dimensions. In the case of reaction-subdiffusion equations (systems with memory), it is necessary to distinguish between the cases of subdiffusion limited and activation limited reactions. In the former case, the system is governed by models with fractional time derivatives, and the front is described by a traveling wave solution. In the latter case, the system is subject to “aging”, which is described by integro-differential equations with two time variables, and the velocity of the front decreases with time.

ADVANCED NUMERICAL SIMULATIONS

Numerical simulation of advection-diffusion of a passive solute in unsteady water flow

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Different diffusion/dispersion (diffusion in the following) models are tested in a two-dimensional solute transport simulation in unsteady shallow water flow. The shallow water and the solute flow equations are coupled in order to avoid numerical instabilities [1]. The system of equations is solved with an explicit finite volume scheme in a triangular unstructured mesh. In the experiment considered in this work, a solute is released in a channel flow after breaking a side dam. An schematic plot of the laboratory setup is depicted in the attached figure. The width/depth ratio is approximately 15, in good agreement with the shallow water approximation. In this work we explore several formulations of the diffusion coefficients K in order to match the experimental data of the solute concentration evolution at a control section: (i) In the literature [2], K is a diagonal matrix with different components, longitudinal and transverse. These components are usually taken to be proportional to the water depth and the so-called shear velocity, times a directional factor. (ii) In this work we propose a new approach, where the anisotropy is carried by a variable said 'directional shear velocity'. (iii) Additionally an isotropic diffusion coefficient has been used, (iv) and finally a simulation without diffusion has been done in order to explore the numerical diffusion of the advection scheme. Different experimental cases, with obstacles introduced to modify the flow, are considered in the performed simulations. In addition, different initial depth levels in the solute tank -higher and lower than the channel depth- have been used. Each simulation corresponds to a laboratory experiment [3] with fluorescein as solute, its concentration measured along the unsteady event at a transverse section of the channel with the help of an Ar continuous laser. The depth averaged experimental concentration has been compared with the simulations. The differences between the different diffusion models will be discussed as well as the repercussions of the flow changes -due to obstacles, etc- on the solution.

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Numerical study of instability between two cylinders in the case of 2D flow

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Investigations of flow stability between two cylinders have besides fundamental interest, also large practical sense, because such flows often meet with different technical equipments. Mathematical model based on inviscid compressible gas model and involve integral laws of conservation of mass, energy, kinetic momentum. The system of equations closes by equation of state of ideal gas. Supposed, that number of Reynolds (numerical Reynolds) sufficiently great, that flow is unstable. In the capacity of initial data takes the Couette flow. In the middle of clearance between cylinders carries in the local perturbation of radial componentry of velocity with small amplitude and define frequency. At the border used nonflow conditions. Numerical simulation is conducted using the TVD method. The simulation was carried out on polar mesh. Also, was carried out the investigations on clearing of character of mesh influence, they showed, that mesh small influencing on scale of large vortexes. At reducing of mesh, the numerical viscosity was decreasing, and correspondingly the numerical Reynolds was increasing. The investigation had taken on several parameters of job: difference of velocities of internal and external cylinders, width of clearance between cylinders, amplitude and frequency of disturb. In process of calculations, inner cylinder was resting, external was rotating. Finding of investigation showed, that how large the difference of velocity thereby unsteady the flow. At certain width of clearance the dependence graph of time from width of clearance have minimum. The amplitude of perturbation influences the flow weakly. In case frequency of perturbation, had observed long-wave instability: than less the frequency of perturbation, that earlier flow becoming unstable. Beginning of the instability is going with birth of large vortexes. Bearing, the vortexes is beginning actively interaction between itself and are coupling, in total to end of calculations have remained several vortexes with size about width of clearance between cylinders.

Incompressible Navier-Stokes and other new capabilities in FLASH-4

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FLASH is the component based scientific application software with an embedded high level framework which enables flexibility and extensibility. The code has traditionally been used simulating the compressible, reactive flows found in many astrophysical environments. Over the past couple of years the extensible framework has been exploited to expand the code capabilities, and therefore its reach to other research communities. The notable new capabilities are in the fields of Computational Fluid Dynamics with Fluid-Structure Interactions (CFD/FSI) and High-Energy Density Physics (HEDP). A more open version of the code with CFD/FSI capabilities will be available from the mirror site at George Washington University. In this tutorial paper we give an overview of the FLASH code architecture with emphasis on the new CFD/FSI capabilities. We also include examples of customized applications in incompressible flows, such as Direct Numerical Simulations (DNS) of turbulent boundary layers at high Reynolds numbers and their interaction with bluff bodies.

Two-dimensional turbulence: where do we stand?

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Turbulence in two spatial dimensions is an idealized form of turbulence having unique properties including an inverse cascade of kinetic energy and a forward cascade of enstrophy. The applicability of the idealized Kriachnan theory of forced, dissipated two-dimensional turbulence to real physical system will be discussed, and the main strong conclusions regarding 2D turbulence will be presented. Many features of 2D turbulence are realized in physical systems from the vortex-gradient stretching mechanism of enstrophy transfer in the forward cascade to the existence of a Kraichnan-Kolmogorov inverse energy cascade. Other properties are validated from very high resolution numerical simulations. The impact of these results on more complicated physical systems such as planetary atmospheres will be discussed.

On vortex tube temperature separation effect

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The vortex tube is a simple device, having no moving parts, which produces hot and cold air streams simultaneously at its two ends from a source of compressed air (Fig. 1). Main feature of swirling flow that develops inside vortex tube is the gas temperature separation effect that was closely investigated in various experiments [1]. Numerical simulation of quasi-3D inviscid gas flow in vortex tube is conducted using finite volume approach and method [1, 2]. The present paper is devoted primarily to the observed temperature effect and analysis of its dependence on different parameters . For this purpose different configuration of vortex tube geometry and inlet nozzle were investigated as well as a range of compressed air pressure. New way of applying inlet boundary conditions were designed and tested for better reproduction of its physical characteristics. Example of temperature field distribution is found.

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Investigation of spectrum characteristics of the vortex cascades in shear flow.

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In this poster we present new results obtained in numerical modeling of the vortex cascade phenomenon in an unstable shear flow in case of an initial deterministic velocity perturbation in the form of one Fourier mode: As in the case of a random initial perturbation in the velocity [1,2], the vortex cascade comes into existence in case the following conditions are met: (1) The width of the channel is more than in X-direction; (2) The length of the channel is more than in Y-direction; (3) The amplitude of initial disturbances is larger than of the shear velocity V. We obtained a dependence of the kinetic energy on wave number by means of the Fourier expansion of the velocity components. Also we demonstrated existence of an inertial interval for the kinetic energy. Developed turbulence in shear flow and dependence of the kinetic energy on wave number.

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Hydrodynamic instability theory of the causes and projections of climate change

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During the last sixty years there have been large changes in Southern Hemisphere autumn and winter circulation and reductions in rainfall particularly in the southern Australian region. Here we examine the corresponding changes in hydrodynamic instability modes ranging from storm tracks, onset of blocking modes, Northwest cloud-band disturbances, Antarctic low frequency modes, intraseasonal oscillations and African easterly waves. We employ a global two-level primitive equation instability-model and here we examine changes in a wide variety of atmospheric modes of variability growing on reanalyzed observed May and July three-dimensional basic states for the periods 1949-1968, 1975-1994 and 1997-2006. We relate the reduction in the winter rainfall in the Southwest of Western Australia since the mid-1970s and in South-eastern Australia since the mid-1990s to changes in growth rate and structures of leading storm track and blocking modes. We find that cyclogenesis and onset of blocking modes growing on the subtropical jet have significantly reduced growth rates in the latter periods. As well there is a reduction of the intensity of the subtropical storm track and increase in the polar storm track particularly in autumn. On the other hand there is a significant increase in the growth rate of Northwest cloud-band modes and intraseasonal oscillations disturbances that cross Australia and some smaller increase in the intensity of African easterly waves. The implications of our findings are discussed. The relationship between changes in the baroclinic instability and changes in rainfall during the twentieth century is discussed. We also consider projected changes and trends in rainfall and baroclinic instability in SRES scenarios using results from CMIP3 climate change models. In particular, we focus on changes between the periods (2040 – 2059) and (1980-1999), and (2080-2099) and (1980-1999). We elucidate the roles of anthropogenic forcing and internal variability. Our results show that the impact of further increases in anthropogenic CO_2 concentrations can lead to further large reductions in baroclinic instability, by the end of the 21st century, that are more than twice those simulated by models at the end of the 20th century, relative to pre-industrial conditions. Associated reductions in southern hemisphere rainfall in a band near 30S, including southern Australia, can also be as much as twice those seen at the end of the 20th century.

C.S. Frederiksen, J.S. Frederiksen, J.M. Sisson and S.L. Osbrough: Australian winter circulation and rainfall changes and projections. Int. J. Clim. Change Strat. Mang., 3, 170-188, (2011). C.S. Frederiksen, J.S. Frederiksen, J.M. Sisson and S.L. Osbrough: Changes and projections in Australian winter rainfall and circulation: Anthropogenic forcing and internal variability. Int. J. Clim. Change Impacts Responses, 2, 143-162, (2011). Frederiksen, J.S., C.S., Frederiksen, S.L. Osbrough, J.M. and Sisson: Causes of changing southern hemisphere weather systems. Managing Climate Change, Chapter 8, 85–98 (2010). CSIRO Publishing, 278 pp. Frederiksen, J.S., and C.S. Frederiksen: Interdecadal changes in southern hemisphere winter storm track modes. Tellus, 59A, 599–617 (2007).

Collaborative comparison of high-energy-density physics codes

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Advances in plasma physics, powerful lasers, and pulsed-power machines have made possible experiments allowing detailed exploration and exciting discoveries about states of matter at high temperatures and energy densities. Simulations play an important role in understanding these experiments due to the complexity associated with diagnosing and performing them. A number of sophisticated radiation-hydrodynamic codes have been developed to perform this task. We will describe a new collaboration to compare some of these codes for a variety of HEDP test problems and experiments. Current members of this collaboration are the Flash Center at the University of Chicago, the Center for Radiative Shock Hydrodynamics (CRASH) at the University of Michigan, Los Alamos National Laboratory, and Lawrence Livermore National Laboratory. Currently we are comparing efforts to simulate ongoing radiative shock experiments being conducted by CRASH at the OMEGA laser facility that are relevant to a wide range of astrophysical problems. The experiments drive a collapsed planar radiative shock through a Xenon-filled shock tube. Attempts to obtain agreement between simulations and experiments have uncovered various challenges. Code-to-code comparisons enable us to understand differences in numerical methods, physical approximations, microphysical parameters, etc. The net result will be an improvement in the codes and higher confidence in the simulation results.

Compressibility effects in Rayleigh-Taylor flow: influence of the stratification.

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Many physical process simulations require high accuracy solutions (stability theory, numerical simulation of turbulent flows and acoustics in fluid dynamics, for example). On the other hand, length and time scales may strongly change with time. To meet these two requirements a pseudo-spectral adaptive Chebyshev multidomain numerical method has been devised. In this method, the distribution of collocation points is given by the set of M subdomains, in which a coordinate transform is used which depends on a real parameter. As a result, the set of collocation points is defined by 2M - 1 real parameters. A criterion which minimizes the interpolation error is used to dynamically determine these parameters. A numerical code which solved the full Navier-Stokes equations and based on Chebyshev-Fourier-Fourier expansions has been developed. A stability analysis code based on the same equations and algorithm has also be developed. The Rayleigh-Taylor flow for two miscible compressible viscous fluids is then solved in the linear and nonlinear regimes. Three main parameters govern the compressibility effects: the stratification parameter—attached to the hydrostatic equilibrium—and the adiabatic indices of the two fluids—attached to the fluids. The present communication reports on the influence of the stratification on the turbulent mixing layer development. To this end, two direct numerical simulations of the Rayleigh-Taylor flow have been carried out with a stratification parameter equal to Sr=2 (slightly stratified) and 6 (strongly stratified), and an Atwood number equal to 0.25. A careful data analysis is performed: characteristic quantities of the turbulence and mixing structures, and various contributions to the mean flow quantities are considered (source terms of the turbulent kinetic energy equation: density fluctuations variance, density-velocity, pressure-dilatation correlations, and the vorticity equation). In particular, it appears that stratification strongly modify the mixing layer development. For large values of the stratification, the flow is stabilized and no self-similar regime appears.

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Comparison of turbulence models for hydrodynamic study of forward facing step using open FOAM

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Flow separation and subsequent reattachment occurring due to sudden expansion or contraction plays an important role in the design and operation of devices where heating or cooling of the medium is present. Significant effect of mixing of high and low enthalpy fluid happens in the reattached regions of these devices. Such geometries are the best model through the backward-facing step or the forward-facing step. The flow has features such as separation, reattachment and recirculation. In forward-facing step (FFS) geometry, the flow field is more complicated as compared to that in backward-facing step. Studies of FFS under laminar flow conditions are reported in literature. In our earlier work, conjugate heat transfer in FFS geometry was analysed using the k-omega model. However, the applicability of this model in the presence of flow separation, reattachment and recirculation needs to be investigated. This problem is taken up in this paper. In the current work, the hydrodynamics of FFS geometry is analysed using the standard k-epsilon, k-omega, SST, RNG k-epsilon, Realizable k – epsilon , Non-linear Shih k – epsilon, Lien cubic k – epsilon, and q − zeta turbulence models. The open source CFD code OpenFOAM has been suitably modified and used in this analysis.

Application of turbulent mixing flows: Rayleigh-Taylor instability

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Turbulent and mixing flows remain a fundamental challenge for computational fluid dynamics. Turbulent flow occurs characteristically at high Reynolds numbers. Mixing flows often involve steep concentration gradients or discontinuities. In a combination of mixing and turbulence, the interface defined by the concentration interface may become highly convoluted. The Rayleigh-Taylor instabilities are classical acceleration driven fluid instabilities. The growth rate of the mixing layer, characterized by a dimensionless but non-universal parameter, describes the outer edge of the mixing zone. The combination of Front Tracking/Large Eddy simulations reveals non-universality of the growth rate and agreement with experimental data. Experiments are typically conducted in a tank subject to a vertical

acceleration, with a heavy fluid placed below a light one. The entire apparatus is then accelerated rapidly downward, in effect reversing the direction of gravity. In this geometry, the size of the mixing region is given by the penetration distance of the light fluid (bubbles) into the heavy and the heavy fluid (spikes) into the light. Our simulations have shown agreement between simulation and experiment for Rayleigh-Taylor turbulent mixing rates. A long standing controversy concerning the initial conditions for the experiments, and specifically the possibility of small amplitude long wave length perturbations of the initial, nominally flat interface between the two fluids are studied. We have quantified the allowed long wave length perturbation amplitudes, by an analysis of the early time data, which were recorded. We estimate the uncertainty in growth rate of the mixing layer to be 10% or less, based on simulations which included (I) no initial long wave length perturbation and (II) double the reconstructed long wave length perturbation amplitudes.

Numerical simulations of countercurrent flow in a separating gas centrifuge

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The separation of a binary mixture over the radius due to spinning can be significantly enhanced by using an axial countercurrent flow (circulation). An advantage of centrifugation is that the separation process can be controlled by the temperature on the lateral wall because a countercurrent circulation in a rapidly rotating rotor can be originally excited by nonuniformly heating its wall. In this work approximate solutions for linear temperature distribution at the wall were obtained assuming that the axial countercurrent flow introduces small perturbations into the basic (isothermal solid-state) spinning of the gas in the two-dimensional (axisymmetric) approximation. In this way the linearized equations of motion of the viscous and heat conductive gas and mass transfer were numerically solved using second-order accurate implicit schemes in space. The resulting field of axial velocity component is found. Then steady concentrations distribution of separated two-component mixture was found by means of obtained gas characteristics. The most unexpected result obtained in the simulation was that the stability loss of the basic flow gives rise to several countercurrent flows with their streamlines nested into one another.

Dimensionality influence on the passive scalar transport observed through numerical experiments on turbulence shearless mixings.

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We present new results concerning the passive scalar turbulent transport in two and three dimensions in a shear-less mixing layer. We consider the system where one energetic turbulent isotropic field is left to convectively diffuse into a low energy one. In this system the region where the two turbulent flows interact is associated to a high intermittent thin layer that propagates into the low energy region. We have seen that the diffusion process in 2D is faster then in 3D. In 2D the time growth of the interaction width is super-diffusive, while in 3D is slightly sub-diffusive, as in the wind tunnel experiments by Veeravalli and Warhaft (JFM 1990). In both cases the passive scalar temporal spreading follows the spreading of corresponding kinetic energy field. The presence of the turbulent energy gradient is felt on the distribution of statistical quantities, as the skewness, kurtosis and spectra, across the layer. In two dimension, the passive scalar spectrum computed inside the mixing region presents an exponent in the inertial range which is half of the usually met exponent of the velocity fluctuation spectrum, typically close to - 3. In three dimension, we instead observed a mild difference between these two spectral exponents. The present results are obtained from direct numerical simulations of the diffusion of the passive scalar across an interface which separates the two isotropic turbulent fields. The size of the computational domain is 4pix2pi (1200 x 600^2 grid points, Re_λ=150) in the 3D simulations and $(2\pi)^2$ (1024^2 grid points, Re_λ equivalent of the order of 10^2) in the 2D simulations.

Effect of initial conditions on single and two-mode Rayleigh-Taylor instability

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The dependence on initial conditions of single and two-mode Rayleigh-Taylor instability (RTI) is investigated using Direct Numerical Simulations (DNS). The numerical results of single-mode RTI simulation compare well with the linear stability analysis and the experimental results of Waddell et al.; in addition, the bubble velocity reaches a quasi-constant value during the potential flow evolution of the instability. To ensure that the solution is fully converged, extensive resolution studies were also performed. A new stage, chaotic development stage, was found after the re-acceleration stage in single-mode RTI. During the chaotic stage, the instability experiences seemingly random acceleration and deceleration phases as a result of complex vortical motions. The vortexes are generated at the interface and the subsequent interactions are very sensitive to details of the initial perturbation shape, such as diffusion thickness and perturbation amplitude. Although the initial perturbation shape influences the early and late time behavior, it has a minimal role during the potential flow regime and the 'constant velocity' prediction remains robust during this regime. We have also studied the effect of initial conditions on two-mode RTI, and found that the mixing layer growth is strongly affected by the combination of mode numbers and amplitude as well as phase shift between modes. At late time, the motions becomes quite complicated, however, some new phenomena, such as leaning, ejections, and mode resonance, can be identified as significantly influencing the mixing layer growth rate.

EXPERIMENTS and EXPERIMENTAL DIAGNOSTICS

Investigation of the mechanisms of microparticles cloud formation by shock wave arrival on condensed matter free surface

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The results of the first experiments to study the mechanism of cloud formation of microparticles when the shock wave exits at the free surface layer of the condensed matter due to the development of instabilities of various types in laboratory conditions are describe. The experiments of two types - in both flat and cylindrical geometries are performed. In the first case shock waves were initiated by an impact of a thin layer of water. In the second case shock waves were created by electrical explosion of wires at the axis of the cylindrical sample of the condensed matter. Characteristic scale of velocity ~ 300 m / s. The velocity of microparticles was detected by PVD technique. The size of microparticles was detected by the projection technique.

First results from the variable density turbulence tunnel

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We report measurements of the streamwise and spanwise velocity fluctuations in decaying wind tunnel turbulence behind a passive grid. The experiments were conducted in the recently completed variable density turbulence tunnel at the Max Planck Institute for Dynamics and Self-Organization. We used two fluids, air and sulfur hexafluoride, and adjusted the pressure of the gas in the tunnel between 1 and 15 bar to vary the kinematic viscosity by a factor of 100. In doing so, we varied the Taylor microscale Reynolds number by more than an order of magnitude, from 130 to 1700 without changing the flow speed or grid geometry. We discuss the dependence of the large-scale characteristics, the inertial range scaling, and the energy dissipation rate on the Reynolds number. The measurement section in the tunnel had a cross-sectional area of 1.9 square meters, and was 8.8 meters long. The flow was driven in the recirculating tunnel with a 240 kW fan at a speed of 5 m/s. A biplanar grid of crossed bars generated the turbulence, of classical construction. The solidity of the grid was 35% and the mesh spacing was 107 mm. The velocities of the flows were measured with hot wire anemometers 67 times the mesh spacing, i.e., 7.1 m, downstream of the grid. The wire probes were mounted on a pair of linear translation stages. The turbulence intensity and the integral length were approximately constant with Reynolds number, and were about 2.5% and 9 cm, respectively.

Rayleigh-Taylor instability between stable stratifications

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Our understanding of Rayleigh-Taylor instability between two homogeneous layers is finally reaching maturity. After painfully slow progress has been over the last twenty or more years, we can finally say we understand much of what is going on, even if there are many details where precise understanding remains elusive. It is timely, therefore, to move on and consider the next level of complexity in Rayleigh-Taylor instability. In this paper we will move away from an unstable interface separating two homogeneous layers (of different densities) and explore the evolution of a Rayleigh-Taylor unstable interface embedded in an otherwise stable density stratification. While the nonlinear instability will initially accelerate in a manner similar to the classical t^2 growth, the density difference between the top and the bottom of the mixing zone will progressively decrease as it eats into the stable stratification, bringing about a reduction in growth rate and eventual saturation with a mixing zone of finite vertical extent. We will examine both the evolution of the flow, and explore what this can tell us about mixing in stably stratified flows.

Rotating thermal convection: a review

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Thermal convection with rotation about a vertical axis plays an important role in many geophysical and astrophysical contexts. Laboratory realizations of Rayleigh-Benard convection began in the middle of the 20th century although the first measurements of heat transport were performed by Rossby in 1969. I will review laboratory experiments of rotating convection including flow visualization, heat transport and local temperature and velocity measurements that set the stage for recent experimental and numerical work on rotating convection over the last several years.

Of particular interest is the enhancement of heat transport by Ekman pumping of the boundary layer by localized vorticies and the lateral homogenization of temperature gradients with rotation that leads to appreciable vertical gradients of temperature.

Laboratory models for hydrodynamic instability investigation

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Introduction of laboratory tasks within the framework of university gas-dynamics course into the practice of students' educational process is actual and at the same time complicated problem. The difficulties are of organizational character and connected with a necessity of use in a gas-dynamic experiment dangerous pulse power sources (high explosives, compressed gases, electric explosion etc). In this report two installations for carrying out laboratory tasks are presented with the purpose of study: - Rayleigh-Taylor instability at the gas-liquid interface; - cumulation processes of the converging cylindrical shock-wave and cumulation limitation due to the instability development. The first installation is based on the use of the atmospheric shock tube (Patent of Russia №2393546, 2010) in which the energy of atmospheric air is used as a pulse power source. In the second installation the imitation of converging cylindrical shock-wave is done by means of the use of hydrodynamic model of "shallow water". Presented installations are absolutely safe and don't require any special admission for work. They can be used not only for carrying out the laboratory tasks but for conducting the investigation work by students.

Effect of initial conditions on Rayleigh-Taylor mixing: wavelength interaction

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The effect of initial conditions on the Rayleigh-Taylor experiments were investigated in the water channel facility [1] at Texas A&M University (TAMU) at low Atwood numbers is investigated. Earlier work by Kuchibhatla et al. [2] probed the novel setup of a controllable mechanism for reliably generating multi-modal initial conditions at the two-fluid interface. In this present work, experiments were performed to observe the effect of imposing smaller wavelengths on larger wavelength RTI flows using the flapper mechanism. Sets of experiments with varying number of modes and wave number ratios were performed for this parametric study at the new Water channel setup commissioned at TAMU. As part of the preliminary study, high-resolution images of the flow structures corresponding to bi-modal initial conditions with one large and another small component wave number were acquired. Temperature profile measurements using fast thermocouples for these flows were performed in several planes in order to provide mixing data. The later part of the study involved repeating the above experiments by increasing the number of modes up to five components. Calculated mixing variables indicate that the higher mixing is achieved by the introduction of larger wave numbers and also by increasing the number of modes.

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Flow Structures of Scalloped and Forced Lobed Mixers

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An Experimental study of internal forced lobed mixers similar to those used in jet aircraft engines is performed using whole field species concentration and velocity measuring techniques. Measurements using Planar Laser Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV) are performed for lobed, lobed scalloped and splitter mixers in aqueous solution. Specific emphasis is given to study scallops or notches cut into the mixer trailing edge and their role in mixing enhancement. Mixing is compared through velocity and species concentration measurements on axial and cross streamwise planes for the three dimensional forced mixers in a confined constant area mixing duct. Scalloped lobed mixer results clearly indicate an additional pair of small-scale streamwise vortices shed periodically, not observed in the results obtained for the lobed mixer. The scalloped geometry seems to do a better job of mixing compared with the lobed shape, most likely due to generation of an additional vortex pair near the core of the mixing layer. Additionally, impingement of the cross stream velocity on the mixing duct is further downstream than for the lobed mixer under same test condition. Lastly, the decay of cross stream velocity shows the scalloped mixer to decay from the exit plane while the lobed mixer indicates initial rise in magnitude before decay.

Transformation of flying cylindrical water shell model

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The hydrodynamic laboratory of SarPhTI NRNU "MEPhI develops the technology of suppression of large-scale (wood-riding) fires by water shells accelerated by the pressure of the products of burning or/and the detonation of the combustible gas mix. The report presents the results of the first stage of work -- the experimental research of the process of deformation (under the influence of aerodynamic forces) and disintegration (owing to the development of hydrodynamic instabilities) of a model of a cylindrical water shell flying in the air. The flight of the shell's model was its free falling from the height of up to 10 meters. The flow was recorded by photocamera Casio Exilim EX-F1 in the mode of video shooting with a speed up to 1,200 shots per second. In the experiments, the diameter and length of the shell's model were varied.

Some peculiar features of hydrodynamic instability development

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The paper presents a review of experiments performed with the participation of the author of this paper. The experiments illustrate some features of a turbulent mixing zone structure at the gas-liquid interphase (Raileigh-Tailor instability) and at the gas-gas interphase accelerated by shock waves. The peculiar feature is the existence of a heavier substance concentration jump at the interphase between heavy medium and a turbulent mixing zone. It is assumed that the existence of this jump is a generic feature of any developed turbulent mixing zone and is the necessary condition for its continuous development. In case of the gas-liquid interphase the stable existence of this jump provides a stable top of gas bubbles penetrating into liquid in a turbulent mixing zone. The peculiar feature of development of interphase instability accelerated by unsteady shock is the decaying ability (up to full suppression) of the interphase instability in case, when a decaying wave passes through the interphase in the direction from light to heavy medium.

Some peculiarities of turbulent mixing growth and perturbations at hydrodynamic instabilities

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The author presents a review of some experimental works devoted to research of evolution of large-scale perturbations and turbulent mixing in liquid and gaseous media during growth of hydrodynamic instabilities. In particular, it is shown that growth of perturbations and turbulent mixing in gases is sensitive to the Mach number of shock wave; character of gas front penetration into liquid is not changed as the Reynolds number of flow increases from 5×105 to 107; change of the Atwood number sign from positive to negative causes stop of gas front penetration into liquid, but mixing zone width is expanded under inertia.

Microscopic electron-optical recording of particle ejecta from free surface of shock-loaded lead

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The authors present results of microscopic electron-optical recording of particle ejecta from free surface of shock-loaded lead, where the free surface has different roughness levels (Rz80, Rz20, Rz5), after shock wave arrival to the surface at pressure of >> 15 GPa. The process was recorded by video camera through a system with relatively high optical magnification coefficient. Short laser pulse (4 ns) was used for illumination of the process. Lead particles with sizes of 3 mm and more were recorded, and their spectrum was depicted.

Local perturbation growth on gas-liquid interface at Rayleigh-Taylor instability

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The authors present results of experimental investigation of growth of hemispherical local perturbations on the gas-liquid interface at the Rayleigh-Taylor instability. A liquid layer (a low-strength jelly of water gelatin solution) was accelerated by compressed air in a channel with the internal diameter of 210 mm (KU-210). Displacement of the liquid layer reached S = 350 mm; the Reynolds' number reached Re = 107; the acceleration value reached $102g_0$ - $103g_0$. A local perturbation was specified on a knowingly instable surface of the jelly layer as a hemispherical recess with the radius R = 2 mm, R = 3 mm, or R = 6 mm. The process was recorded by video camera. It is revealed that when displacing the layer for S < 50 mm and increasing the initial size of perturbation from R = 2 mm to R = 6 mm, velocity of its growth in the liquid increases about 2 times. When displacing the layer for S > 50 mm, growth velocities of local perturbations become approximately similar.

Turbulent convection at very high Rayleigh and Taylor numbers

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Turbulent convection is studied at very high Rayleigh and Taylor numbers using helium gas in a cylindrical containers of diameter-to-height aspect ratios ½, 1 and 4 . For convection under rotation, the heat transport at high Rayleigh numbers is always observed to be smaller than that for the non-rotating case for all Rossby numbers investigated in a wide range about unity and for steady rotation about the vertical axis. When the rotation rate varied periodically in time, however, a sharp transition to a state of significantly enhanced heat transport is observed. In non-rotating convection at moderately high Rayleigh numbers, the Nusselt number generally follows an approximately 1/3 power of the Rayleigh number but an enhancement of heat transport is observed for higher Rayleigh numbers, coinciding with a substantial increase in Prandtl number as well as in various measures of Boussinesq conditions, and marking the transition from the region in which Nu ~

0.064 $Ra^{1/3}$ to another in which Nu ~ 0.078 $Ra^{1/3}$. This transition does not occur at a unique value of the Rayleigh and Prandtl numbers and so cannot be mistaken for the 'ultimate regime' of Kraichnan. Instead, we empirically find, by comparing various experiments performed under different conditions (but in the apparatus with the same horizontal surfaces), that this enhancement correlates well with substantially negative values of a non-dimensional parameter related to fluid conductivity and viscosity. Finally, Low temperature conditions allow oscillations of the solid surface temperatures and in this way we can directly measure an effective thermal diffusivity. These experiments allow us to deduce the thickness of a highly conducting core region at very high Rayleigh numbers.

Short review of the RFNC-VNIITF experimental investigations on gravitational turbulent mixing

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Operation of any devices by which investigations in the region of the high-density energy are carrying out is particularly sensitive with respect to a number of physical processes, including the gravitational instabilities which lead to turbulent mixing. The Rayleigh-Taylor and Richtmyer-Meshkov instabilities are sorts of hydrodynamic instabilities which emerge at the interface between two media of different density when it is either an impulsive or quasi-steady acceleration. For example, in the ICF-targets gravitational hydrodynamic instabilities emerge at the contact boundaries and change the dynamics of the process. Experimental study of regularities of these instabilities evolution and gravitational turbulent mixing with using just the ICF-targets is a greatly difficult problem, so another way is using in VNIITF. These instabilities and turbulent mixing are investigated by using modeling installations, and the results are employed for development of physic-mathematical codes to calculate the target dynamics and optimize it. A short review of basic experimental works on study gravitational turbulent mixing carried out by using the RFNC-VNIITF modeling installations is presented in the given work, and new directions of investigations are observed.

Static and dynamic testing of apparatus to study scale effects of gas-filled bubbles

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The apparatus intended to investigate dynamics of gas-bubble compression was used to perform static and dynamic tests. Static tests were used to measure the deflection of the membrane-shaper under various static pressures in liquids, while dynamic tests were used to measure velocity of one of membrane-shapers under quick relief of pressure in the gap between the rapture membrane and the second membrane-shaper. Both dynamic and static tests were performed under the pressure up to 30 atmospheres. Comparison of experimental and calculated data was made.

Experimental study of gas-bubble evolution on single exposure to variable pressure field

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This paper gives experimental results for the geometry of a gas bubble floating up in liquid in the case of single exposure to the pressure pulse. The apparatus operated in the mode of rarefaction-compression wave generation in liquid was used for experiments with two media: gas-air and liquid-water. Geometrical sizes were registered with the help of the optical shadow method. Experimental results were used to determine how evolution of dimensionless volume of the upfloating gas bubble depends on time $\left(V(t)/V0\right)$ in the case of exposure to the variable dimensionless-pressure field in time $P(t)/P0$.

Experimental apparatus to investigate gas-filled bubbles in liquids

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Two experimental apparatus are developed to investigate dynamics of gas-bubble compression. Both apparatus are manufactured; main elements of apparatus and rapture membranes are tested. This paper describes the design of both apparatus and identifies physical and functional aspects of the experimental setup.

The investigation of fluctuating liquid interfaces with X-ray surface scattering

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X-ray surface scattering has been used during the past decade to investigate a variety of fluctuation phenomena at liquid surfaces. These include studies of thermally induced capillary fluctuations whose amplitudes span length scales from 0.1 nm to 20 nm and whose in-plane length scales vary from nanometers to micrometers or larger. Studies have probed fluctuations at single, free interfaces, as well as oscillations of two interfaces that are coupled through a very thin intervening layer of liquid. These studies provide an improved understanding of interfacial fluctuations and their effect on the scattering of x-rays, as well as a probe of the effect of intermolecular interactions acting across thin films.

PLIF analysis on the fractal dimension of high-Schmidt number scalar mixing in fractal-generated turbulence

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Fractal-generated turbulence created by multiscale fractal grids, proposed by Hurst & Vassilicos (Physics of Fluids, 2007), has a couple of singular natures in turbulence scales and the dissipation coefficient of turbulence kinetic energy (Seoud & Vassilicos, Physics of Fluids, 2007). Our present work attempts to investigate the

high-Schmidt number scalar mixing in fractal-generated turbulence by means of the recently improved high accuracy planar laser induced fluorescence (PLIF) technique. In our PLIF technique, the time variation of various quantities such as the fluorescence quantum yield and the camera gain leading to serious noise have been corrected at every pixel by a pixel-by-pixel correcting method. Fractal dimension was calculated by the box counting method in a two-dimensional measuring region of the scalar mixing layer. Two types of grids were used to generate the quasi-homogeneous and the quasi-isotropic turbulence: the one is a regular grid consisting of square-rod, square-mesh and biplane construction, and another is a square-type fractal grid with four iterations. The Reynolds number based on the effective mesh size of the grid and cross-sectionally averaged mean velocity is 2,500 for both cases. Rhodamine B was used as a high-Schmidt-number passive scalar. The Schmidt number is about 2,100. Velocity fields were measured using the time-resolved particle image velocimetry. The results show that a fractal dimension in the regular grid turbulence does not significantly vary in the downstream direction and its value is about 1.45 at x/M_{eff} = 10, where x is the streamwise distance from the grid and M_{eff} is the effective mesh size of the grid (~10 mm in the regular grid). On the other hand, a fractal dimension in the fractal-generated turbulence increase in the downstream direction and its values is about 1.55 at x/M_{eff} = 80, where M_{eff} = 5.68 mm in the fractal grid.

Measuring Lagrangian accelerations using an instrumented particle

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Hydrodynamic flows are usually characterized by means of optical methods such as PIV, LDV or PTV. Although laboratory mixers can be designed to give access for such measurement techniques, “real world” mixers such as those employed in chemical industry lack a sufficient number of windows to experimentally characterize the flow inside. However, a profound knowledge of the flow is crucial to efficient mixing. In some cases Eulerian probes – e.g. Hot-Wire/Hot-Film Anemometers and Pressure sensors –can provide information on the flow; nevertheless their use is limited and these techniques don’t enable one to measure in a Lagrangian reference frame. We developed a novel measurement apparatus – an instrumented particle - with an embarked 3D accelerometer operating at 330Hz and a wireless transmission system. The instrumented particle is neutrally buoyant in water, operates up to one week and is similar to the one that had been used to obtain a Lagrangian temperature within a Rayleigh-Bénard convection cell [Shew et al RSI, 2007; Gasteuil et al PRL, 2007]. Because of its small size and the wireless data transmission, the system can be used in industrial mixers allowing a better understanding of the flow within. We demonstrate the capabilities and precision of the particle by comparing its transmitted acceleration to simultaneous 6-dimensional particle tracking resolving both position and absolute orientation in a turbulent von-Kármán-flow [Zimmermann et al RSI 2011, Zimmermann et al PRL 2011]. Our apparatus shows to be a promising tool to measure Lagrangian turbulence.

INDEX of PRESENTATIONS

AUTHORS' INDEX

A

B

C

D

L

M

N

O

P

Q

R

S

T

V

W

Y

Z

NOTES